

*Centre for Sustainable Electricity and
Distributed Generation*

**Cost Benefit Methodology for Optimal
Design of Offshore Transmission
Systems**

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List of Abbreviations

AC	Alternating Current
DC	Direct Current
BERR	Department for Business, Enterprise and Regulatory Reform
EEC	Expected Energy Constrained
GB	Great Britain
HVDC	High Voltage Direct Current
Ofgem	Office of Gas and Electricity Markets
OTEG	Offshore Transmission Experts Group
ROCs	Renewable Obligation Certificates
SGT	Super Grid Transformer
SQSS	GB Security and Quality of Supply Standard

Executive Summary

This document summarises the results of a cost-benefit analysis (CBA) based methodology developed to determine the optimal design of offshore transmission grid to connect offshore wind farms and gas turbines to onshore electricity networks. Although work was conducted in two phases this report presents the combined results of both of these activities. The CBA methodology implemented was used for the development of the new GB Security and Quality of Supply Standard (SQSS) for Offshore Transmission Networks, as a part of the activities carried out by the GBSQSS sub-group of OTEG. The recommendations for an offshore standard made on the basis of this cost-benefit analysis have since been consulted on and the majority of the initial recommendations for the basis of an offshore security standard were agreed by BERR.¹

It was assumed that the offshore transmission system, for which a schematic diagram is presented in Figure 1, will operate at 132kV or above. Furthermore, such systems will be composed of a (i) cable undersea network and (ii) single or multiple offshore platforms with transformers for HVAC transmission or converters for HVDC together with associated switching and compensation equipment and (iii) on-shore circuit and (iv) the on-shore substation that connects the offshore system to the onshore one.

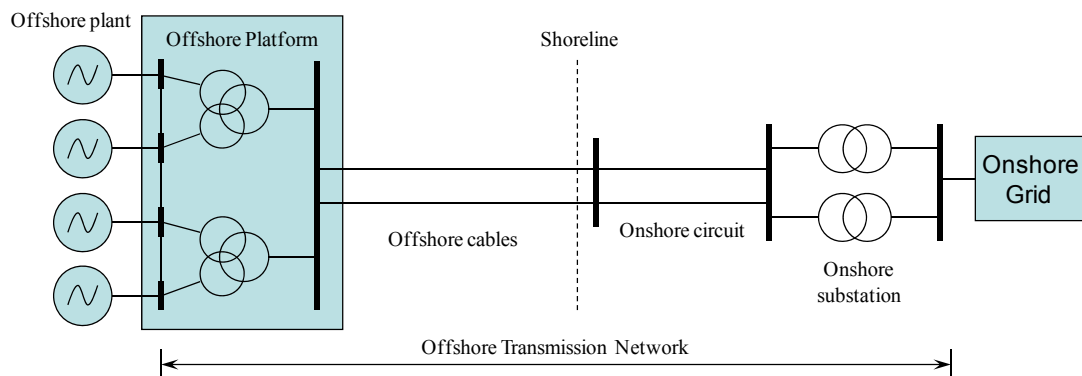


Figure 1 – Schematic diagram offshore transmission system considered

The cost benefit approach developed and applied to determine the optimal design of offshore networks is conceptually identical to the one used in the planning and design of onshore systems². A balancing exercise between the following two broad categories of costs is carried out to determine the optimal network design:

¹ The Government's decision is available on the BERR website at:

<http://www.berr.gov.uk/files/file38855.pdf>

² The network design according to the GBSQSS for on shore networks is centred around two sets of considerations (i) peak security (defined through “planned transfer” and “interconnection allowance”) followed by (ii) a CBA that can be used to justify investment over an above those driven by security consideration. Unlike conventional generation, wind power makes a very limited contribution to securing peak demand and hence peak security considerations in network design for wind power are not practically relevant (and are hence ignored in this analysis), as the network investment will be

- cost of offshore transmission system investment, that is composed of:
 - costs of undersea cable network
 - cost of platform with associated equipment (transformers, reactive compensation and switchgear)
 - cost of onshore circuits and substation and reactive compensation
 - capitalised cost of corrective maintenance and
- capitalised cost of expected constrained energy due to preventive and corrective maintenance and losses over the period of the asset life.

Based on evaluating the above two cost components for a spectrum of feasible offshore transmission system configurations with different levels of redundancy, we have identified optimal designs for undersea cable network and offshore platforms (including compensation both onshore and offshore), for a range of wind farms with ratings up to 1500 MW and for a range of offshore gas turbines (GTs) with ratings up to 200 MW and various distances ranging from 25 km to 100 km. Furthermore, optimal designs of onshore circuits with length ranging from 1 to 50 km and onshore substations have been identified.

This analysis suggests that economically efficient offshore networks for *wind energy* should be designed with no redundancy, due to the significantly higher cost of undersea cables when compared to overhead lines (with a factor of about 20), the absence of demand offshore, the relatively low load factor of wind generation (40%) and the low capacity (security) value of offshore wind generation that can be relied upon to secure onshore demand. Hence, the suggested designs tend to be radial rather than interconnected, although in some cases there will be benefits of sharing connections among wind farms that are located geographically close to each other. Hence, for offshore wind farms, all four offshore network sections (offshore platform, offshore cable connection, onshore network and onshore substation that makes the connection to the onshore grid), are all design with no redundancy. In case of GT with capacities greater than 100 MW (but less than 200MW), minimum rating of individual transformers in multiple transformer offshore substations should provide (N-1) redundancy, while all other three sections of the offshore grid would not have any redundancy.

Although the optimal network design for wind farms requires no redundancy, the security of the connection can be very significant, particularly for larger wind farms. This is driven by the power transfer limitations of AC undersea cables³. Currently used 132kV AC cables can carry up to about 250MW while modern 400kV overhead lines can carry over 2000MW over longer distances⁴. For example, the connection of a 600 MW wind farm offshore will require the installation of at least three 132 kV cables due to the limited power transfer capability of undersea cables. Hence, a loss of one of those cables will result in an expected energy curtailment that is only

driven by CBA (cost of constraints and losses versus cost of investment, considering both normal operation and maintenance (corrective and preventive). Hence, conceptually the design of on and offshore networks follow the same principles.

³ Application of HVDC technologies for this purpose and distances involved may still not be competitive.

⁴ Note that the application of 400 kV AC is not competitive due to single-core based design and very significant reactive compensation requirement.

around 8 % of the total energy production that would be expected to be achieved before the fault is repaired. Given the relatively small number of expected cable faults over the lifetime of the scheme, the expected energy constrained (EEC) due to outages of offshore network components (for wind costed at £75/MWh and including the value of ROCs) will be relatively small and cannot justify the building of redundant offshore networks.

Although no consideration has been given to the financial compensation arrangements for partial losses of transmission system access (or the relevant offshore transmission charging arrangements), it is important to stress that there is no fundamental difference in the design philosophy between on and offshore systems⁵.

Furthermore, our previous assessment⁶ indicates that after all Round 2 projects are connected, the expected cost of offshore wind energy that will be constrained due to failures on the network is between £10.8m and £13.1m per annum, even under conservative assumptions regarding network repair times. When compared with post BETTA constraint costs - that are in the region of £100m - costs of offshore wind driven constraints would make a relatively modest contribution to the overall constraint costs.

It is however important to stress that the methodology developed (and consequent recommendations for the planning standard) is based on the assumption that the wind energy curtailed associated with every network design (and the corresponding costs) represents a long term average (expected) value of energy curtailed over the life time of the project. Expected values of energy curtailed would be approximately achieved from operating a large number of offshore schemes over a long period of time. In practice, there will be a potentially significant variation in the energy curtailed associated with individual wind farms, as these may experience a higher or lower number of outages than the expected long term average would suggest, and hence higher or lower levels of curtailed energy than the long term average. Clearly, the risks of achieving higher values of energy curtailed than the long term average value, on a specific project (particularly small projects that would be connected to a single cable), may be sufficiently higher than that used in the study, and if considered in isolation, it might warrant a network design with higher levels of redundancy than optimal (and higher, inefficient, corresponding investment costs).

Specific recommendations

The detailed cost-benefit analysis suggested that the design of offshore network systems could be separated into four main sections:

- the offshore platform (i.e. the AC transformer circuits and HVDC converters on the offshore platform);

⁵ Balancing the cost of investment against the cost of losses and constraints is the basis of economically efficient design of both on and off shore networks. In other words, the cost benefit used for offshore network design determines the economically efficient design of offshore networks and is conceptually identical to that used onshore although the detailed solutions are different due to different cost structure of the network assets and the fundamental characteristics of generation.

⁶ P Djapic, G Strbac, Grid Integration Options for Offshore Wind Farms, December 2006, www.berr.gov.uk/files/file36129.pdf

- the offshore cable network (i.e. the transmission cable circuits linking the onshore network and the offshore platform);
- the onshore circuit if necessary
- the onshore substation if necessary

Each of the four sections can be considered separately for single and multiple generation plants connections. However, the potential for coordination of preventative maintenance activities across offshore assets has been considered.

It should be noted from the results presented that each of the key input parameters has been tested to find the value at which the conclusion changes. A number of the key items of the input data to the cost benefit analysis have been tested (average repair times, cost of wind or gas turbines energy curtailed, etc.) to investigate at what level these would change the design recommendations of the cost benefit analysis. A comprehensive set of more than 35,000 sensitivity studies was performed to propose the optimal design and to demonstrate the robustness of the recommendations made.

Offshore transmission network design for wind farms

The following recommendations for offshore transmission system for wind farms are drawn:

- Minimum number of submarine cables with no redundancy. The total capacity of cables can be lower than the maximum export capacity of wind farms connected (see X factor in table below)
- Maximum rating of single transformer substation for offshore platform is 90MW. Minimum rating for multi-transformer substations is 50% of the wind farm rating and there is no impact of preventive maintenance
- Design of 132 kV overhead lines for wind farms to 400 MW is given in Table 1. For wind farms up to 1100 MW it is double circuit and above that is two double circuits. Design of 220 kV overhead lines are given in Table 2. Design of onshore underground cables will follow design of offshore subsea cables. However, there might be benefit of connecting two subsea cables to one onshore underground cable.
- Maximum rating of single transformer substation for onshore substation is 120-180MW

Table 1 – Results for 132kV onshore overhead lines (with generic maintenance of OH lines)

Length (km)	Wind farm capacity (MW)		
	150	250	400
1	SC	DC	DC
10	SC	SC/DC	DC
25	SC	SC	DC
50	SC	SC	SC/DC

- SC – Single circuit
- DC – Double circuit

Table 2 – Results for 220kV onshore overhead lines (with generic maintenance of OH lines)

Length (km)	Wind farm capacity (MW)				
	400	600	800	1000	1060
≤2	DC	DC	DC	DC	DC
≤4	SC	DC	DC	DC	DC
≤8	SC	SC	DC	DC	DC
≤25	SC	SC	SC	DC	DC
≤50	SC	SC	SC	SC	DC

As the diversity of wind power output was considered to potentially have an impact on the design of cable network, two extreme wind profiles are used:

- a non-diversified profile, characteristic for relatively small wind farms occupying relatively small geographical areas, and
- a diversified profile, characteristic for relatively large wind farms occupying relatively large areas. In this case, due to the dispersed locations of the wind generators, statistically there is a relatively low probability that full output of all individual wind generators will be available at any given time.

Offshore platform

The quantitative assessments demonstrated that offshore platform capacity should be about 95% of the maximum export capacity of the wind farm connected (for AC solutions). Furthermore, for wind farms with a capacity of 90MW or greater, following an outage (planned or unplanned) of any offshore platform transformer, there should be, at a minimum, 50% of the installed platform transformer capacity remaining. Significant benefits of the flexibility have been observed. It is important to stress however, it is sufficient that the switching supply from one to the other circuit (in case of a fault) is manual (rather than automatic) provided that it is completed within the time frame that is on average significantly shorter than the average repair times of transformers and cables (6 and 2 months respectively)

DC Offshore platforms are built with no redundancy.

Offshore Cable Network

For cable networks, the total optimal capacity installed can be lower than the maximum export capacity of the wind farm connected, due to the cost of installing offshore transmission assets to full capacity (X factor in table below). For the non-diversified wind profile (appropriate for relatively small wind farms, occupying small geographical areas) the installed network capacity should be above 95% of the maximum output of the wind farm, while in the case of a diversified wind profile (appropriate for relatively large wind farms occupying relatively large areas) the installed network capacity should be above 90% of the maximum output of the wind

farm. In cases where this value requires an additional cable to be installed, consideration should be given to installation of network capacity below 95% for a non-diversified profile and below 90% for diversified profiles. The optimal values of the X factor will be a function of the distance as shown in the table below.

X factor (%)		Cable length (km)			
Wind farm profile	Condition - Increase in	25	50	75	100
Non-diversified wind profile	Cable rating	>95			
	Number of cables	>91	>88	>86	>84
Diversified wind profile	Cable rating	>90			
	Number of cables	>85	>82	>79	>77

For wind farms connected through HVDC technology, following an outage (planned or unplanned) of any single offshore platform DC converter module, the loss of power infeed is proposed not to exceed the existing onshore Normal Infeed Loss Risk (1000MW). However, it would be economically efficient to connect wind farms of 1500MW (maximum considered) to a single offshore transmission circuits.

Onshore overhead lines and cables design

Onshore overhead lines are preferable solution due to high cost of onshore cables. Design of 132 kV overhead lines for wind farms up to 400 MW is given in Table 1. For wind farms between 400MW and 1100 MW it was found that a double circuit overhead line would be optimal, while for capacities of 1100MW and above that the design should be based on two double circuits. Design of 220 kV overhead lines are given in Table 2. Note that a single size conductor for 220 kV overhead lines was considered.

If cables are to be used, the design should follow one developed for offshore (the obtained data revealed that underground cables are significantly more expensive than equivalent undersea cables). However, there might be a benefit of connecting two subsea cables to a system of single-core onshore underground cable.

Onshore substation design

For wind farms of 120MW or greater, there should be a minimum of 2 transformers installed onshore, with the capacity such that following a planned or fault outage of a transformer there is a minimum of 50% of installed capacity remaining. This is driven by planned maintenance requirements.

Offshore transmission network design for GTs

The recommendations for the optimal design of offshore transmission networks for GTs are as follows:

- Design of offshore substations for GT capacity up to 100 MW a single transformer offshore substation and for capacity greater than 100 MW

minimum rating of individual transformers in multiple transformer offshore substations with full (N-1) redundancy⁷

- Design of submarine link: single cable
- Design of onshore link: single circuit
- Design of onshore substation: single transformer

The impact of preventive maintenance is also analysed including coordination of maintenance of different network assets. The analysis demonstrated that design of offshore infrastructure for GT generation was not impacted by preventive maintenance outages.

⁷ In the analysis conducted only single rating of GT of 100MW was used.

