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The NOWITECH Reference Wind Farm

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Abstract

The NOWITECH Reference Wind Farm is a base case wind farm model created for research and benchmarking. The reference wind farm is using an adapted version of the DTU 10 MW reference turbine, and is similar to the Dogger Bank Creyke Beck A wind farm in terms of size and distance to shore. The focus of this paper has been to research cost effective solutions for the internal grid in an offshore wind farm. As offshore wind farms and wind turbines grow in size, it could be a better solution to install 66 kV collector grids within the wind farm rather than 33 kV collector grids. In order to save costs it is also researched if it is possible to eliminate the expensive transformer substation within offshore wind farms connected to shore with HVDC technology, as the HVDC converter platform already contains a transformer. The reference wind farm was implemented as a MATLAB Simulink model in order to run load flow simulations to analyze the efficiency of these internal grid configurations. A cost analysis was also carried out for the internal grid in the wind farm. Results show that installing a 66 kV collector network saves cost both in terms of lower power losses and cheaper cables. Overall cost might still increase due to more expensive transformers, but uncertainties in the cost estimates makes it difficult to assess whether 33 or 66 kV collector grids are more economical. Eliminating the transformer substation also saves a large amount of costs, as long as the distance between the clusters of wind turbines and the HVDC converter platform is moderate. The savings is realized mainly due to the elimination of the expensive platform structure, but is offset by higher cable costs as distance to the converter platform increases. A more detailed study of challenges related to removing the transformer platform in terms of fault handling and redundancy should be conducted in the future.

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Reference Wind Farm; 66 kV collector grid; transformer substation; cost reduction;

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1. Introduction

Offshore wind is a quickly growing industry. Over 5 GW are now installed globally, with the UK and Germany leading the way with 3.6 GW and 0.5 GW grid connected capacity respectively [1,2]. It is expected large investments in the coming years, especially in the North Sea, and the tendency is that the wind farms becomes larger and are situated further from shore. This is driving up costs, and further innovations, effects from economies of scale, experience, and research are required to decrease the costs in the offshore wind energy sector.

The NOWITECH reference wind farm (NRW) is a model of a typical large scale wind farm that has been made to serve as a base case model for researching and benchmarking of offshore wind farms (OWFs). The NRW has been made to resemble the Dogger Bank Creyke Beck A [3] wind farm in terms of size and distance to shore. The wind turbines deployed in the NRW has rotor, tower and foundation as specified in the DTU 10 MW reference turbine [4], and an electrical system as specified in the 10 MW NOWITECH reference turbine [5]. These turbines represent the current trend that offshore wind turbines are becoming larger. The largest turbine to date is the Vestas 8 MW V164 that is currently under testing [6].

The initial focus in the NRW has been the design of internal electrical grids. As the size of the turbines, the farms themselves and the distance to shore becomes larger, the traditional solution is not necessarily the most cost effective. A topic under research [7,8] is whether it would be more suitable to use a 66 kV collector grid in the offshore collector grid network than the traditional solution of 33 kV. This would enable longer strings of turbines, lower losses in cables, lower short circuit levels in the collector grid and lighter substation transformers. The technological readiness for this solution is high; the Vestas V164 will be delivered with an option of a 66 kV transformer, and several companies deliver 66 kV transformers and switchgear for use in turbines. Although there are commercially available 66 kV submarine cables, they are not yet certified or qualified for use in OWFs, but this might change soon. One of the purposes to create the NRW is to analyze whether concepts such as 66 kV collector grids are feasible and more cost effective than alternative solutions, which has been one of two focus areas in this paper.

The other focus area of this paper is a novel design option for electrical systems in OWFs. To minimize costs in the internal electrical grids, it could be possible to eliminate the offshore substation transformer platform in OWFs that are connected to shore via HVDC cables [9]. The motivation for this is that the transformer platform is expensive. The substation and converter station makes up about 7 % of the total cost for an OWF, not including installation costs [10]. Furthermore the transformer in the offshore converter station is able act as a MV/HV transformer, suggesting that the transformer substation platform might not be necessary.