1. Background, Overall Aims and Scope of Work

The Ofgem scoping document on ‘Offshore electricity transmission’ published in April 2006⁸ identified issues that required further consideration in order to implement an offshore electricity transmission regime. The scoping document noted that DTI and Ofgem would take this work forward in conjunction with industry through a working group, OTEG (Offshore Transmission Expert Group).

OTEG then established a sub group (‘the GBSQSS sub-group’) to undertake review work to assist Ofgem/DTI decisions relating to offshore transmission system security requirements. The purpose of the GBSQSS sub-group was to assist OTEG by completing a review of the current GBSQSS and consequently considering:

- a) whether it is appropriate to apply to the present onshore standard to offshore transmission networks
- b) if amendments are needed to extend the GBSQSS offshore; and
- c) the range of options that exist for alternative security standards for offshore transmission networks.

The BERR Centre for Sustainable Electricity and Distributed Generation provided analytical and numerical support in performing studies, analysing results and providing recommendations to the GBSQSS sub-group. This work was based on a cost benefit methodology and software tools that were developed to provide quantitative cost estimates of alternative configurations and levels of redundancy. The aim of the cost benefit analysis was to determine an optimum economic and technical solution for offshore transmission networks, taking into account the key driving factors that were likely to have an impact on the design of the offshore transmission systems.

The aim of the analysis has been to assess the minimum cost solution and then to justify any reinforcement above that value. The results that are presented along with this note illustrate the total cost for each solution, which includes the capital cost of the assets to be installed, cost of system losses, value of estimated energy curtailed, cost of reactive compensation and cost of maintenance over the lifetime of the assets.

Wind farms of up to 1500 MW of installed capacity and up to 100 km from connection point at the onshore grid are considered in this analysis. The network models created were populated with data from a set that was collated from suppliers, developers and the three onshore transmission licensees.

It should be noted from the results presented that each of the key input parameters has been tested to find the value at which the conclusion changes. These demonstrate the robustness of the recommendations made.

Although it was recognised that the Grid Code conditions will also be reviewed as part of the project to introduce an offshore transmission regulatory regime, these

⁸ The Scoping Documents is available on the Ofgem website at:
<http://www.ofgem.gov.uk/Pages/MoreInformation.aspx?docid=3&refer=Networks/Trans/Offshore/ConsultationDecisionsResponses>

were considered to be outside of the scope of the GBSQSS review. The studies carried out in this report confirmed that the voltage fluctuation considerations and reactive power requirements can be decoupled from the design of the main offshore infrastructure. No specific consideration has been given to the security of connection on the distribution network should offshore transmission networks connect to the DNO network.

The study has been performed in two phases: phase one included design of offshore platform and offshore cable system under normal and forced outage conditions while phase two adds studies on offshore GTs, onshore assets of offshore transmission systems and impact of planned maintenance.

2. Cost Benefit Analysis Methodology

A cost benefit analysis approach was used to determine the optimum capacity of offshore transmission systems (transformers on the offshore platforms and undersea cable networks). This analysis identified the key parameters which impact on the proposed solution and considered a range of possible values to demonstrate the robustness of proposals against a range of input data.

This analysis has considered all wind farm connections anticipated to be connected to an offshore transmission network from Rounds 1 and 2, along with all characteristics of the assets to be installed in the network that will have an impact on the outcome of the analysis.

Generic offshore wind farms were modelled to include the consideration of single and shared, AC and DC connections. The objective of this analysis was to determine the optimum economic and technical solution for an offshore network connecting to the onshore electricity grid system.

In this analysis, it is assumed that offshore transmission networks will be cable circuits for the connection from the offshore high voltage platform to the first substation that the circuit reaches onshore.

Figure 2 shows the concept of cost-benefit analysis.

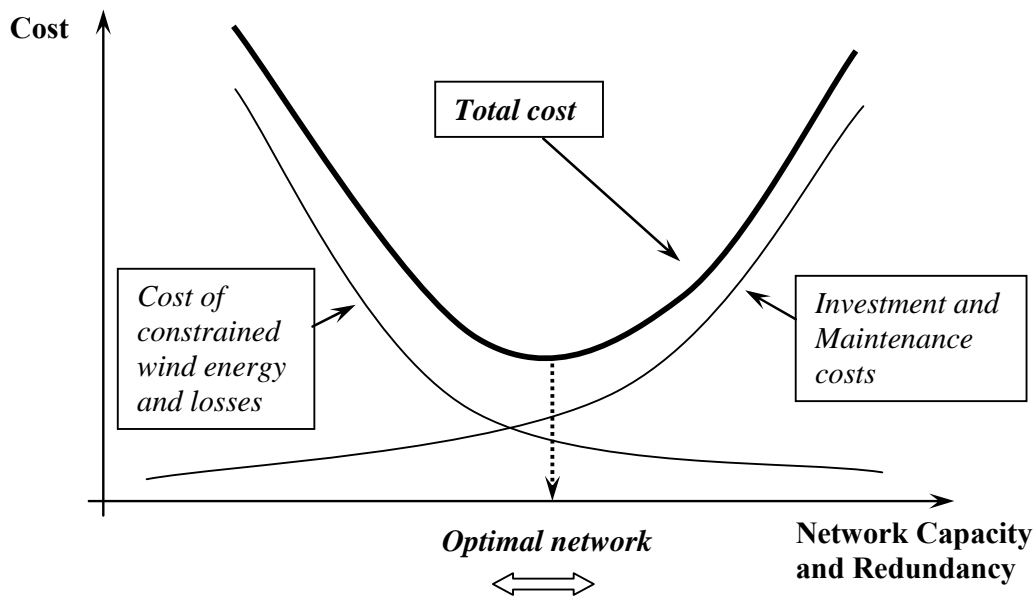


Figure 2 – Concept of cost-benefit analysis

The developed cost benefit analysis is employed to find optimal tradeoffs between the following two broad categories of costs:

- cost of offshore transmission system investment, that is composed of:
 - costs of undersea cable network
 - cost of platform with associated equipment (transformers, reactive compensation and switchgear)
 - cost of onshore circuits and substation and reactive compensation

- capitalised cost of corrective maintenance and
- capitalised cost of expected constrained energy due to preventive and corrective maintenance and losses over the period of the asset life.

Based on evaluating the above two cost components for a spectrum of feasible offshore transmission system configurations with different levels of redundancy, we have identified optimal designs for undersea cable networks and offshore platforms (including compensation both onshore and offshore), for a range of wind farms with ratings up to 1500MW and various distances ranging from 25km to 100km.

Figure 3 shows cost comparison of various transmission network solutions.

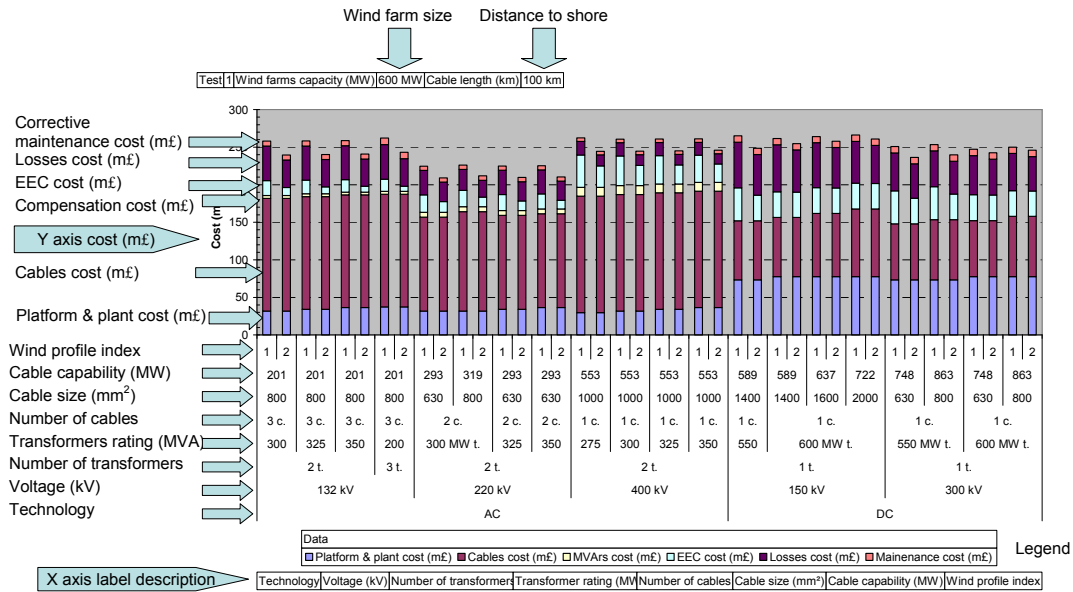


Figure 3 – Comparison of various transmission networks solutions

The information necessary for the calculations of all cost components is available on the GBSQSS sub-group webpage⁹. The platform and plant costs are generic and consist of fixed costs for foundation, float out and erect and variable costs for topsides with plant costs being linearly dependent on the number and rating of the transformers. The compensation plant is costed separately. The cost of cables, supply, lay and bury are also generic and for a specific cable rating are given per km.

⁹ <http://www.dti.gov.uk/energy/sources/renewables/policy/offshore-transmission/offshore-transmission-experts-group/page31187.html>

3. Offshore Transmission Network Topologies

As discussed above, offshore transmission systems are composed of two main components:

- the offshore platform (i.e. the AC transformer circuits and HVDC converters on the offshore platform); and
- the offshore cable network (i.e. the transmission cable circuits linking the onshore network and the offshore platform).

A number of different offshore network configurations are analysed. Figure 4 shows a layout of a directly connected offshore wind farm via a single platform, while Figure 5 shows an example of a shared or joint connection.

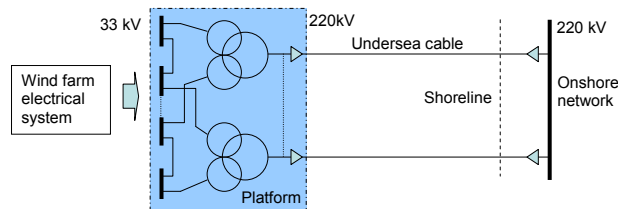


Figure 4 – An example of a directly connected offshore network.

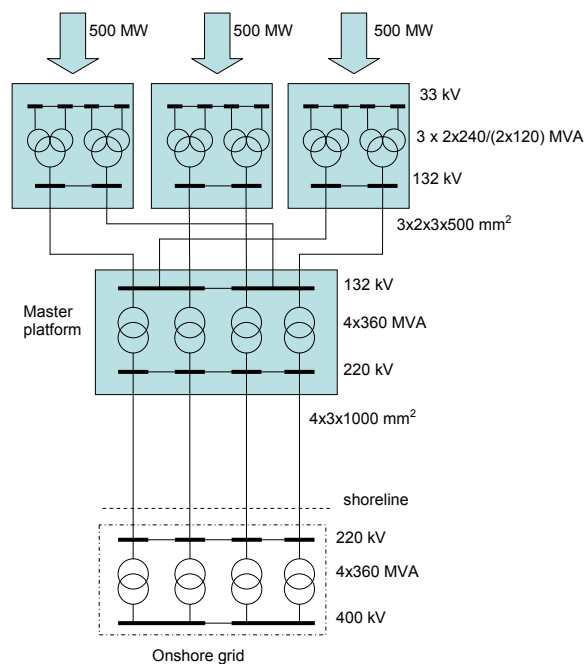


Figure 5 – An example of a shared connection.

Interconnected offshore network topology is not investigated. To get an example of HVDC transmission network connections one should replace in AC networks the connection to the onshore by HVDC components (see Figure 6).

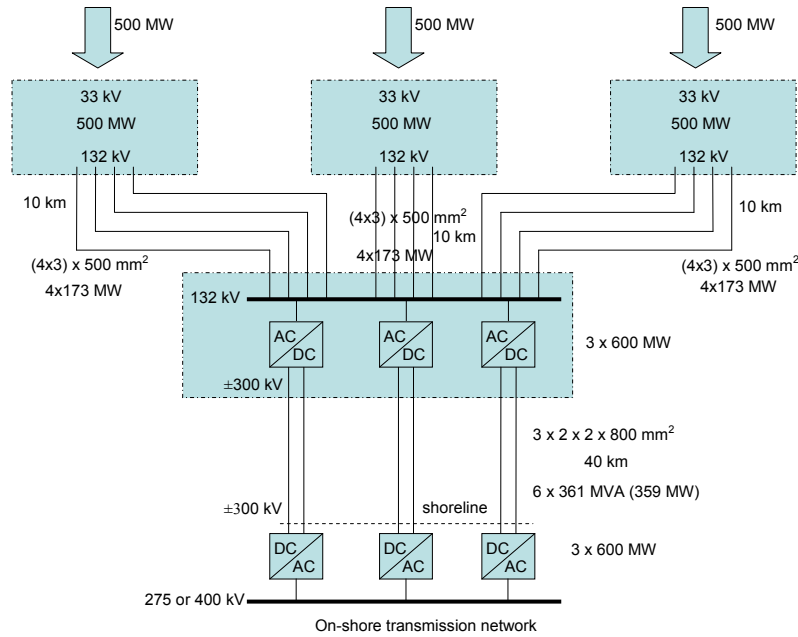


Figure 6 – An example of the use of HVDC technology

3.1 Design Principles of Offshore Transmission Systems

A comprehensive analysis was carried out to demonstrate that the design of platforms can be conducted separately from the design of the undersea cable network (see Figure 8), so that these can be independently designed as shown in figures below¹⁰. Similarly, shared connections can be also designed in steps as shown in Figure 9. This simple design paradigm is depicted in Figure 10.