In order to analyze the feasibility and cost effectiveness of the 66 kV collector grid in OWFs with large scale turbines, and whether it is possible to eliminate the offshore transformer platform, the NRW MATLAB Simulink model has been used. An analysis has been performed by constructing three scenarios that are compared with regard to installation and components cost, as well as efficiency and cost of power losses. To acquire power losses for the various design options, load flow simulations have been run in Simulink together with a MATLAB script that minimizes losses for various production levels. The cost analysis is performed on basis of data found in literature.

Nomenclature

NPV	Net present value
NRW	NOWITECH reference wind farm
OWF	Offshore wind farm

2. Study method

The following sections give an overview over the NRW, the three scenarios and the load flow study.

2.1. The NRW

The NRW is a 1200 MW wind farm with 120 DTU reference turbines adapted with the electrical specification for the 10 MW NOWITECH reference turbine. Some electrical specifications are presented in Table 1:

Table 1: The DTU/NOWITECH reference turbine specifications [4,5]

Parameter	Value
Rated power	10 MW
Rotor diameter	178.36 m
Wind power density	400 W/m^2
Generator type	Direct drive, permanent magnet generator
Rated generator voltage	4 kV
Converter type	Fully rated back to back
Converter topology	3-level neutral point clamped
Rated converter power	11 MVA
Rated converter voltage	6.5 kV
Modulation type	Pulse width modulation with 3. harmonic injection

The turbine structure is a full truss tower, and the nacelle height is about 138 m. The water depth on the wind farm site is about 20 – 30 m, and the rated wind speed is over 10 m/s. The turbines are evenly spaced with a distance of 8D, or 1440 m, in three clusters. Each turbine therefore takes up about 2 km^2, and one cluster about 80 km^2. Depending on the scenario each cluster is either connected to the converter platform via a 10 km long HV cable from a substation, or 66 kV cables from the individual strings of turbines with an average length of about 8 km. The distance to shore from the converter platform in the middle of the wind farm is 150 km, and there is a further 50 km in land to the 400 kV onshore grid connection point.

The shore connection is done with HVDC cables rated at ±420 kV with the capability to transfer 1200 MW. The rated power of the converter station has been set to 1300 MVA in order to be able to deliver reactive power to the internal grid in the OWF. ABB and Siemens are currently delivering VSC HVDC systems rated at about 1 GW and ±320 kV[11,12], but it is expected that the development of larger converter stations with higher voltage ratings will enable the use of the selected shore connection option. In the converter station there are two transformers that transform the voltage in the wind farm up to 450 kV.

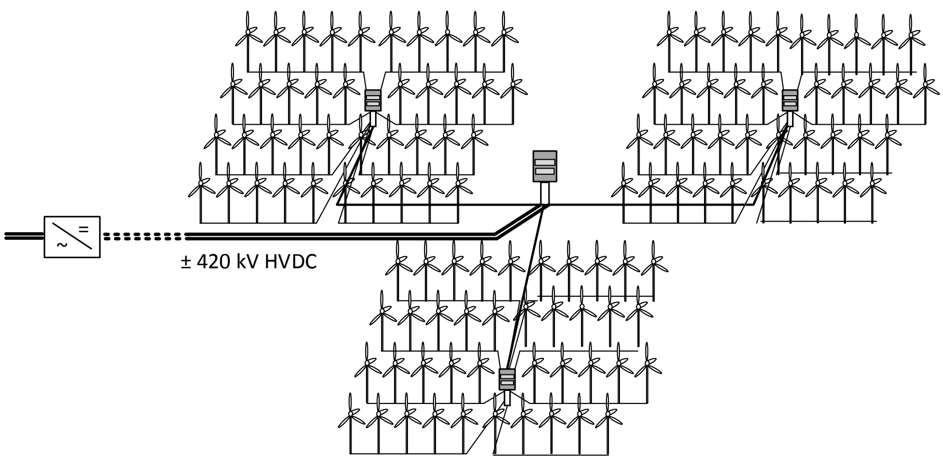

Figure 1: The NRW principle lay out[1]

The NRW has not yet fully defined parameters such as detailed turbine spacing based on wake loss modelling, and implementation of control systems for turbines, HVDC system and park supervision is not yet complete. The specification for the internal grid, which is the topic of this paper, is studied by employing three different scenarios.

2.2. Scenario 1:

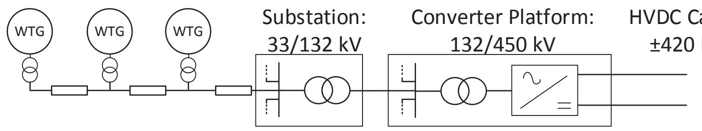

Figure 2: Internal grid design in scenario 1

Scenario 1 is the base case scenario that employs the standard internal grid design concept with 33 kV collector grid and substations with 33/132 kV transformers. The chosen redundancy scheme for the wind farm is the multi ring concept visualized in figure 3. This concept provides a high level of redundancy and lower power losses, while being only slightly more expensive than a design providing no redundancy [13].

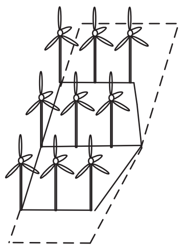

Figure 3: Multi ring type of redundancy

Due to the chosen redundancy scheme and large turbine size, each string only connects three turbines to the substation, meaning that each of the three substations has 13 strings plus one extra turbine. The transformer substation connects 400 MW to the converter station via three 800 mm^2 132 kV cables. The transformers in the transformer substation are overrated 10 % to provide the capability to transfer reactive power, and two transformers are used rather than one in order to provide redundancy. The transformer power is therefore 2 x 220 MVA. This scenario uses 400 mm^2 for cables between turbines in each string, and 800 mm^2 cables between the last turbine and the transformer platform.

[1] Not the final substation placement and string configuration

2.3. Scenario 2

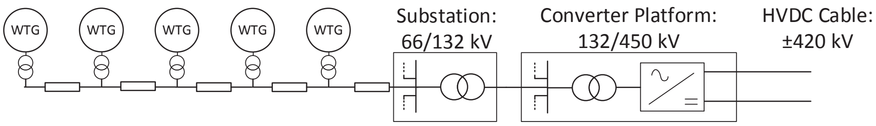

Figure 4: Internal grid design in scenario 2

Scenario 2 uses a collector system voltage of 66 kV, and this gives the opportunity to connect more turbines in each string. The multi ring concept for redundancy is used in this scenario as well, and 5 turbines have been coupled in each string. Using the 66 kV option in scenario 2 means that the short circuit levels become lower, the power losses becomes lower, and lower cross sections for cables can be used. This scenario uses 300 mm^2 for cables between the first four turbines in each string, and 630 mm^2 cables between the last two turbines and the transformer platform. The transformer platform is configured as in scenario 1, with the exception of the primary winding voltage rating.

2.4. Scenario 3

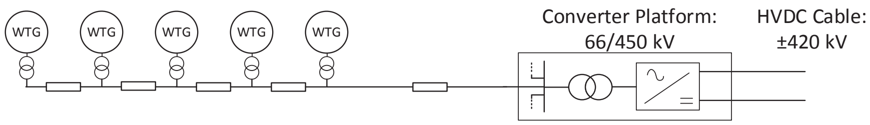

Figure 5: Internal grid design in scenario 3

Scenario 3 eliminates the transformer substation, so that there are only 66 kV cables in the internal grid in the OWF. There are still 5 turbines per string connected in multi rings, but each string is now terminated at the converter platform. That there is a longer stretch with 66 kV cables rather than 132 kV cables results in higher cable losses in this scenario, however, the transformer losses are eliminated. This means that depending on the distance between the transformer and converter platform, scenario 3 might provide higher or lower losses in the internal grid than scenario 2. The cable cross sections are equal to scenario 2.

Eliminating the transformer platform creates some complications in an OWF. One effect is that the short circuit levels become higher, as the transformer impedance is no longer present. This is not a huge complication as fault levels for turbines with fully rated converters are lower than for other generator types, and the short circuit levels are lower than normal due to the 66 kV collector grid voltage rating [9]. The earthing system in the OWF is also affected when eliminating the transformer substation, as the closest grounding point for the turbines is in the converter platform. The reason for this is that the turbine transformers are normally connected to the collector grid with delta windings. Furthermore, 600 MW will be shorted if there is a fault on the busbar in the converter station MV side. Besides from providing very high fault currents, this is also a redundancy issue. If one of the two busbars in the converter station is faulted, then 600 MW will be offline. This issue can be solved by for instance incorporating redundancy in the breaker scheme. Another way to address this issue is to install several converter transformers in parallel to minimize the effects of one fault. This will however raise the space required in the converter station, thereby also raising the prize of the converter platform. The reliability of the system is improved by realizing fewer components when removing the transformer substation. A more thorough short circuit analysis and redundancy study should be performed in order to address the issues regarding fault effects and redundancy.