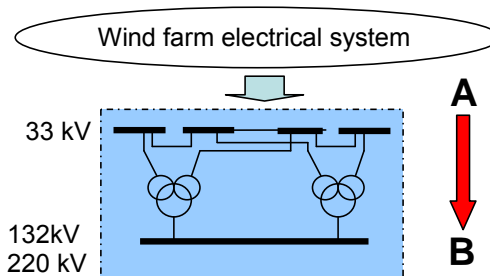


Figure 7 – A platform design

¹⁰ The increase in network capacity that this simplifying assumption introduces is found to be small

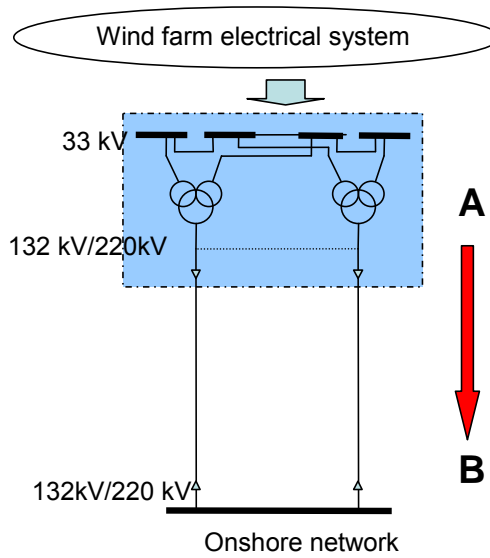


Figure 8 – Direct connection design

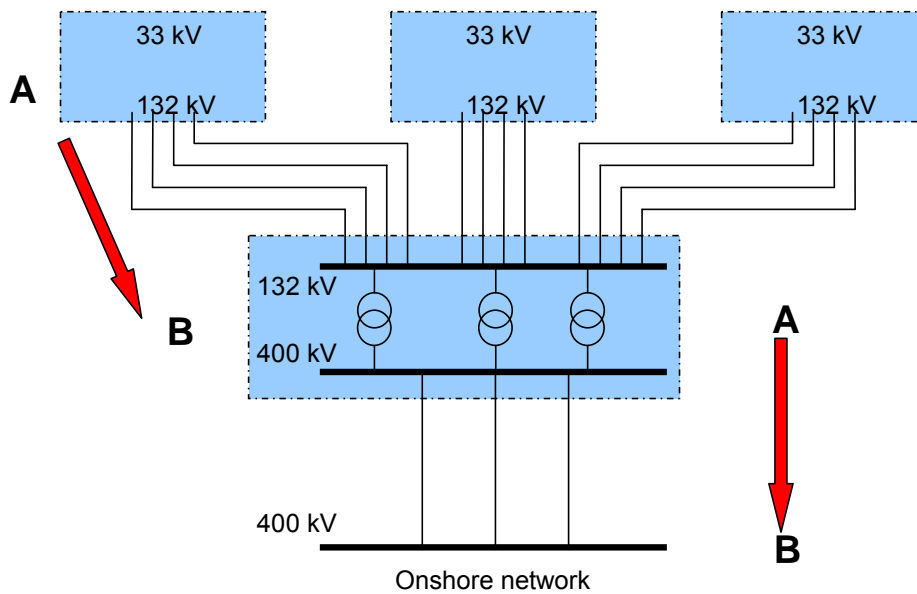


Figure 9 – Shared connection design



Figure 10 – A design principle (where the arrow can represent either the offshore platform or undersea cable network)

This feature considerably simplifies the analysis and the form of the standard.

4. Evaluation of EEC and Losses

The volume of energy losses and expected energy may be curtailed due to unavailability of transformers and cables of offshore transmission networks. The methodology for this evaluation is based on the assumption that wind energy curtailed associated with every network design (and the corresponding costs) represents a *long-term average* (expected) value of energy curtailed. In practice, the expected value of energy curtailed can be approximately achieved from operating a large number of offshore schemes over a relatively long period of time. In practice, there will be potentially significant variations in the energy curtailed associated with individual wind farms, as they may experience higher or lower number of outages than the expected long-term average, and hence higher or lower levels of curtailed energy than the long-term average. Clearly, the risks of achieving higher values of energy curtailed than the long-term average value on a specific project may be sufficiently higher than that used in the study that it might warrant a network design with higher levels of redundancy (and higher corresponding investment costs).

Although no consideration has been given to the financial compensation arrangements for loss of transmission system access (or the relevant offshore transmission charging arrangements), it is important to bear in mind that the methodology developed and the corresponding network design are based on the expected long term average values of wind energy curtailed. In practice, this can be achieved from averaging the curtailed energy across a significant number similar of the wind farms.

We consider two 40% load factor normalised wind farms output profiles. We use two extreme wind generation output profiles, diversified and non-diversified, to assess network requirements. For large wind farms, or groups of wind farms, spread across a very wide geographical area the diversity effects may be significant (“diverse” wind out profile may be appropriate), while small wind farms covering a small geographical area will be characterized by lower diversity (“non-diverse” wind output profiles may be appropriate). However, no specific wind data was available to make firm recommendations regarding the application of diverse or non-diverse wind profiles in relation to specific areas that wind farms may occupy.

Although it is not anticipated that the differences in offshore transmission system design between diversified and non-diversified will be very significant, these have however been routinely assessed to ensure robustness of any recommendations made.

In the following sections the evaluation methodology is described, while the date used is provided in Section 14, while an example application using the developed methodology and data is given in Section 11.

4.1 Wind Power Characteristics

The output of a wind farm is fundamental to the output of the cost benefit analysis due to a need to establish the volume of energy curtailed during various outages of components of individual offshore transmission system designs. The features of the wind output profiles can be statistically assessed from the frequency distribution of

wind generation, considering corresponding annual time series. The frequency distributions of the half-hourly wind power output for diversified and non-diversified wind generation profiles are shown in Figure 11.

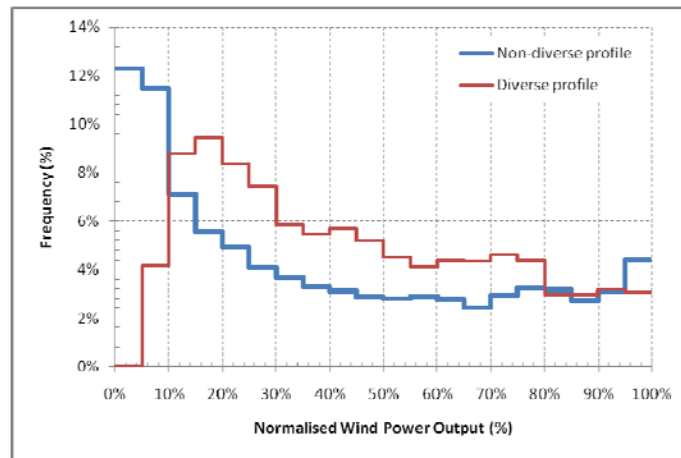


Figure 11 – Normalized wind output

From the two frequency distributions, we can conclude that in the case of non-diversified wind, the output of the corresponding wind farm would be more variable and that the duration of extreme outputs (zero and full output) will last longer than that of the diversified wind output profile. On the other hand, the output of a diversified wind farm will be less variable and will less time spent at the extremes.

The sea area requirement for offshore wind farms is such that for the majority of Round 2 developments this will be in the tens of kilometres squared.

Figure 12 shows these two types of wind generation duration profiles. Characteristics of these two profiles are summarised in the Table 3.

Table 3 – Characteristics of wind generation profiles

Profile	Load factor (%)	Loss load factor (%)
Non-diversified	40	29
Diversified	40	23

In order to assess the constrained energy due to reduced capacity of the offshore transmission system (caused by outages of various components), we have constructed diagrams presented in Figure 14 from the evaluations explained in Figure 13. The process can be explained through an example. Let us assume that the available capacity of the offshore transmission system is 0.6 p.u. (60% of the installed capacity of wind farm) as shown in Figure 13. The shaded area represents the volume of the expected constrained energy. This area is about 11% of the total area below the diversified load duration curve. Repeating this calculation for the other values of available transmission network capacities, we created curves shown in Figure 14. It shows that the constrained energy for a non-diversified wind generation profile is always greater than for a diversified one. For example, in the case where the available transmission network capacity is 0.6 p.u., the constrained energy for a non-diversified and a diversified profile are 0.21 and 0.11 p.u., respectively. The consequence of this is that the transmission network capacity

requirements for non-diversified wind outputs will tend to be greater than for diversified wind outputs (in relative terms).

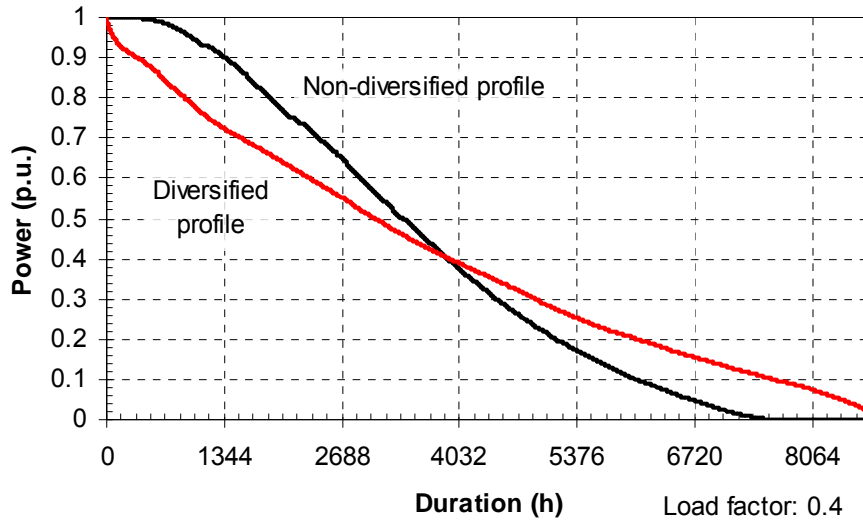


Figure 12 – Wind generation duration profiles.

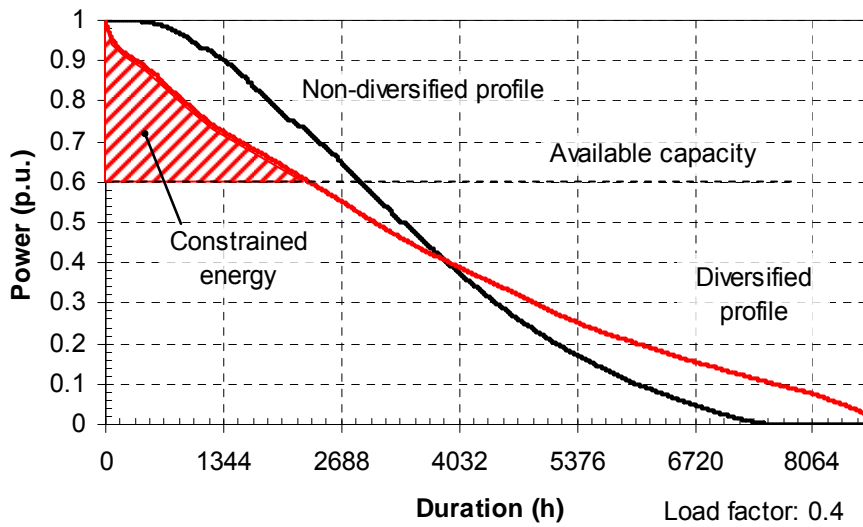


Figure 13 – Calculation of constrained wind energy.

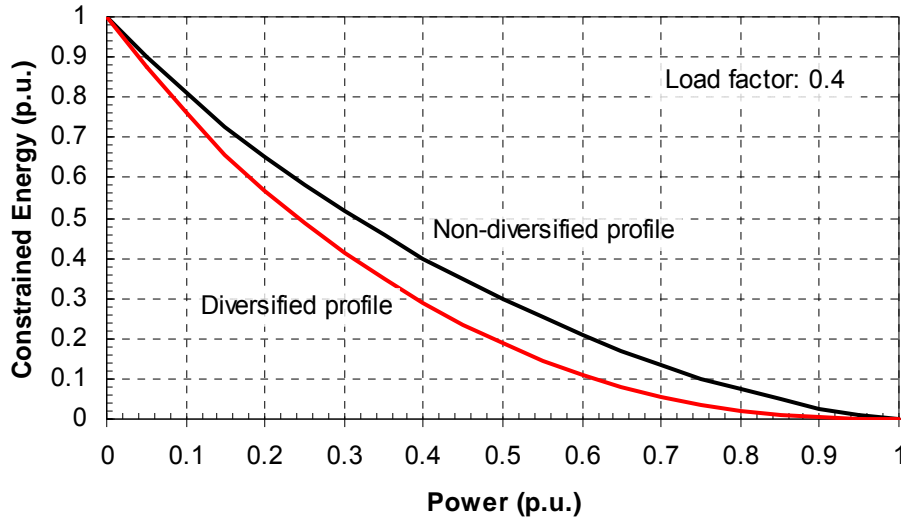


Figure 14 – Constrained wind energy.

4.2 Evaluation of Capacity Outage Probability Tables for Offshore Transmission Systems

The reliability performance of the offshore transmission system is evaluated using analytical reliability techniques based on the concept of the Capacity Outage Probability Tables. The capacity outage probability tables for the offshore transmission system are derived from two-state representations of individual network components (in service or in outage).

4.2.1 Two-state Elements

The basic model for assessing the reliability of two-state elements is generally through the use of capacity outage probability tables. The theory relating to these can be found in various reliability texts (for example, Billinton and Allan 1992 and 1996). In order to form the capacity outage probability table for two-state elements, the capacity (C) and associated critical period availability (A) should be known for that element. The capacity outage probability table, for that case, is shown in Table 4.

Table 4 – Capacity outage probability table for two-state elements.

State	Capacity	Probability
1	C	A
2	0	$1-A$

A general form of the capacity outage probability table for a system composed of a number of two-states elements is shown in Table 5.

Table 5 – General form of capacity outage probability table with N states.

State	Capacity	Probability
1	C_1	p_1
2	C_2	p_2
...
N	C_N	p_N

Note: $C_i > C_j$ for $i < j$ and $\sum p_i = 1$

It is assumed that capacity outage probability tables are known for each network element. The capacity outage probability table for a group of elements (such a system of transformers and cables connected in parallel or in series) is formed by convolving the tables of the individual elements together. For example, if two capacity outage probability tables are convolved together, the resulting capacity outage probability table is derived by combining each state of the first table with each state of table second table. Therefore, a new table has the characteristics shown in **Algorithm 1**. After creating the new table, states with the same capacity are combined as shown in **Algorithm 2**.

Algorithm 1 – Convolution of two capacity outage probability tables A and B

- the theoretical number of states in the new table is the product of numbers of states in table A and in table B,
- the capacity quantities in the new table for parallel elements are simply the sum of the equivalent states in tables A and B and for elements in series are the minimum of the equivalent states in tables A and B, whilst the probabilities are the products of the equivalent states (see equation (1)),
- states with zero probability are omitted.

$$C_k = \begin{cases} C_{Ai} + C_{Bj}, & \text{for elements in parallel} \\ \min(C_{Ai}, C_{Bj}), & \text{for elements in series} \end{cases} \quad (1)$$

$$P_k = P_{Ai} \cdot P_{Bj}$$

where $i = 1..N_A, j = 1..N_B, k = 1..N, N = N_A \cdot N_B$

Algorithm 2 – Combining states of the capacity outage probability table

After creating a new table, the states are sorted in descending order according to "capacity-in" column, and states with the same capacity are combined. The capacity of a combined state is the same as the capacities of each individual state, where probability of the combined state is the sum of individual probabilities. The new capacity outage probability table has the same structure as the one shown in Table 5.

4.2.2 Characterisation of Wind Power Output for Reliability Evaluations

Various wind generation output levels (between zero and maximum output) are represented as a multi-state generator characterized by its available capacities and associated probabilities. A practical approach to form such output probability tables is to characterise the variable as a time-varying parameter with its chronological behaviour fully represented. A schematic illustration of a generation pattern is shown

in Figure 15. In the case of multiple wind farms connected to the same demand group, the outputs of the individual farms should be aggregated and used as the chronological generation pattern. This enables diversity within and between sites, i.e. the footprint, to be taken into account.

The steps in the assessment process are described in the **Algorithm 3**.