2.5. *Load flow analysis*

In order to perform a cost analysis, the energy losses in the internal grid; the inter array cables, the substation and the cables from the substation to the converter platform, must be determined. In order to analyze the losses in the internal grid for the three scenarios, a load flow study has been carried out. A MATLAB script was used to determine the optimal reactive power flow for each production level in the OWF by running simulations for different reactive power flows in the selected production level. The losses in each simulation were computed, and the minimum registered losses for each production level were selected as the optimum power flow solution. From these results the efficiency in the internal grid for the different production levels were identified. A time series of wind farm power production was then used to determine the duration of each production level, and an average efficiency for the internal grid was found. The data used in simulations for subsea cables are found in ABBs cable reference guide for subsea cables [14]. Data for transformers and converters are based on a combination of in house knowledge and confidential data from industry partners.

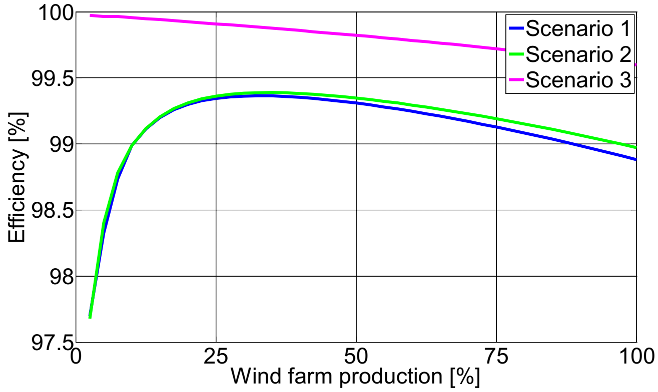

Figure 6: Efficiency vs power production for the three scenarios

As can be seen, the efficiency of scenario 1 and 2 are nearly identical. The shape of the efficiency curve for these two cases is dominated by the transformer efficiency curve. The lower losses achieved in scenario 2 can be explained by the higher voltage level, but the difference between the cases is small due to lower diameter cables. Scenario 3 has the lowest losses, which is due to the elimination of the transformer losses in the substation.

A sensitivity analysis of the losses in scenario 3 based on distance between the transformer platform and converter platform has been carried out, as shown in figure 7.

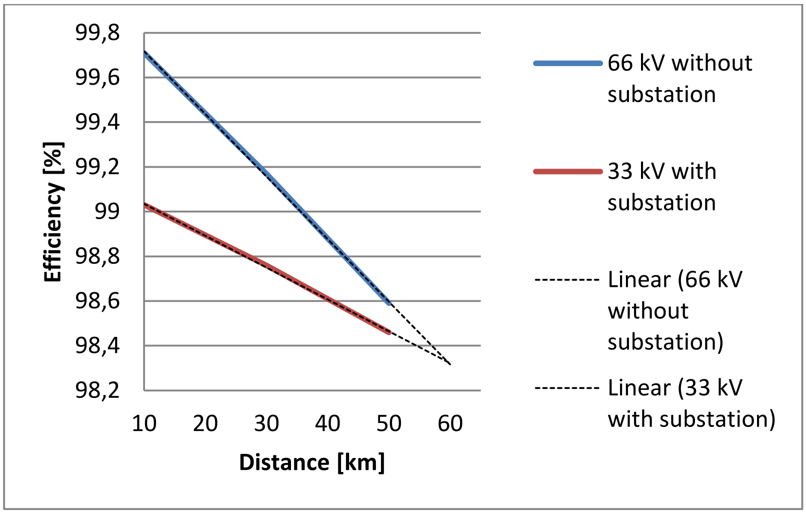

Figure 7: Efficiency sensitivity when the distance between the converter station and the turbine cluster is varied

From the extrapolated curve in Figure 7 it can be seen that scenario 3 is likely to be less efficient than the base case when the distance between the turbine cluster and converter station is larger than about 60 km.