Algorithm 3 – Creation of capacity outage probability table for intermittent generation

- identify the time dependent generation pattern
- consider a generation level G_i
- identify the occasions when “the generation is at least equal to G_i ”
- count the number of times, n_i , that this occurs and the duration, t_i , of each of these occasions
- therefore, if T is the total time period of the generation pattern, the cumulative probability (CP) that the generation is at least equal to G_i is given by:

$$CP_i = \sum_i n_i \cdot t_i / T \quad (2)$$

- this can be repeated for all generation levels between the lowest and highest generation levels, from which a generation model can be determined. Each capacity state is given by G_i and the cumulative probability by CP_i and all states are mutually exclusive
- the states probability is determined from cumulative probabilities. A state capacity (SC) is given by equation (3), and the state probability (SP) by equation (4)

$$SC_i = (G_i + G_{i+1}) / 2 \quad (3)$$

$$SP_1 = CP_2 \quad (4)$$

$$SP_i = CP_{i+1} - CP_i, i > 1$$

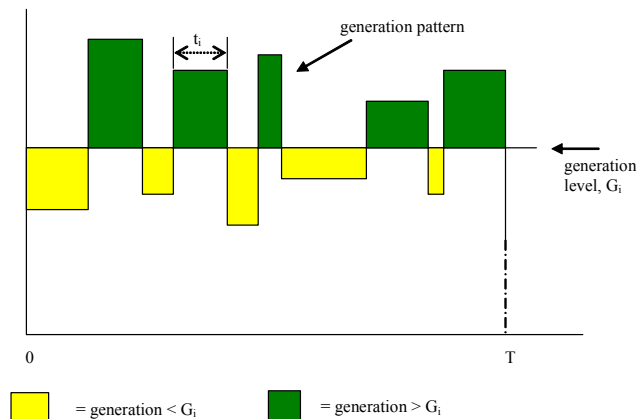


Figure 15 – Determining model for intermittent generation.

4.3 Evaluation of Expected Energy Curtailed

For each half-hour, a system capacity outage probability table at the onshore grid entry point is calculated. The techniques used for this are explained in section 4.2. Then the volume of constrained wind power is calculated for each state in system capacity outage probability state. Summating the product of the corresponding power

that is constrained with and probability of that state, an expected power curtailed is obtained. Summating the product of the expected power curtailed and the duration of each half-hour period, the volume of the expected energy curtailed is evaluated.

4.4 Cost of Expected Energy Curtailed

The cost of EEC is given by expression (5), while the calculation of the EEC is explained in section 4.3:

$$EECC = EEC \cdot cec \quad (5)$$

where:

EECC EEC cost
EEC expected energy constrained per year
cec capitalised energy cost

4.5 Evaluation of Losses

The costs of transformers/converters and cables losses are given by (6) and (7), respectively. The total cost of losses is given by (8). The following assumptions are made in order to simplify calculation of losses:

- there is no outage¹¹
- power factor is assumed to be 1
- voltage is assumed to be rated voltage
- a resistance at 90°C is used

$$CTL = n_T \cdot \left[\frac{1}{TLF} + \frac{(A_w \cdot P_w^M / (n_T \cdot pf))^2}{S_T^2} \cdot \delta \right] \cdot r_T \cdot S_T \cdot T \cdot cec \quad (6)$$

$$CCL = k \cdot nc \cdot r_c \cdot L_c \cdot \left(\frac{A_w \cdot P_w^M}{V \cdot pf} \right)^2 \cdot \delta \cdot T \cdot cec \quad (7)$$

$$CL = CTL + CCL \quad (8)$$

where:

CL cost of losses
CTL cost of losses in transformers or converters
CCL cost of losses in cables
n_T number of transformers
TLF ratio of maximum variable transformer losses and fixed transformer losses
A_w wind generation availability

¹¹ This assumption introduces some relatively minor errors in the loss evaluation process. For a single circuit when there is an outage of that circuit there is obviously no transfer of power, therefore during the outage losses are zero. For multiple circuits, if one is in outage the power is transferred through the remaining circuits which will in reality increase losses for the same power transferred. However, these errors do not change the design of offshore transmission systems.

P_w^M	maximum wind generation output transferred through transformers or converters and cables
S_T	transformer/converter MVA/MW rating
δ	loss load factor
k	current type cables loss factor (1 for HVAC, 0.5 for HVDC)
nc	number of sets of cables
r	resistance at average temperature (index T for transformer and c for cable)
V	cable rating voltage
pf	power factor (for HVDC $pf = 1$)
cec	capitalised energy cost
T	duration of a year in hours ($T = 8760h$)

5. Reactive Compensation

Given the significant costs associated with undersea cables, it is important to ensure that the ability of the offshore transmission system to transport active power is not undermined by inadequate reactive power compensation or voltage fluctuation limits.

The power transport capability of cables is calculated under the assumption that the power factor on the offshore GEP (grid entry point), busbar 1, is kept at 1 as shown in Figure 16. Furthermore, the voltage at the onshore GEP is kept at 1 p.u. The cables and transformer thermal limits are considered. The maximum possible active powers at offshore GEP P_1 for various cables and distances to the onshore GEP are shown in Table 6. The table also shows the used values of total rating of offshore transformers for each particular cable. It should be noted that the offshore transformers are likely to be three winding, but due to its simplicity, the equivalent two winding transformers are used in the model. Table 7 shows the required compensation at the offshore and onshore side of cable to achieve maximum utilisation of the cable. Furthermore, Table 8 shows voltages at busbar 2 in this condition.

The compensation plant is costed separately as in (9). The compensation plant on offshore has different cost than one on onshore as is reflected in equation.

$$CCP = cc_{off} \cdot QC_{off} + cc_{on} \cdot QC_{on} \quad (9)$$

where:

- CCP cost of offshore and onshore compensation plants
- cc unit compensation cost where index off denote offshore, and on onshore
- QC compensation rating

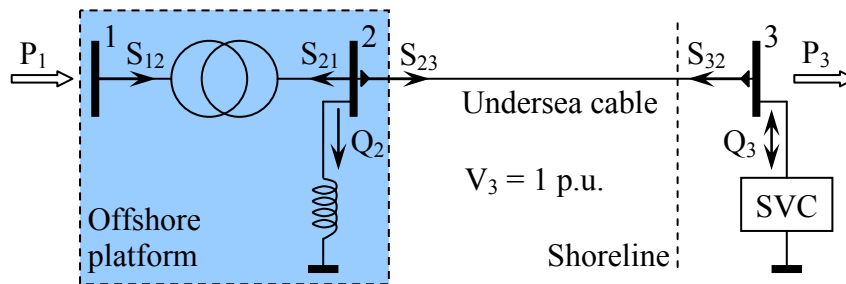


Figure 16 – Network configuration for calculation of cable capability. P_1 and P_3 active power at offshore and onshore GEP, respectively.

Table 6 – Maximum active power output of wind farm in MW

Cable parameters			Offshore substation rating (MVA)	Cable length (km)			
Voltage (kV)	Size (mm ²)	Rating (MVA)		25	50	75	100
132	500	169	180	168	168	168	166
	630	187	200	186	186	186	184
	800	203	220	202	202	202	200.5
	1000	217	220	216	216	216	214
220	500	279	280	277.5	277.5	273.5	266
	630	308	315	306	306	301.5	293
	800	335	360	333.5	333.5	328	319
	1000	359	360	357	357	351	341
400	800	603	630	599.5	587	559.5	517
	1000	646	630	641.5	628.5	599	553
	1200	683	710	679	656	612.5	543
	1400	703	710	699	673	625.5	548
	1600	718	710	713	684.5	632.5	546
	2000	747	800	741.5	711	655	563

Table 7 – Required offshore and onshore compensation in MVar to maintain the maximum active power transfer capabilities of the offshore transmission system (conditions given in Table 6)

Cable parameters		Offshore compensation (MVar)				Onshore compensation (MVar)			
		Cable length (km)				Cable length (km)			
Voltage (kV)	Size (mm ²)	25	50	75	100	25	50	75	100
132	500	0	0	0	12	1.6	21.8	46.8	60
	630	0	0	0	13	2.6	22.3	48.8	62.6
	800	0	0	0	11	4.4	20.7	47.4	63.6
	1000	0	0	0	12	6.3	20.9	50	68
220	500	0	0	22	49	5.4	54	82.2	107.1
	630	0	0	26	56	6.8	60.4	89.7	117
	800	0	0	30	62	8.7	65.9	95	124.2
	1000	0	0	31	66	6.3	68.2	101.4	133.1
400	800	0	67	154	246	68.4	161.6	241.1	322.8
	1000	0	66	160	261	67.2	173.7	259.5	346.4
	1200	0	107	224	349	105.3	209.7	315.4	423.3
	1400	0	115	241	373	111.6	221.7	332.5	449.9
	1600	0	125	258	401	119.6	234.1	351.3	472.8
	2000	13	143	281	430	123.3	244.7	369.2	497.3

The table above shows that relatively modest amounts of reactive compensation are required to be installed offshore, for cables 132kV and 220kV, while more

significant ratings of reactive compensation may be required onshore. Regarding 400kV cables, these require significantly larger amounts of compensation, particularly for larger distances.

We have also evaluated voltage profiles at the offshore side of the cables and these are presented in Table 6. It can be observed that in the case of 132kV cables of small ratings and for large distances, voltage rise effects may become visible. This is caused by the resistive component of the cable impedance.

Table 8 – Voltage at the offshore side of cable (busbar 2) for the conditions given in Table 6

Voltage (kV)	Cable size (mm ²)	Cable length (km)			
		25	50	75	100
132	500	1.010	1.023	1.041	1.054
	630	1.008	1.020	1.037	1.049
	800	1.007	1.017	1.033	1.045
	1000	1.005	1.015	1.030	1.041
220	500	1.006	1.015	1.022	1.029
	630	1.005	1.013	1.020	1.026
	800	1.004	1.012	1.018	1.023
	1000	1.003	1.011	1.016	1.021
400	800	1.003	1.006	1.009	1.011
	1000	1.002	1.005	1.008	1.010
	1200	1.002	1.005	1.007	1.008
	1400	1.002	1.004	1.006	1.009
	1600	1.002	1.004	1.005	1.006
	2000	1.002	1.003	1.004	1.005

It is our overall conclusion that, at the unity power factor, an appropriate reactive power compensation (optimised across onshore and offshore) can deliver full utilisation of offshore infrastructure, while delivering reactive power capability requirements at the onshore Grid Entry Point (GEP), assuming that a voltage variation of $\pm 10\%$ offshore is acceptable.

6. Evaluation of Costs of Assets and Corrective (Post Fault) Maintenance¹²

The platform and plant costs shown in (10) are generic and consist of (i) fixed costs for foundation, float out and erect and (ii) variable cost for topsides with plant cost being linearly dependent on the number and rating of transformers. The term within the square bracket is the cost multiplier which allows the costs to be adjusted if there are more or less than two transformers at the platform.

$$PPC = FC + [1 + dc(n_T - 2)] \cdot c_{2T} \cdot n_T \cdot S_T \quad (10)$$

where:

- PPC* platform and plant cost
FC fixed costs for foundation, float out and erect
dc cost factor which allows costing for a different number of transformers/converters on a platform
n_T number of transformers/converters per platform
S_T apparent/real power rating of a single transformer/converter
c_{2T} cost per MVA/MW quoted for two transformers/converters on a platform

The costs of undersea cables shown in (11) are also generic and cover cost of supply and cost of lay and bury and for each specific cable these are given per km. The cost is given for a set of cables which means one for a 3-core cable, three for single-core cables, and two (bipole) single core cables for a DC application.

$$CC = nc \cdot (ccs + cclb) \cdot l \quad (11)$$

where:

- CC* cost of cables
nc number of a set of cables
ccs cost of supplying of a set of cables
cclb cost of lay and bury of a set of cables
l length of a cable

The cost of corrective maintenance is calculated from reliability parameters and quoted separately.

$$MC = [n_T / (1/FR_T + MTTR_T/T) \cdot mc_T + n_c / (1/FR_c + MTTR_c/T) \cdot mc_c] \cdot CF \quad (12)$$

where:

- MC* cost of corrective maintenance
n number of elements (index *T* for transformers and *c* for cables)
FR failure rate (1/year) (index *T* for transformers and *c* for cables)
MTTR mean time to repair (h) (index *T* for transformers and *c* for cables)
T duration of a year in hours ($T = 8760\text{h}$)

¹² In this context, corrective maintenance relates to post-fault replacement or repair of faulty equipment

mc average cost per maintenance (index *T* for transformers and *c* for cables)
CF capitalisation factor (years)

7. Minimum Capacity Factor – X Factor

The cost benefit analysis demonstrated that the total optimal capacity of the offshore transmission systems installed can be lower than the maximum export capacity of the wind farm connected due to the cost of installing offshore transmission assets to full capacity (X factor).

Table 9 shows the maximum size of wind farm in MW that will be optimally supplied for different cable configurations. For example, if distance to the shore is 50 km, then a wind farm of a size of between 322 and 352 MW will be optimally connected to the grid with one cable at 220 kV 800 mm². Dividing cable capabilities given in Table 6 with the corresponding values in Table 9 the X factor is obtained. Table 10 shows these values.

Table 9 – Wind farms capacity (MW) that change cable optimum configuration (change from one cable rating to the next and change in number of cables used).

Wind farms capacity (MW)			Non-diversified wind profile				Diversified wind profile			
Voltage (kV)	Number of cables	Cable size mm ²	Cable length (km)				Cable length (km)			
			25	50	75	100	25	50	75	100
132	1	500	176	178	178	176	188	190	192	194
		630	196	196	198	196	208	212	214	214
		800	214	216	218	218	230	236	240	240
220	1	500	292	292	290	282	306	310	310	304
		630	322	322	320	312	338	342	342	336
		800	350	352	346	338	366	372	370	364
		1000	392	406	410	408	434	456	470	474
132	2	800	426	428	430	430	450	462	-	-
220	2	500	555	565	575	560	600	605	605	595
		630	640	645	635	620	665	675	670	660
		800	695	700	690	675	720	730	730	715
		1000	770	790	795	780	845	875	885	885
	3	500								

Similar analysis is carried out for the different ratings of transformers. The maximum size of wind farm that can be optimally supplied by two transformers is shown in Table 11. Dividing total transformers rating with the size of corresponding wind farms, the X factors for transformers are obtained. The values are shown in Table 12.