3. Economic analysis

3.1. Cost of energy losses

Based on the efficiencies found in section 2.5 and a yearly capacity factor of 48 %, the costs for the power losses in the internal grid can be estimated. The price for the produced energy in the wind farm has been set based on the assumption that the wind farm is built in the UK in 2018 under the Contracts for Difference support scheme [15]. The operators of the OWF will then receive 140 £/MWh for the first 15 years of operations. For the last 5 years in the assumed lifetime of 20 years, the power will be sold at spot price. Average UK electricity price is forecasted to stabilize at about 90-100 £/MWh in the years after 2025 [16]. A spot price of 100 £/MWh has therefore been used for the last five years of the NPV analysis. The input parameters and results of the NPV analysis can be seen in table 2 and 3. Scenario 3 shows a significant cost reduction due to the eliminated transformer losses.

Table 2: NPV input data

NPV analysis parameters	Value
Discount rate	9 %
Lifetime	20 years
Rated yearly production	10.51 TWh
Capacity factor	48 %
Produced energy per year	5.05 TWh

Table 3: NPV results for the three scenarios

Scenario 1		Scenario 2		Scenario 3	
Average efficiency	99.03 %	Average efficiency	99.10 %	Average efficiency	99.71 %
Total energy costs	79.74 M€	Total energy costs	73.99 M€	Total energy costs	23.84 M€

3.2. Cost of installation

The installation costs for the internal grid consists of the installation of: inter array cables; cables between the transformer and converter platform; the transformer platform; and the converter platform. Cost parameters for installation are very uncertain, as market prices for installation vessels are volatile and dependent on demand.

Cable installation costs are more dependent on the amount of cable stretches rather than the actual length and diameter of the cables [17]. The reason for this is that terminating the cables is more time consuming than laying the cables. The following figures are used for installation costs for each stretch of cable:

Distances shorter than 4 km: 120 k€
Distances larger than 4 km: 240 k€

The costs for installing the substations are dependent on the chosen installation strategy. Here it is proposed that one heavy lift vessel and two transportation vessels are used. The weight of a substation of this size without living quarters and a relatively simple design can be approximated to about 2500 tons. The heavy lifting vessel would have to travel to site, and then install the foundation, which would take perhaps 5-6 days, and then lift on the topside to the foundation, which can be done in one day [18]. Approximately it would then take two days of travel, and 6x3 = 18 days to install the three substations. The day rate of a heavy lifting vessel is in the range of 500 000 €/day, and 50 000 €/day for a transport vessel [17]. The total installation cost for the substations is therefore in the range of 12 M€, not accounting for the possibility of bad weather. A probability analysis for weather is not included in this cost model, but expected cost for the heavy lift vessel will be higher due to bad weather conditions.

3.3. Component costs

The cost for the components in the internal grid has been estimated using data provided in [19]. This data is uncertain, exact prices will vary between different providers and customers. The formulas are presented below:

$$C_{TR} = 42.688\, {P_{TR}}^{0.7513}\ k€ \tag{1}$$

Transformer cost, where P_{TR} is the transformer rating [50 MVA < P_{TR} < 800 MVA].

$$C_{SG,MV} = 40.543 + 0.76\, V_n \tag{2}$$

MV Switchgear cost, where V_n is rated voltage.

$$C_{C,MV} = \alpha + \beta^{\gamma I_n/10^5} \tag{3}$$

Cable cost, where I_n is rated current and α, β and γ are coefficients dependent on voltage level.

The costs listed above have also been checked with [17], but must be thought of only as a rough estimate as the price of components vary from vendor to vendor and also with the overall market situation.

The cost for the substation has been approximated based on power rating and price of other substations as reported in literature and at [20]. The substations in Barrow (120 MW) and Gunfleet Sands (240 MW) have a cost of approximately 0.1 M€/MVA. A cost study by NREL [21] has an approximation for substation cost of about 0.06 M€/MW for a 500 MW wind farm, while the report from [17] has data that can be used to approximate substation costs in a 600 MW wind farm to 0.06 M€/MVA. The costs of the transformer substation in this OWF is likely in the lower part of this regime, as it has low requirements for complexity. The reason for this is that there is a converter station in the OWF that might have the back-up diesel generator for the OWF, accommodation for technicians and so forth. An approximation of 0.07 M€/MVA have been chosen as a cost parameter for the 440 MVA substations in the NRW. When upgrading to a 66 kV collector network, the weight of the transformer in the substation will go down [7]. This effect is not accounted for in this paper, but will be likely to decrease transformer platform costs.

4. Results

4.1. Total lifetime costs in the internal grid

The total cost for the internal grid in the OWF for the three scenarios is presented in table 4.

Table 4: Lifetime costs of the internal grid in the NRW for the three scenarios

	Cost parameter	Specification	Price [M€]
Scenario 1:	Turbine switchgear	120x 33 kV	7,87
	Cables LV	209 km 33 kV	92,26
	Cables HV	90 km 132 kV	67,61
	Cable deployment	MV & HV cables	16,20
	Substation platform	3x 33/132 kV	92,40
	Substation installation	18 days, 2 vessels	12,00
	Converter switchgear	3x 132 kV	2,76
	Energy losses	99.03 % efficiency	79,74
	Total Costs		**370,84**
Scenario 2:	Turbine switchgear	120x 66 kV	10,88
	Cables LV	209 km 66 kV	89,64
	Cables HV	90 km 132 kV	67,61
	Cable deployment	MV & HV cables	16,20
	Substation platform	3x 66/132 kV	92,40
	Substation installation	18 days, 2 vessels	12,00
	Converter switchgear	3x 132 kV	2,76
	Energy losses	99.10 % efficiency	73,99
	Total Costs		**365,48**
Scenario 3:	Turbine switchgear	120x 66 kV	10,88
	Cables LV	329 km 66 kV	163,92
	Cable deployment	MV cables	17,28
	Converter switchgear	24x 66 kV	2,18
	Energy losses	99.71 % efficiency	23,84
	Total Costs		**218,10**

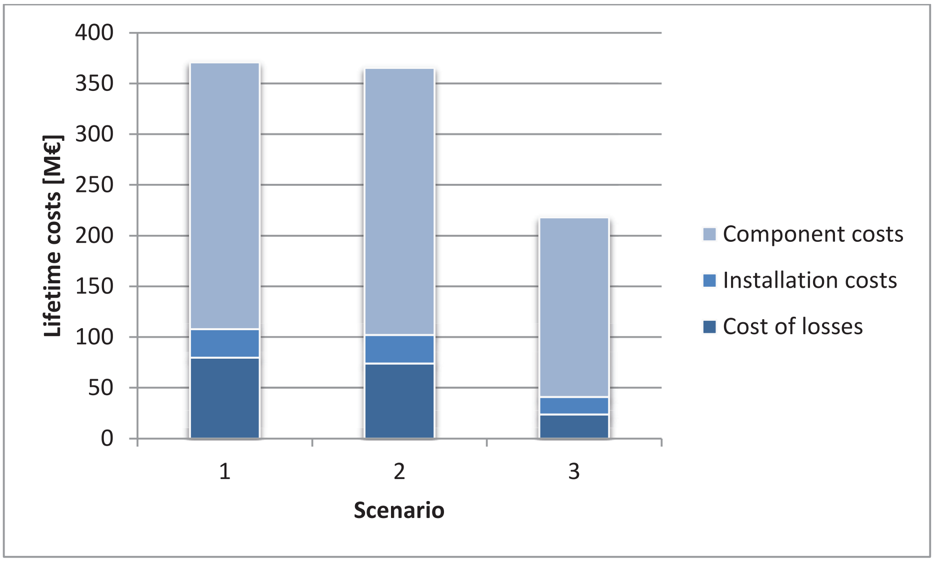

Figure 8: Lifetime costs of the internal grid in the NRW for the three scenarios

It is seen here that scenario 3 is by far the most cost effective option with approximately two thirds of the total costs of scenario 1. The large reduction in cost comes from eliminating the transformer substations, which costs almost 100 M€, not including installation. It is clear that if good technical solutions without transformer substations can be realized in OWFs, very large cost savings can be realized. The other biggest difference between the scenarios is the cost of energy loss, which is much lower in scenario 3 due to the elimination of the transformer losses. The losses are lower in scenario 2 compared to scenario 1, the reason that the efficiency increase is not bigger is that the decrease in losses due to the higher voltage level is offset by the decreased cable cross section. Switchgear and cable costs show some variation between scenario 2 and scenario 1, both are slightly higher in scenario 2. The reason for the small price increase in cables is the possibility to use lower diameter cables when the rated voltage is 66 kV.