Table 10 – X factor for cables

X factor (%)			Non-diversified wind profile				Diversified wind profile			
Voltage (kV)	Number of cables	Cable size mm ²	Cable length (km)				Cable length (km)			
			25	50	75	100	25	50	75	100
132	1	500	95.5	94.4	94.4	94.3	89.4	88.4	87.5	85.6
		630	94.9	94.9	93.9	93.9	89.4	87.7	86.9	86.0
		800	94.4	93.5	92.7	92.0	87.8	85.6	84.2	83.5
220	1	500	95.0	95.0	94.3	94.3	90.7	89.5	88.2	87.5
		630	95.0	95.0	94.2	93.9	90.5	89.5	88.2	87.2
		800	95.3	94.7	94.8	94.4	91.1	89.7	88.6	87.6
		1000	91.1	87.9	85.6	83.6	82.3	78.3	74.7	71.9
132	2	800	94.8	94.4	94.0	93.3	89.8	87.4	-	-
220	2	500	100.0	98.2	95.1	95.0	92.5	91.7	90.4	89.4
		630	95.6	94.9	95.0	94.5	92.0	90.7	90.0	88.8
		800	96.0	95.3	95.1	94.5	92.6	91.4	89.9	89.2
		1000	92.7	90.4	88.3	87.4	84.5	81.6	79.3	77.1
	3	500								

Table 11 – Wind farm capacity (MW) that change transformer size solution.

Wind farm capacity (MW)		Non diversified profile				Diversified profile			
No transformers	Transformers rating (MW)	Length (km)							
		25	50	75	100	25	50	75	100
2	85	178	178	178	178	188	190	192	192
2	90	188	188	188	188	194	194	194	194
2	95	200	200	200	200	208	212	214	214
2	100	210	210	210	210	216	216	216	222
2	105	220	220	220	220	230	236	240	240
2	140	294	294	294	294	306	310	310	-
2	155	326	326	326	326	338	342	342	336
2	160	336	336	336	338	344	344	344	364
2	165	346	346	346	346	356	356	370	-
2	205	428	428	430	430	450	462	470	474
2	280	585	585	585	585	600	605	605	
2	290	610	610	610	610	625	625	625	
2	300	630	630	630	630	645	645	645	660
2	310	650	650	650	650	665	675	670	665
2	320	670	670	670	675	685	690	685	715
2	330	690	690	690	690	710	710	730	-
2	360	755	760	760	765	835	835		
2	370	775	780	785	780	845	860		
2	380	795	795	795	795	-	875	885	885

Table 12 – X factor for transformers

X factor (%)		Non diversified profile				Diversified profile			
No transformers	Transformers rating (MW)	Length (km)							
		25	50	75	100	25	50	75	100
2	85	95.5	95.5	95.5	95.5	90.4	89.5	88.5	88.5
2	90	95.7	95.7	95.7	95.7	92.8	92.8	92.8	92.8
2	95	95.0	95.0	95.0	95.0	91.3	89.6	88.8	88.8
2	100	95.2	95.2	95.2	95.2	92.6	92.6	92.6	90.1
2	105	95.5	95.5	95.5	95.5	91.3	89.0	87.5	87.5
2	140	95.2	95.2	95.2	95.2	91.5	90.3	90.3	
2	155	95.1	95.1	95.1	95.1	91.7	90.6	90.6	92.3
2	160	95.2	95.2	95.2	94.7	93.0	93.0	93.0	87.9
2	165	95.4	95.4	95.4	95.4	92.7	92.7	89.2	
2	205	95.8	95.8	95.3	95.3	91.1	88.7	87.2	86.5
2	280	95.7	95.7	95.7	95.7	93.3	92.6	92.6	
2	290	95.1	95.1	95.1	95.1	92.8	92.8	92.8	
2	300	95.2	95.2	95.2	95.2	93.0	93.0	93.0	90.9
2	310	95.4	95.4	95.4	95.4	93.2	91.9	92.5	93.2
2	320	95.5	95.5	95.5	94.8	93.4	92.8	93.4	89.5
2	330	95.7	95.7	95.7	95.7	93.0	93.0	90.4	
2	360	95.4	94.7	94.7	94.1	86.2	86.2		
2	370	95.5	94.9	94.3	94.9	87.6	86.0		
2	380	95.6	95.6	95.6	95.6		86.9	85.9	85.9

The drivers for minimum capacity factor are:

- Cable length: X reducing with increasing length
- Diversity:
- Cable size: relatively large value of X
- Voltage level: medium value of X
- Increase of number of cables: relatively small value of X

Recalculation of X factor for different values of wind farm availabilities is given by the following equation $X_a = (A / 0.95) X_{95}$ where X_a is X factor for desired availability A and X_{95} is X factor for 95% availability. The assessment demonstrated that offshore platform capacity should be about 95% of the maximum export capacity of the wind farm connected.

For cable networks, the total optimal capacity installed can be lower than the maximum export capacity of the wind farm connected due to the cost of installing offshore transmission assets to full capacity (X factor in table below). For non-diversified wind profile (appropriate for relatively small wind farms, occupying small geographical areas) the installed network capacity should be above 95% of the maximum output of the wind farm, while in case of diversified wind profile (appropriate for relatively large wind farms occupying relatively large areas) the installed network capacity should be above 90% of the maximum output of the wind

farm. In cases where this value requires additional cable to be installed, consideration should be given to installation of network capacity below 95% for non-diversified profile and below 90% for diversified profiles. The optimal values of the X factor will be a function of the distance as shown in the table below. For example, consider a wind farm at 100km offshore for which we consider connection of 1 or 2 cables. If the rating of the cable is 77% (or more) of the wind farm installed capacity, installing 2 cables would not be justified.

Table 13 – Minimum capacity factors – X factors (%) for shared connections

X factor (%)		Cable length (km)			
Wind farm profile	Condition - Increase in	25	50	75	100
Non-diversified wind profile	Cable rating	>95			
	Number of cables	>91	>88	>86	>84
Diversified wind profile	Cable rating	>90			
	Number of cables	>85	>82	>79	>77

8. Sensitivity Analysis – Robustness of Design

8.1 Platform Design

8.1.1 Number of Transformers

This study case investigates an optimal number of transformers on a platform. The following analysis is carried out for wind farm of 379 MW that are 95% available. The solution is tested to sensitivity of energy constraint cost and cost of losses of £50/MWh, £75/MWh, and £100/MWh. The summary of the results is shown in Table 14. The values in the table represent a MTTR that require more transformers or more redundancy. For example, for energy cost of £75/MWh if MTTR is less than 4.5 months one transformer on a platform represents the optimal solution. If however MTTR is greater than 4.5 and less than 10.5 months, the installation of two transformers on a platform would be more cost effective. We concluded that using two SGT instead of one may be justified, while the application of three SGT instead of two is unlikely to be efficient. However, increasing redundancy above N-0 is unlikely to be justified.

Table 14 – Mean time to repair in months

Substation solution	Cost of energy (£/MWh)		
	50	75	100
1x360 MW	< 6.5	< 4.5	< 3.2
2x180 MW	< 15.5	< 10.5	< 8
2x240 MW	< 23.5	< 15.5	< 11.5
3x150 MW	< 34	< 23	< 17.5
3x180 MW	-	-	-

We now consider wind farms of higher ratings. We analyse a wind farm of 560 MW and it is assumed to have 95% availability. The objective of this case is to establish if a design with two transformers of 270 MW is preferred over a design with three transformers of 180 MW.

The results are shown in Table 15. There are two sub-cases. In the first one the MTTR is increased up to point where both solutions have the same total costs. The first figure is for diversified wind profile, the last figure is for a case when total costs are equal for non-diversified wind profile. The figure in the middle is for the case when the average costs for both wind profiles are equal. For the energy cost of £50/MWh, the impact of cable network (25 and 50 km cable length) is also investigated. It is concluded that the presence of cables in the calculation does not change the solution at the platform. In the second sub-case, a sensitivity of solution to energy cost is analyzed. It is concluded that the cost of constraint energy would need to be very high to justify the use of three instead of two transformers on the platform. Note that the presence of the cable network in the calculation does not significantly change the solution.

Table 15 – Break-even parameters shown in bold. The first figure is associated with diversified wind profile, second represent the average value, while the third refers to non-diversified wind profile

Case	Cable length (km)	MTTR (months)	Energy cost (£/MWh)
MTTR case	-	18 – 21 – 24	50
	25	18 – 21 – 24	50
	50	18.5 – 21 – 23.5	50
	-	12 – 13.5 – 15.5	75
	-	9 – 10 – 11.5	100
Energy cost case	-	3	300 – 330 – 370
	25	3	300 – 330 – 370
	50	3	300 – 330 – 360

It can be seen from the two tables above that N-0 is the preferable configuration.

8.1.2 Maximum Rating of a Single Transformer Connection

A maximum rating of a single transformer is analysed. As the cost of smaller transformers is not well represented by the generic cost function used, a set of cost data of specific transformers is analysed (in Table 68 of Appendix). The data allows the comparison of platform capacities of 60, 90 and 120 MW. The results are shown in Figure 17, Figure 18 and Figure 19.

Figure 17 shows that the most cost effective solution for a wind capacity of 60 MW carried out through a single platform is a single transformer of 60 MVA. The conclusion is even further reinforced by the fact that two transformers require more expensive busbar and switchgear systems. Similar conclusion can be drawn for a wind capacity of 90 MW, although not as strong as for the previous example. For a wind capacity of 120 MW, it can be seen that solutions with one transformer and two transformers are similar and this is down to the fact that wind power is more or less diversified. Although a full set of data for the assessment of the costs of transformers of higher ratings was not available, the observed trend was considered to be strong enough and a break-even point of 120 MW is proposed.

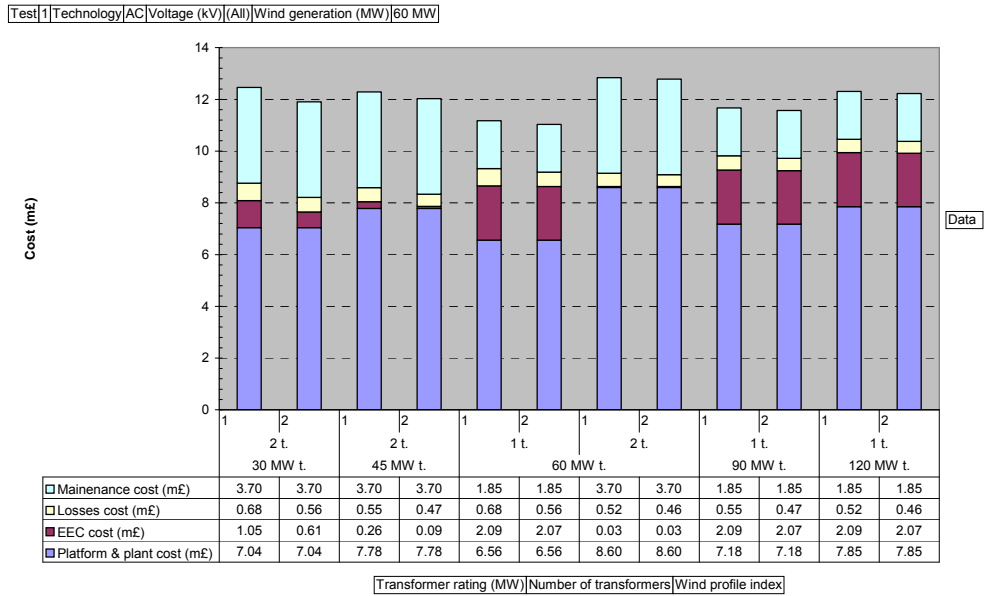


Figure 17 – Platform capacity of 60 MW

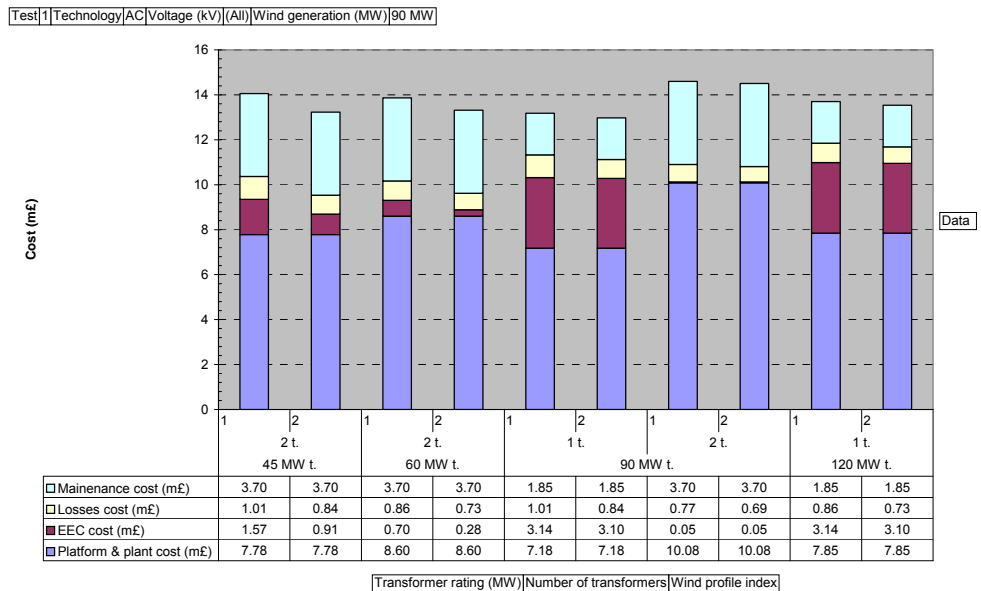


Figure 18 – Platform capacity of 90 MW

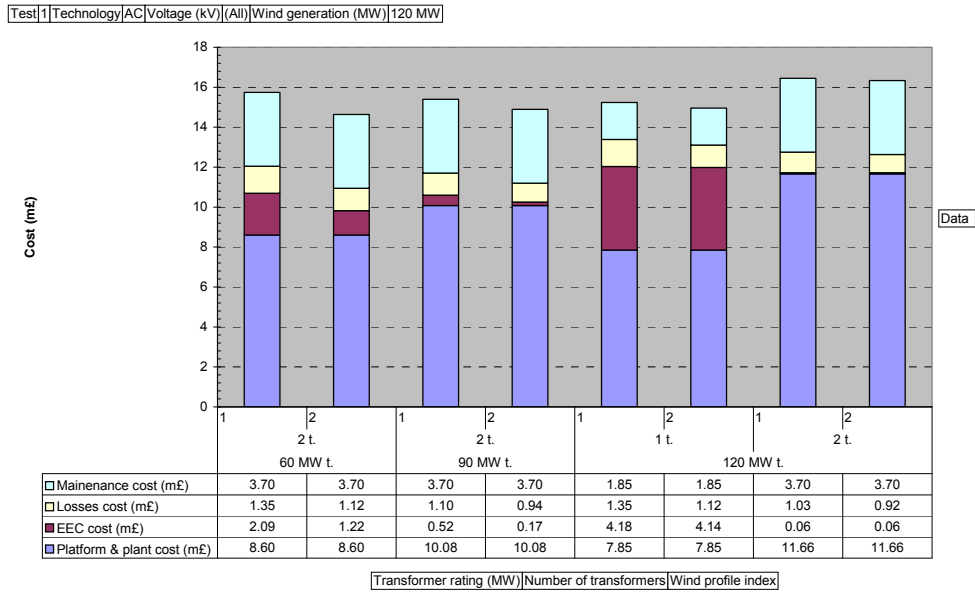


Figure 19 – Platform capacity of 120 MW

8.2 Cable System Design

8.2.1 Number of Cables

The impact of the design driving parameters MTTR and energy cost is shown on the following two examples.

In the first example, the break-even values of this parameter are calculated such that it makes two different designs, one with a single cable and the other with two cables, equally desirable. To show this, an example constituting of a wind farm rated at 280 MW and availability of 95% is developed. This wind power output can be transported through a single 220 kV 500 mm² cable. Furthermore, two transformers of 135 MW can supply one or two cables. The transformers’ MTTR are 6 months. The results of the break-even values of the MTTR¹³ for cables, depending on the cable length and energy costs, are shown in Table 16. Given relatively high values of MTTR, we conclude that a single cable is a preferable solution, as the MTTR would need to be exceptionally high to favour a solution with two cables.

In the second example, a wind farm of 600 MW and availability of 95% is connected through two transformers of 285 MW and two or three 220 kV 630 mm² cables.

In this example, the break-even values of MTTR are calculated such that two different designs, one with two cables and the other with three cables, are equally efficient. The results are shown in Table 17. Similarly to the previous example, a minimum number of cables is likely to be the optimal value.

¹³ It should be stressed that MTTR represents an average repair time, so that in some instances actual repairs may last longer than the average value, but there will also be occasions when these will be shorter.

Table 16 – Break-even parameters shown in bold. The values below break-even favour a single cable while those above favour a two cable design.

Length (km)	25	50	75	100	Fixed value
MTTR case	MTTR (months)				Energy cost (£/MWh)
	19.5	21	23.5	26.5	50
	12.5	13	14	15	75
	9	9.5	9.5	10	100
Energy cost case	Energy cost (£/MWh)				MTTR (months)
	300	300	310	310	2

Table 17 – Break-even values of MTTR are shown in bold

Length (km)	25	50	75	100	Fixed value
MTTR case	MTTR (months)				Energy cost (£/MWh)
	23	24.5	25.5	26	50
	14.5	15	15.5	15	75
	10	10.5	10.5	10.5	100
Energy cost case	Energy cost (£/MWh)				MTTR (months)
	310	320	310	310	2

From these two examples, it is concluded that design of the cable system should follow the principle of installing a minimum number of cables required to transmit the maximum wind power output.

A sensitivity analysis associated with cable failure rate is also carried out. Three values of failure rate for cables are used in calculation: 0.08 (central value), 0.12 (50% more) and 0.04 (50% less). The other parameters are wind farm availability 95%, MTTR for transformers 6 months, MTTR for cables 2 months. The break-even parameters for a change of number of cables from 1 to 2 or from 2 to 3 for various failure rate are analysed. Table 18 shows these break-even values of MTTR, while Table 19 shows break-even values of energy cost.

Table 18 – Break-even MTTR of cables

MTTR (months)		1 or 2 cables			2 or 3 cables		
Energy cost	Cable length	Failure rate (1/year.100km)					
£/MWh	Km	0.04	0.08	0.12	0.04	0.08	0.12
50	25	39	19.5	13	45	23	15.5
	50	43	21	14.5	48	24.5	16.5
	75	47	23.5	16	50	25.5	17
	100	52	26.5	18	51	26	17.5
75	25	24	12.5	8.5	28	14.5	9.5
	50	26	13	9	30	15	10
	75	28	14	9.5	30	15.5	10.5
	100	29	15	10	30	15	10
100	25	17	9	6	20	10	7
	50	18	9.5	6	21	10.5	7
	75	19	9.5	6.5	21	10.5	7
	100	20	10	7	21	10.5	7

Table 19 – Break-even energy costs

Energy cost (£/MWh)		1 or 2 cables			2 or 3 cables		
MTTR	Length	Failure rate (1/year.100km)					
months	km	0.04	0.08	0.12	0.04	0.08	0.12
2	25	420	300	230	410	310	250
	50	430	300	240	420	320	250
	75	430	310	240	420	310	250
	100	440	310	250	420	310	250

This analysis clearly suggests that the design involving the minimum number of cables is robust.

8.2.2 Cable Redundancy Analysis

Within this analysis, the optimum level of redundancy is considered. An offshore wind farm of 350 MW and availability of 95% is connected through two transformers each 170 MW capable. Assumed MTTR for transformers is 6 months. Only one cable of 220 kV 800 mm² is sufficient to transmit the wind power onshore. The alternative configurations are i) partial redundancy – two 220 kV 500 mm² cables or ii) full redundancy – two 220 kV 800 mm² cables. The cables MTTR is increased up to the point where the cost of base case (no redundancy design) is equal to the cost of one of these two cases with increased redundancy. The results for various energy costs and cable lengths are shown in Table 20. Given that the smallest value is 7 months for cables MTTR (it should be noted that this is an average value), it can be concluded that any level of redundancy is unlikely to be cost effective.

Table 20 – Break-even MTTR (months) shown in bold

Cable length km	Energy cost £/MWh	Redundancy	
		Reduced	Full
25	50	15	17.5
75	50	17	20
25	75	9.5	11
75	75	11.5	12.5
25	100	7	8
75	100	7.5	8.5

Table 21 shows break-even MTTR of cables in redundancy study for various energy costs and cable failure rates.

Table 21 – Break-even MTTR of cables

MTTR (months)		Reduced redundancy			Full redundancy		
Energy cost £/MWh	Length Km	Failure rate (1/yr.100km)					
		0.04	0.08	0.12	0.04	0.08	0.12
50	25	30	15	10	35	17.5	12
	50	34	17	11.5	41	20	14
75	25	19	9.5	6.5	22	11	7.5
	50	21	11.5	7	24	12.5	8.5
100	25	14	7	5	16	8	5.5
	50	15	7.5	5	17	8.5	6

Again, the analysis clearly suggests that the design involving no redundancy is robust.

8.2.3 Voltage Level

This example compares two offshore network configurations with different voltage levels. They supply identical wind farms of 350 MW and availability of 90%. The first configuration consists of two transformers 132/22 kV 160 MW and two three core cables 132 kV 500 mm². The second configuration consists of one transformer 220/33 kV 320 MW and one three core cable 220 kV 800 mm². The summary of total costs associated with these configurations for various energy cost is given in Table 22. It can be concluded that one circuit of 220kV is more cost efficient than two circuits of 132kV, independently from their lengths.

Table 22 – Total cost (m£) of 132 and 220 kV configurations.

Energy cost (£/MWh)	Voltage (kV)	Wind profile index	Cable length (km)			
			25	50	75	100
50	132	1	56.8	84.4	112	140
		2	54.2	80.4	106.8	133.5
	220	1	47.6	69.1	90.9	112.7
		2	46.7	67.7	89.1	110.5
75	132	1	62.9	93.1	123.6	154.3
		2	58.9	87.2	115.6	144.4
	220	1	53.7	77.2	100.9	124.7
		2	52.4	75.1	98.2	121.3
100	132	1	69	101.9	135.1	168.6
		2	63.7	94	124.5	155.4
	220	1	59.9	85.3	111	136.7
		2	58.1	82.5	107.3	132.1

8.3 Onshore Circuit Design

This study considered number of circuits involved and their ratings. In addition, the flexibility of connections is considered (simple interface versus substation). The scope of this study is limited to length of circuit to be between 1 and 50 km. Common mode failures are also considered. The impact of end-substation equipment is ignored.

Onshore Overhead Line Design

The cost of 220 kV overhead line is derived from cost of 275 kV one and in general the volume of available data for this voltage level is limited, particularly for 220 kV (275 kV) overhead lines.

Table 23 shows results for 132 kV overhead lines. Up to 400 MW wind farm a single circuit (SC) is sufficient. Above 400 MW and up to 1100 MW a double circuit (DC) is required. Above 1100 MW two double circuits are required. The next column gives the rating in MW of required circuits.

For 220 kV onshore overhead circuits a minimal number of circuits should be installed i.e. up to 1250 MW wind farm single circuit and in the remaining scope (up to 1500MW), two circuits.

We also observed that there is a benefit of connecting two undersea cables to one overhead line.

Table 23 – Results for 132 kV onshore overhead lines: number, type and rating in MW of circuits

Wind farm capacity (MW)	Onshore overhead lines length (km)			
	1, 10, 25, and 50		Exception for 50	
150	1SC	150		
250	1SC	250		
400	1SC	400		
500	1DC	500		
550	1DC	800	1DC	500
900	1DC	800		
1100	2DC	500		
1500	2DC	800		

In the calculation, the reliability model of overhead lines shown in Figure 20 is used. Table 24 shows used parameters.

Markov model of states of double circuit; tower outage is modelled separately from other common-mode faults

O – component in service
 Ô – component out of service

Indexes
 1, 2 – circuits
 3 – tower

λ – forced outage rate
 μ – repair rate
 λ_C – common-mode failure rate excluding tower forced outage rate
 λ_T – tower forced outage rate
 μ_T – tower repair rate

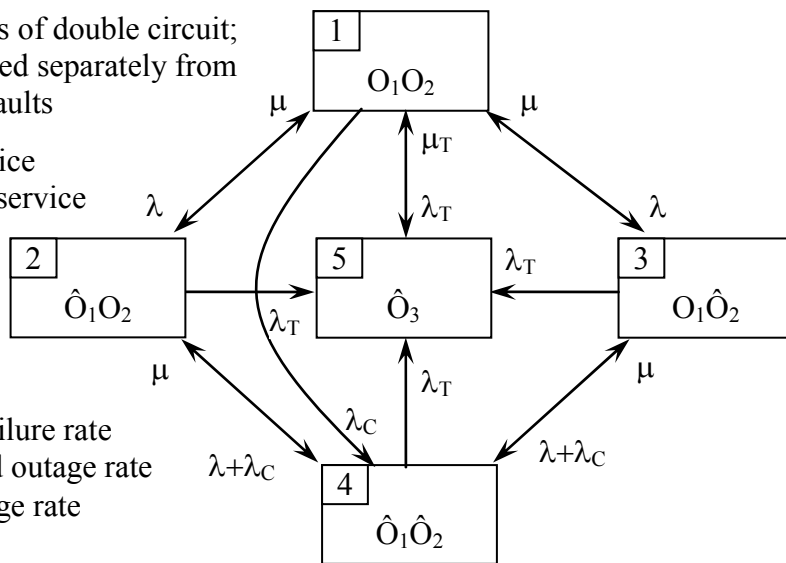


Figure 20 – Overhead lines reliability model

Table 24 – Parameters for Markov model of overhead lines

Volta ge (kV)		FOR (1/y.100 km)	MTTR (h)	CMFOR (1/y.100km)	TFOR (1/y.100km)	TMTTR (h)	OC	TOC (£k)
132	SC	0.11	26.2	0	0	-	£56.4k	-
	DC	0.1	21.6	0	0.01	72	£22.0k	400
220	SC	0.69799	56	0	0	-	1.5%	-
	DC	0.6714	56	0.02659	0	-	1.5%	-

where

- FOR forced outage rate
- MTTR 1/repair rate
- CMFOR common-mode failure rate
- TFOR tower forced outage rate
- TMTTR 1/tower repair rate
- OC outage cost
- TOC tower outage cost

8.4 Onshore Substation Design

Design of onshore substation is conceptually similar to those offshore, described above. The outputs of exercise are the optimal number and ratings of transformers. Data set however included typical ratings (note that costs of 300MVA (400 or 275/132 kV) is similar to costs of 1100MVA (400/220 kV) transformers).

It is recommended that number of transformer in 400/220 kV substation should be one for up to 640MW of wind power and double above 640 MW. Three transformers are not justified within the scope of wind farm up to 1500 MW.

For onshore transformation to 132 kV it is recommended a minimum number of transformers of 240 MVA in onshore substation without redundancy as shown in Table 25.

Table 25 – Wind farm ratings for which a breakeven costs are obtained (for wind farm ratings above 500 MW only diversified wind profile, wind profile index 2, are used)

Voltages (kV)	Number	Transformers rating (MVA)				
		240	300	360	400	460
400/132	1 vs. 2	260	320	380	420	480
	2 vs. 3	500	660	780	860	980
275/132	1 vs. 2	260	320	380	400	440
	2 vs. 3	500	660	780	840	940

8.5 Offshore Transmission System Design for GT

In addition to offshore wind farms, a design of offshore transmission system for offshore GT generation is studied. The scope of this study includes connection up to 200 MW of GT with unit size up to 100 MW. The availability of this type of generation is assumed to be 80%. It is assumed that the plant operates 80% of the time at full output and 20% of the time at zero output. Therefore load and loss load factor are 80%. Electricity cost of £40/MWh is used and a capitalisation factor of 10 is used. Offshore transformer failure and repair parameters are: failure rate 0.03 faults/year and mean time to repair 6 months. Submarine cables parameters are: failure rate 0.08 faults/year, 100km and mean time to repair 2 months.

Recommendations are as follows:

- Design of offshore substations for GT capacity up to 100 MW a single transformer offshore substation and for capacity greater than 100 MW minimum rating of individual transformers in multiple transformer offshore substations with full (N-1) redundancy
- Design of submarine link: single cable
- Design of onshore link: single circuit
- Design of onshore substation: single transformer

Robustness of solutions is tested by finding MTTR for which solution is changed.

8.6 HVDC VSC Design

Figure 21 shows total costs of various solutions for an offshore network. Relevant data for the case are also on the figure. Offshore networks should connect an 800 MW wind farm to the onshore grid. Distance to the onshore connection point is 100 km. The energy cost used in this example is £75/MWh. The cost bars are colour-coded to visually show the proportion of various cost components in the total cost of individual solutions. From the Figure, it can be concluded that the cost of losses for the HVDC solutions are significant compared to those of AC solutions. Furthermore, HVDC solutions may be competitive for wind farm ratings of above 800MW.

Given that this technology is still in development and that the losses can be reduced, a new study should be carried out and conclusions given here tested.