The change of transformer cost is not accounted for in this study, but it can be estimated. The magnitude of the wind turbine and substation transformer cost is in the order of 50 M€ [22] and 15 M€ [19] for the whole wind farm. The cost increase of the WTG transformer is estimated to 20 – 30 % according to [23]; the expected cost decrease of the substation transformer is unknown. If the substation transformer cost did not decrease significantly, the 66 kV scenario could have a price increase in the order of 13 M€ due to a higher overall transformer cost. A reasonable assumption would therefore be that the total cost increase would be in the order of 10 – 13 M€. This cost increase would make scenario 1 more economical than scenario 2.

The investment cost for an OWF is in the order of 2.2-4 M€/MW [24]. The total investment cost for the NRWs might therefore be in the order of 4 Bn€, and the investment costs in scenario 1[2] is approximately 7.5 % of the total investment cost in an OWF[3]. The investment cost in scenario 3 is reduced slightly less than 30 % compared to scenario 1, which translates to about 2.4 % savings in the investment cost for the entire OWF.

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[2] Lifetime costs minus the cost of power losses

[3] Costs related to installation and electrical equipment in the turbine is traditionally not counted as internal grid investment costs.

4.2. Sensitivity analysis

The data used for the cost analysis is somewhat uncertain, as actual costs for installation and price of the components generally are unavailable. A number of cost reports, cost analysis and the cost of realized projects have been used to decrease this uncertainty.

The most critical parameter in the analysis is the transformer substation cost. The cost used in this analysis is an average of the costs of other similar projects and other cost analysis, scaled by linearizing the relation between cost and rated power of the substation. Scaled with installed power, the spread in the cost data employed in the analysis is from 78 – 178 M€. As earlier mentioned the costs of the transformer substation in this OWF is likely in the lower part of this regime, as it has low complexity since there is also a converter station in the OWF. However, the results of the cost analysis is unchanged over the whole spread of cost, scenario 3 is still the most economical solution by far. The fact that transformer weight decreases in scenario 2 is not accounted for will strengthen scenario 2, especially in comparison to scenario 1.

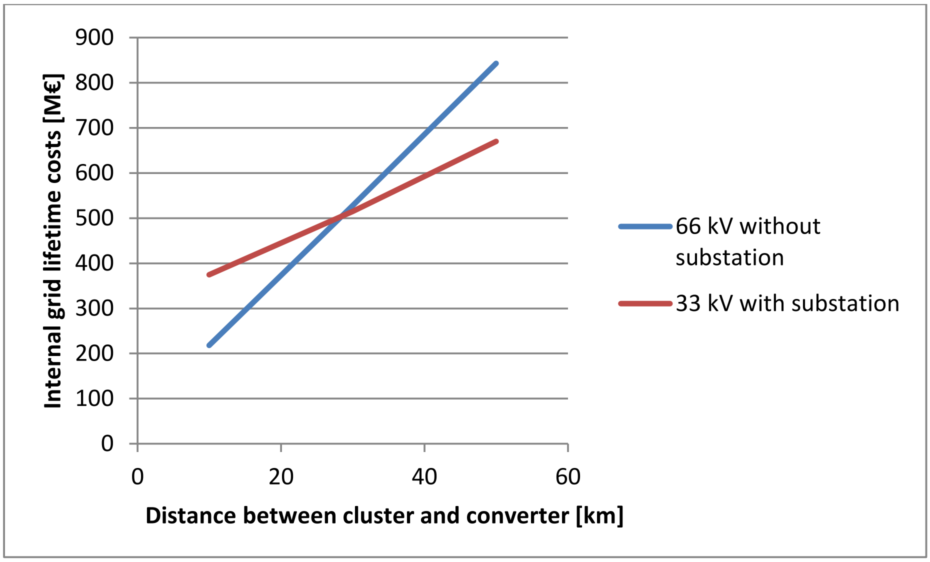

Figure 9: Lifetime cost sensitivity when the distance between the converter station and the turbine cluster is varied