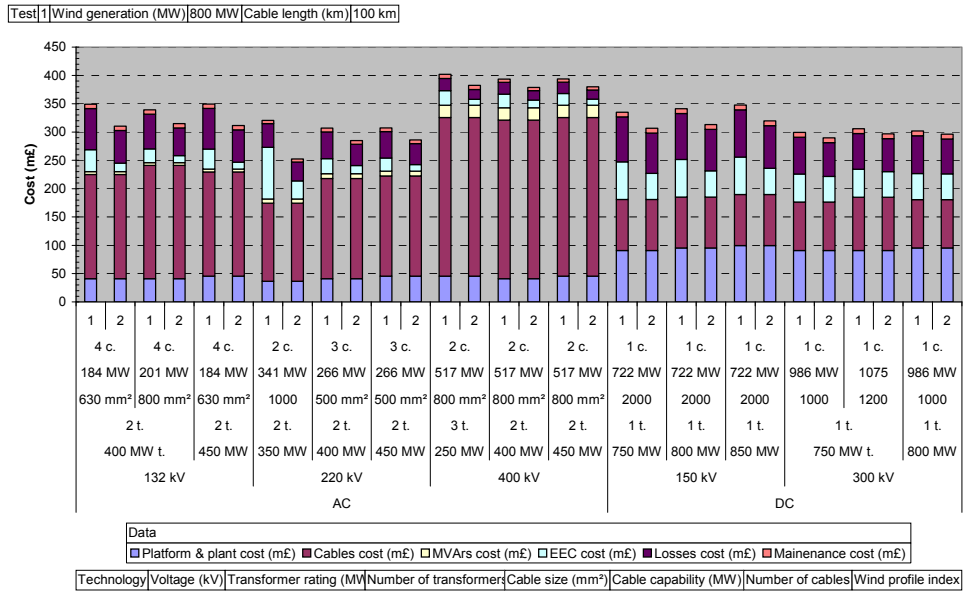


Figure 21 – Total costs for various solutions for offshore network

9. Impact of Planned Outages of Offshore Infrastructure for Wind Based Generation

9.1 Background

From the information and advice on maintenance practices from three DNOs covering 132/33kV transformers and 132 kV lines, the following generic preventive maintenance schedule is derived. For 132/33kV transformers the minor maintenance occurs every 4 years with duration of 2 to 5 days while major occurs every 8 years with duration of 6 to 10 days. The maintenance of overhead lines 132 kV every 15 years and it is coordinated with transformer maintenance.

Information on maintenance practices for 400/132kV transformers and 275/400kV OH lines was received from National Grid.

The following questions are considered

- Maximum ratings for single on & offshore transformers & circuits
- Minimum rating of on and offshore multi-transformer substations and circuit

9.2 Methodology for Inclusion of Impact of Planned Outages on Design of Offshore Transmission Equipment

The step 2 is added to the previous methodology which is now as follows

- Step 1: Carry out an initial design that is based on the solutions that do not include preventive maintenance outages
- Step 2: Increase the ratings of transformers to balance the additional capital cost and expecting energy curtailed due to preventive maintenance outage

It is assumed that the preventive maintenance period will be conducted over three summer months, i.e. Jun to August. For that purpose a load duration curve covering that period is shown in Figure 22 and curtailed energy factor in Figure 23. It can be seen that during that period load factor of wind farm is 24% which is less than overall annual load factor of 40%. Furthermore, peak output of wind generation during this period is about 83% of available capacity.

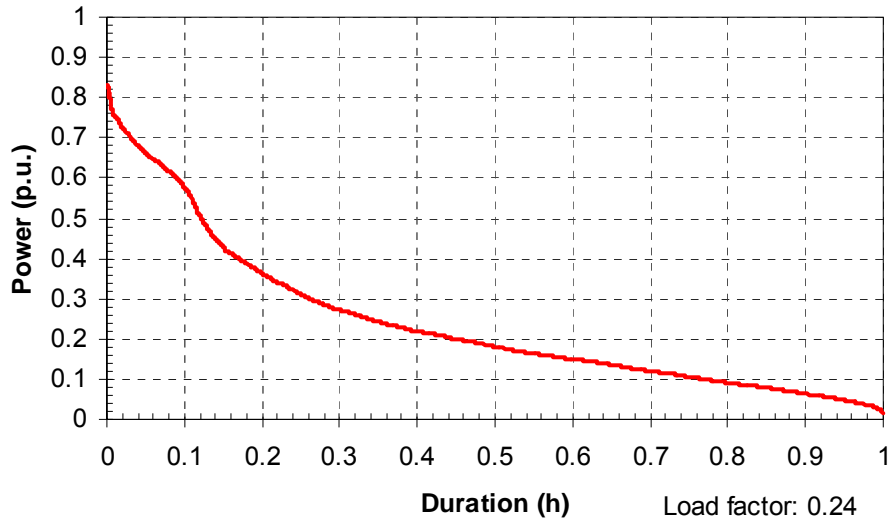


Figure 22 – Load duration curve for diversified wind summer profile during preventive maintenance period (June – August)

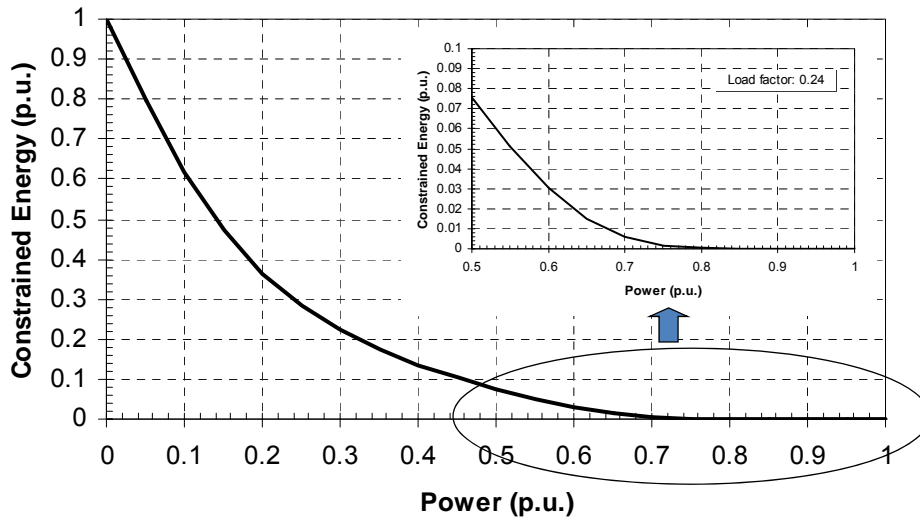


Figure 23 – Curtailed energy factor during preventive maintenance outage

The following example shows the calculation of planned outage cost.

Example. Calculate the cost of 10 hours planned outage of one transformer of two-transformer substation 2x120MW. Consider a wind farm of 250 MW and availability 95%. The cost of energy during maintenance period is £35/MWh and ROC £30/MWh.

Solution

Possible average energy generation during planned outage is given by the following expression:

- $PE = A_W \times W \times LF \times D_{PO} = 0.95 \times 250 \times 0.24 \times 10 = 570 \text{ MWh}$

where PE – possible energy (MWh), A_w – wind farm availability, W – wind farm rating (MW), LF – load factor during maintenance, D_{PO} – duration of planned outage (h)

Planned outage EEC is given as

- $POEEC = N \times PE \times CEF = 2 \times 570 \times 0.08 = 91 \text{ MWh}$

where POEEC – planned outage EEC (MWh), N – number of planned outages per year (2), CEF – curtailed energy factor obtained from Figure 23 (X axis – 120/250 = 0.48 and Y axis then 0.8)

Finally, cost of planned outage EEC is

- $CPOEEC = POEEC \times CE \times CF = 91 \times 65 \times 10 = \text{£}59,150 \cong \text{£}0.059\text{m}$

where CPOEEC – cost of POEEC (£), CE – cost of energy (£/MWh), CF – capitalisation factor

9.3 Design of Offshore and Onshore Substation

9.3.1 Two Transformers per Offshore and Onshore Substation

Designs of both onshore and offshore substations are considered simultaneously. Both substations have two transformers. It is assumed that, during preventive maintenance period, one transformer is in service while the other is on planned outage. Planned outages of both on and offshore substations are of the same durations. The average maintenance duration is between 25 and 55 hours. Two wind farm ratings are considered: (i) 250 MW and (ii) 480 MW and results shown in Table 26 and Table 27, respectively. Availability of wind farms is 95%.

Table 26 – Additional cost due to maintenance for case of wind farm of 250 MW

Offshore platform (MVA)		2x120	2x180	2x240
Onshore substation (MVA)		2x120	2x180	2x240
Additional investment (£m)		0	6.60	13.20
Forced outage EEC (£m capitalised)		3.92	0.83	0.13
Additional cost to base case (£m)		Base case	3.51	9.41
Planned outage EEC cost (£m, capitalised over 25 years)	20 hours (2x1 day)	0.056	0.001	0
	116 hours (2x3 days)	0.324	0.007	0
	212 hours (2x5 days)	0.593	0.013	0
	308 hours (2x7 days)	0.862	0.018	0

Table 27 – Additional cost due to maintenance for case of wind farm of 480 MW

Offshore platform (MVA)		2x230	2x345	2x460
Onshore substation (MVA)		2x230	2x345	2x460
Additional investment (£m)		0	12.65	25.30
Forced outage EEC (£m capitalised)		7.53	1.60	0.26
Additional cost to base case (£m)		Base case	6.71	21.63
Planned outage EEC cost (£m, capitalised over 25 years)	20 hours (2x1 day)	0.107	0.002	0
	116 hours (2x3 days)	0.623	0.013	0
	212 hours (2x5 days)	1.139	0.024	0
	308 hours (2x7 days)	1.654	0.035	0

For example of wind farm of 480 MW shown in Table 27, even if duration of planned outage is 2 weeks, the benefit will be £1.6m (1.654-0.035) which is far below additional cost of £6.71m to achieve that benefit. It can be concluded that for solutions with onshore and offshore substations with 2 transformers, there is no impact of planned outages on the design.

9.3.2 Single Transformer per Offshore Platform

In this section, the maximum rating for single-transformer platform is examined. Given a single-transformer platform and small rating, this study can be performed only on platform and not considering submarine cables, onshore circuits and onshore substation. It is looking for a case when the additional cost of installing two transformers is smaller than the benefit it brings. Three sizes of wind farm (i) 60 MW, (ii) 90 MW and (iii) 120 MW are considered and results are shown in Table 28, Table 29 and Table 30, respectively. These sizes coincide with the typical transformer ratings. The wind farm availability is 95% and two durations of planned outage are considered 10 and 58 hours per transformer.

Table 28 – Additional cost and benefit of installing two transformers for wind farm of 60 MW

Offshore platform (MVA)		1x60	2x30	2x45
Additional investment (£m)		0	0.94	1.79
Corrective maintenance/repair cost (£m)		0.74	1.48	1.48
EEC cost (£m, capitalised over 25 years)	Forced outage	2.07	0.70	0.13
	Planned outage 10 h	0.09	0.01	0.00
	Planned outage 58 h	0.52	0.08	0.00
Total PO 10 h / PO 58 h (£m)		2.9/3.32	2.2/2.26	1.61/1.61
Benefit (£m)		0/0	0.7/1.06	1.29/1.71

Table 29 – Additional cost and benefit of installing two transformers for wind farm of 90 MW

Offshore platform (MVA)		1x90	2x45	2x60
Additional investment (£m)		0	1.05	2.02
Corrective maintenance/repair cost (£m)		0.74	1.48	1.48
EEC cost (£m, capitalised over 25 years)	Forced outage	3.10	1.05	0.38
	Planned outage 10 h	0.13	0.02	0.00
	Planned outage 58 h	0.77	0.12	0.01
Total PO 10 h / PO 58 h (£m)		3.97/4.61	2.55/2.65	1.86/1.86
Benefit (£m)		0/0	1.42/1.96	2.12/2.75

Table 30 – Additional cost and benefit of installing two transformers for wind farm of 120 MW

Offshore platform (MVA)		1x120	2x60	2x90
Additional investment (£m)		0	1.24	2.98
Corrective maintenance/repair cost (£m)		0.74	1.48	1.48
EEC cost (£m, capitalised over 25 years)	Forced outage	4.13	1.40	0.26
	Planned outage 10 h	0.18	0.03	0.00
	Planned outage 58 h	1.03	0.16	0.00
Total PO 10 h / PO 58 h (£m)		5.05/5.73	2.91/3.01	1.74/1.74
Benefit (£m)		0/0	2.14/2.71	3.31/3.99

For wind farm of 60 MW the benefit of having two transformer of 30 MW and considering that duration of planned outage is 10 hours on average is £0.7m while additional cost would be £0.94m (see Table 28). Similarly for wind farm of 90 MW the benefit of having 2 transformers of 45 MVA instead of one of 90 MVA is £1.42m outweigh the additional investment cost of £1.05m (see Table 29). Recommendation is that the maximum rating of a single-transformer platform is 90MW. This finding would be strengthened when considering overlaps with onshore assets maintenance.

9.3.3 Single Transformer per Onshore Substation

In order to find out the maximum size of a single-transformer substation the several cases are considered. The study is performed for the following rating of wind farms 125 MW, 180 MW, 250 MW and 310 MW and results are shown in Table 31, Table 32, Table 33 and Table 34, respectively. The results are presented for the following generic planned outage durations: 10, 58, 106 and 154 hours per transformer.

Table 31 – Additional cost and benefit of installing two transformers at onshore substation. Offshore substation consists of 2 transformers of 60 MW each.

Onshore substation		1x120 MVA	2x120 MVA
Additional investment (£m)		0	3.94
Onshore transformers corrective maintenance cost (£m)		0.25	0.50
EEC cost (£m, capitalised over 25 years)	Forced outage	0.95	0.00
	Planned outage 10/58/106/154 h	0.19/1.07/1.96/2.85	0.00
Total (£m)		1.47/2.75/4.03/5.31	0.5/0.5/0.5/0.5
Benefit (£m)		0	0.97/2.25/3.53/4.81

Table 32 – Additional cost and benefit of installing two transformers at onshore substation. Offshore substation consists of 2 transformers of 90 MW each.

Onshore substation		1x180 MVA	2x120 MVA
Additional investment (£m)		0	3.76
Onshore transformers corrective maintenance cost (£m)		0.25	0.50
EEC cost (£m, capitalised over 25 years)	Forced outage	1.37	0.15
	Planned outage 10/58/106/154 h	0.27/1.55/2.83/4.11	0.00
Total (£m)		1.89/3.17/4.45/5.73	0.65/0.65/0.65/0.65
Benefit (£m)		0	1.24/2.52/3.8/5.08

Table 33 – Additional cost and benefit of installing two transformers at onshore substation. Offshore substation consists of 2 transformers of 120 MW each.

Onshore substation		1x240 MVA	2x120 MVA
Additional investment (£m)		0	3.58
Onshore transformers corrective maintenance cost (£m)		0.25	0.50
EEC cost (£m, capitalised over 25 years)	Forced outage	1.91	0.70
	Planned outage 10/58/106/154 h	0.37/2.15/3.93/5.71	0/0.01/0.02/0.03
Total (£m)		2.43/3.71/4.99/6.27	1.2/1.21/1.21/1.22
Benefit (£m)		0	1.23/2.5/3.78/5.05

Table 34 – Additional cost and benefit of installing two transformers at onshore substation. Offshore substation consists of 2 transformers of 150 MW each.

Onshore substation		1x300 MVA	2x180 MVA
Additional investment (£m)		0	3.76
Onshore transformers corrective maintenance cost (£m)		0.25	0.50
EEC cost (£m, capitalised over 25 years)	Forced outage	2.37	0.49
	Planned outage 10/58/106/154 h	0.46/2.66/4.87/7.08	0/0.01/0.01/0.02
Total (£m)		2.89/4.17/5.45/6.73	0.99/0.99/0.99/1
Benefit (£m)		0	1.9/3.17/4.45/5.73

For a case of wind farm of 180 MW (see Table 32) the additional cost of having two transformers of 120 MVA instead of one of 180 MVA (£3.76m) is breakeven with the benefit where duration of planned outage on average is 5 days (£3.8m). Recommendation is that the maximum rating of a single-transformer substation is between 120 and 180 MW. It should be noted that the cost data given for large transformers are extrapolated only to a lower value to 120 MVA. Hence in these case studies only transformers equal to or greater than 120 MVA are considered.