Another important parameter is the distance between the converter station and the turbine clusters. The graph in figure 9 suggests that the design in scenario 3 is the cheapest as long as the distance between the cluster and platform is lower than 25-30 km. For distances higher than this, the 24 parallel cables from the turbine strings in scenario 3 makes the total cable length so long that the cable costs outweigh the combined costs of the transformer substation and the 132 kV cables.

The installation cost used for the substation is not adjusted for the influence of weather down time. It is not unlikely that installation time is doubled due to bad weather, in this case costs would increase by 12 M€. However, this will only strengthen scenario 3 as the most economical scenario.

It is also seen that the cable costs for the different scenarios are in the same range. The costs are higher when using 33 kV cables, as these must be very large to be able to connect three turbines per string. The 66 kV cables are more expensive, but require lower cross sections. Furthermore, there is possible to achieve a smaller total distance when there are more turbines per string, and approximately 17 km of cable is saved in scenario 2 as compared to scenario 1. This causes the 66 kV cables to be slightly less expensive than the 33 kV cables in these scenarios. The cable installation costs is also similar in the three scenarios, scenario 3 has more cables with long stretches between the strings and the converter platform which makes installation costs slightly higher. The price for 66 kV cables is uncertain, as these are not yet available for use in OWFs.

It is also seen that switchgear costs have a relatively low impact on the total costs. When upgrading from 33 kV to 66 kV in the collector grid, the costs of circuit breakers in the turbines increase slightly. The costs of the substations are approximately the same, as the switchgear costs increase, but the amount of switchgear bays decreases due to a lower amount of strings. If a more detailed analysis is done with regard to redundancy, one consequence might be that a more sophisticated breaker and busbar scheme should be used in the converter platform to increase reliability in scenario 3. In this case switchgear costs may double depending on the selected breaker scheme.

The cost of the converter transformer is assumed equal for all three scenarios and is in the range of 15 M€. The results are therefore not very sensitive to deviations in converter transformer price, but scenario 3 should expect an increase in transformer price and weight which is not accounted for in the study. There is an option to increase the numbers of transformers in the converter station, to for instance 4 transformers, in order to increase reliability. It has not been performed an analysis to examine how this would affect space requirements, and hence also converter platform cost, but this could be the topic of further studies.

5. Conclusions

The costs related to components in the internal grid, installation and power losses in these components over the OWFs lifetime might be significantly reduced if alternative grid concepts are used. As wind turbines and OWFs grow in size, it might be more advantageous to install 66 kV rather than 33 kV collector grids. The reason for this is lower losses, higher power transfer capabilities, lower short circuit levels, and lighter substation transformers. It has been performed a cost analysis comparing the cost of traditional internal grid design and an internal grid with 66 kV collector grid in a 1.2 GW offshore wind farm comparable to Dogger Bank Creyke Beck A. The results show that over the lifetime of the OWF, the costs are about the same. However, the losses are lower with 66 kV cables so the estimated lifetime cost of scenario 2 is lower than scenario 1. These results do not account for possible savings due to smaller transformer platforms, and they do not take into account the decreased cable distance by allowing more turbines per string. Furthermore there is an expected increase in transformer cost in the wind turbines due to the higher voltage level. In general there are uncertainties in the life cycle costs, and the costs also depend on the specific design. The results in this paper are therefore not conclusive concerning whether 33 kV or 66 kV grids are the most economical design in collector grids.

A more novel solution would be to eliminate the transformer substation, which could result in large cost savings. Due to uncertainty related to substation costs it is difficult to provide an exact number, but it is very likely that there are possibilities for savings in the order of 2.4 % of the total investment costs of the OWF if a 66 kV collector network also is used. Further research should be conducted to assess the challenges related to fault handling and redundancy when removing the transformer platform to establish this as a good design configuration.

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