9.4 Design of submarine cables

It is assumed that submarine cables will be maintenance free and, also, the cost of cables the recommendations is that there is no changes in submarine cable design for cables longer than ~500m.

9.5 Design of Onshore Circuit

9.5.1 Design of Overhead Line 132 kV

The results of the analysis are shown in Table 35. It can be seen that for wind farm of 150 MW a single onshore circuit is sufficient. For wind farm of 250 MW for short distances double circuit is optimal while for the long distances single circuit is optimal. For wind farm of 400 MW the optimal solution is double circuit. Details of this analysis are shown from Table 36 to Table 47. The onshore substation is not considered and calculation is carried out for two planned outage durations 10 and 58 hours per overhead circuit.

Table 35 – Results for 132kV onshore overhead lines (with generic maintenance of OH lines)

Length (km)	Wind farm capacity (MW)		
	150	250	400
1	SC	DC	DC
10	SC	SC/DC	DC
25	SC	SC	DC
50	SC	SC	SC/DC

- SC – Single circuit
- DC – Double circuit

Table 36 – Additional cost and benefit of different onshore overhead circuit of length of 1km. Rating of wind farm is 150 MW, availability 95%. Offshore substation consists of 2 transformers of 75 MW each. Submarine cable 132 kV 1x500 mm² 50 km is maintenance free.

Onshore circuit	1SC=150MVA	1DC=300MVA	2SC=300MVA	
Additional investment (£m)	0	0.25	0.45	
Cost of onshore circuits losses (£m)	0.01	0.00	0.00	
Onshore circuits maintenance cost (£m)	0.00	0.00	0.00	
EEC cost (£m, capitalised over 25 years)	Forced outage	0.00	0.00	0.00
	Planned outage 10 h	0.22	0.00	0.00
	Planned outage 58 h	1.29	0.00	0.00
Total PO 10 h / PO 58 h (£m)	0.23/1.3	0.01/0.01	0.01/0.01	
Benefit (£m)	0/0	0.23/1.29	0.23/1.29	

Table 37 – Additional cost and benefit of different onshore overhead circuit of length of 10km. Rating of wind farm is 150 MW, availability 95%. Offshore substation consists of 2 transformers of 75 MW each. Submarine cable 132 kV 1x500 mm² 50 km is maintenance free.

Onshore circuit		1SC=150MVA	1DC=300MVA	2SC=300MVA
Additional investment (£m)		0	2.50	4.50
Cost of onshore circuits losses (£m)		0.08	0.04	0.04
Onshore circuits maintenance cost (£m)		0.01	0.01	0.01
EEC cost (£m, capitalised over 25 years)	Forced outage	0.01	0.00	0.00
	Planned outage 10 h	0.22	0.00	0.00
	Planned outage 58 h	1.29	0.00	0.00
Total PO 10 h / PO 58 h (£m)		0.32/1.39	0.05/0.05	0.05/0.05
Benefit (£m)		0/0	0.27/1.34	0.27/1.34

Table 38 – Additional cost and benefit of different onshore overhead circuit of length of 25km. Rating of wind farm is 150 MW, availability 95%. Offshore substation consists of 2 transformers of 75 MW each. Submarine cable 132 kV 1x500 mm² 50 km is maintenance free.

Onshore circuit		1SC=150MVA	1DC=300MVA	2SC=300MVA
Additional investment (£m)		0.00	6.25	11.25
Cost of onshore circuits losses (£m)		0.21	0.10	0.10
Onshore circuits maintenance cost (£m)		0.02	0.02	0.03
EEC cost (£m, capitalised over 25 years)	Forced outage	0.03	0.01	0.00
	Planned outage 10 h	0.22	0.00	0.00
	Planned outage 58 h	1.29	0.00	0.00
Total PO 10 h / PO 58 h (£m)		0.47/1.54	0.13/0.13	0.13/0.13
Benefit (£m)		0/0	0.34/1.41	0.34/1.41

Table 39 – Additional cost and benefit of different onshore overhead circuit of length of 50km. Rating of wind farm is 150 MW, availability 95%. Offshore substation consists of 2 transformers of 75 MW each. Submarine cable 132 kV 1x500 mm² 50 km is maintenance free.

Onshore circuit		1SC=150MVA	1DC=300MVA	2SC=300MVA
Additional investment (£m)		0.00	12.50	22.50
Cost of onshore circuits losses (£m)		0.42	0.21	0.21
Onshore circuits maintenance cost (£m)		0.03	0.04	0.06
EEC cost (£m, capitalised over 25 years)	Forced outage	0.06	0.01	0.00
	Planned outage 10 h	0.22	0.00	0.00
	Planned outage 58 h	1.29	0.00	0.00
Total PO 10 h / PO 58 h (£m)		0.73/1.79	0.26/0.26	0.27/0.27
Benefit (£m)		0/0	0.46/1.53	0.46/1.52

Table 40 – Additional cost and benefit of different onshore overhead circuit of length of 1km. Rating of wind farm is 250 MW, availability 95%. Offshore substation consists of 2 transformers of 120 MW each. Submarine cable 132 kV 2x500 mm² 50 km is maintenance free.

Onshore circuit		1SC=250MVA	1DC=300MVA	2SC=250MVA
Additional investment (£m)		0.00	0.10	0.60
Cost of onshore circuits losses (£m)		0.02	0.01	0.01
Onshore circuits maintenance cost (£m)		0.00	0.00	0.00
EEC cost (£m, capitalised over 25 years)	Forced outage	0.00	0.00	0.00
	Planned outage 10 h	0.37	0.00	0.00
	Planned outage 58 h	2.15	0.00	0.00
Total PO 10 h / PO 58 h (£m)		0.4/2.17	0.01/0.01	0.01/0.01
Benefit (£m)		0/0	0.38/2.16	0.38/2.16

Table 41 – Additional cost and benefit of different onshore overhead circuit of length of 10km. Rating of wind farm is 250 MW, availability 95%. Offshore substation consists of 2 transformers of 120 MW each. Submarine cable 132 kV 2x500 mm² 50 km is maintenance free.

Onshore circuit		1SC=250MVA	1DC=300MVA	2SC=250MVA
Additional investment (£m)		0.00	1.00	6.00
Cost of onshore circuits losses (£m)		0.23	0.12	0.12
Onshore circuits maintenance cost (£m)		0.01	0.01	0.01
EEC cost (£m, capitalised over 25 years)	Forced outage	0.02	0.01	0.00
	Planned outage 10 h	0.37	0.00	0.00
	Planned outage 58 h	2.15	0.00	0.00
Total PO 10 h / PO 58 h (£m)		0.63/2.4	0.13/0.13	0.13/0.13
Benefit (£m)		0/0	0.5/2.27	0.5/2.28

Table 42 – Additional cost and benefit of different onshore overhead circuit of length of 25km. Rating of wind farm is 250 MW, availability 95%. Offshore substation consists of 2 transformers of 120 MW each. Submarine cable 132 kV 2x500 mm² 50 km is maintenance free.

Onshore circuit		1SC=250MVA	1DC=300MVA	2SC=250MVA
Additional investment (£m)		0.00	2.50	15.00
Cost of onshore circuits losses (£m)		0.58	0.29	0.29
Onshore circuits maintenance cost (£m)		0.02	0.02	0.03
EEC cost (£m, capitalised over 25 years)	Forced outage	0.05	0.02	0.00
	Planned outage 10 h	0.37	0.00	0.00
	Planned outage 58 h	2.15	0.00	0.00
Total PO 10 h / PO 58 h (£m)		1.01/2.79	0.33/0.33	0.32/0.32
Benefit (£m)		0/0	0.68/2.46	0.69/2.47

Table 43 – Additional cost and benefit of different onshore overhead circuit of length of 50km. Rating of wind farm is 250 MW, availability 95%. Offshore substation consists of 2 transformers of 120 MW each. Submarine cable 132 kV 2x500 mm² 50 km is maintenance free.

Onshore circuit		1SC=250MVA	1DC=300MVA	2SC=250MVA
Additional investment (£m)		0.00	5.00	30.00
Cost of onshore circuits losses (£m)		1.15	0.58	0.58
Onshore circuits maintenance cost (£m)		0.03	0.04	0.06
EEC cost (£m, capitalised over 25 years)	Forced outage	0.10	0.04	0.00
	Planned outage 10 h	0.37	0.00	0.00
	Planned outage 58 h	2.15	0.00	0.00
Total PO 10 h / PO 58 h (£m)		1.65/3.43	0.66/0.66	0.64/0.64
Benefit (£m)		0/0	1/2.77	1.01/2.79

Table 44 – Additional cost and benefit of different onshore overhead circuit of length of 1km. Rating of wind farm is 400 MW, availability 95%. Offshore substation consists of 2 transformers of 200 MW each. Submarine cable 132 kV 2x800 mm² 50 km is maintenance free.

Onshore circuit		1SC=400MVA	1DC=500MVA	2SC=400MVA
Additional investment (£m)		0.00	0.05	0.90
Cost of onshore circuits losses (£m)		0.06	0.03	0.03
Onshore circuits maintenance cost (£m)		0.00	0.00	0.00
EEC cost (£m, capitalised over 25 years)	Forced outage	0.00	0.00	0.00
	Planned outage 10 h	0.59	0.00	0.00
	Planned outage 58 h	3.44	0.00	0.00
Total PO 10 h / PO 58 h (£m)		0.66/3.5	0.03/0.03	0.03/0.03
Benefit (£m)		0/0	0.62/3.47	0.62/3.47

Table 45 – Additional cost and benefit of different onshore overhead circuit of length of 10km. Rating of wind farm is 400 MW, availability 95%. Offshore substation consists of 2 transformers of 200 MW each. Submarine cable 132 kV 2x800 mm² 50 km is maintenance free.

Onshore circuit		1SC=400MVA	1DC=500MVA	2SC=400MVA
Additional investment (£m)		0.00	0.50	9.00
Cost of onshore circuits losses (£m)		0.59	0.30	0.30
Onshore circuits maintenance cost (£m)		0.01	0.01	0.01
EEC cost (£m, capitalised over 25 years)	Forced outage	0.03	0.01	0.00
	Planned outage 10 h	0.59	0.00	0.00
	Planned outage 58 h	3.44	0.00	0.00
Total PO 10 h / PO 58 h (£m)		1.22/4.07	0.31/0.31	0.31/0.31
Benefit (£m)		0/0	0.91/3.75	0.91/3.76

Table 46 – Additional cost and benefit of different onshore overhead circuit of length of 25km. Rating of wind farm is 400 MW, availability 95%. Offshore substation consists of 2 transformers of 200 MW each. Submarine cable 132 kV 2x800 mm² 50 km is maintenance free.

Onshore circuit		1SC=400MVA	1DC=500MVA	2SC=400MVA
Additional investment (£m)		0.00	1.25	22.50
Cost of onshore circuits losses (£m)		1.48	0.74	0.74
Onshore circuits maintenance cost (£m)		0.02	0.02	0.03
EEC cost (£m, capitalised over 25 years)	Forced outage	0.08	0.03	0.00
	Planned outage 10 h	0.59	0.00	0.00
	Planned outage 58 h	3.44	0.00	0.00
Total PO 10 h / PO 58 h (£m)		2.16/5.01	0.79/0.79	0.77/0.77
Benefit (£m)		0/0	1.37/4.22	1.39/4.24

Table 47 – Additional cost and benefit of different onshore overhead circuit of length of 50km. Rating of wind farm is 400 MW, availability 95%. Offshore substation consists of 2 transformers of 200 MW each. Submarine cable 132 kV 2x800 mm² 50 km is maintenance free.

Onshore circuit		1SC=400MVA	1DC=500MVA	2SC=400MVA
Additional investment (£m)		0.00	2.50	45.00
Cost of onshore circuits losses (£m)		2.95	1.48	1.48
Onshore circuits maintenance cost (£m)		0.03	0.04	0.06
EEC cost (£m, capitalised over 25 years)	Forced outage	0.15	0.06	0.00
	Planned outage 10 h	0.59	0.00	0.00
	Planned outage 58 h	3.44	0.00	0.00
Total PO 10 h / PO 58 h (£m)		3.73/6.58	1.57/1.57	1.54/1.54
Benefit (£m)		0/0	2.16/5	2.19/5.04

9.5.2 Design of Overhead Line 220 kV

The recommendation for 220 kV onshore overhead circuit is minimum number of circuits i.e. up to 1250 MW wind farm single circuit and in the remaining of scope two circuits.

The result of analysis is shown in Table 48. Given the available data set, only one conductor size is considered for 220 kV overhead lines. It can be a single or double circuit. A more detail study for wind farm capacity of 1000 MW and overhead conductor length of 25 km is shown in Table 49.

Table 48 – Results for 220kV onshore overhead lines (with generic maintenance of OH lines)

Length (km)	Wind farm capacity (MW)				
	400	600	800	1000	1060
≤2	DC	DC	DC	DC	DC
≤4	SC	DC	DC	DC	DC
≤8	SC	SC	DC	DC	DC
≤25	SC	SC	SC	DC	DC
≤50	SC	SC	SC	SC	DC

Table 49 – Additional cost and benefit of different onshore overhead circuit 220 kV of length of 25km. Rating of wind farm is 1000 MW, availability 95%. Planned outage duration is 10 hours per overhead circuit. Onshore substation is not considered.

Onshore circuit (No., type, rating in MVA)		1SC 1250	1DC 2500	2SC 2500
Additional investment (£m)		0.00	7.50	30.00
Cost of losses (£m)		9.23	4.61	4.61
Corrective maintenance cost (£m)		4.50	5.63	9.00
EEC cost (£m, capitalised)	Forced outage	2.60	0.05	0.00
	Planned outage	1.48	0.00	0.00
Total (£m)		17.81	10.29	13.62
Benefit (£m)		0.00	7.52	4.19

9.5.3 Design of Onshore Underground Cable System

Although the detailed studies were not carried out, the design of onshore cable circuits follows those of offshore, given the costs of underground cables, However, given that the onshore cables can be single-core with greater conductor cross section size there might a benefit of connection two offshore cables to one onshore system of three single-core cables.

10. Rating Limits of a Single Circuit – Impact on Frequency Control

Connection of large wind farms, above 1320MW ((1320MW currently represents the maximum credible generation loss-MCGL), will have an impact on the cost of response¹⁴. The additional cost of response was determined by using the following approach.

1. Absolute load levels L_i of the national demand in each half-hourly period of the year concurrent to the wind output are considered to determine the additional response requirements due to an instantaneous power loss of an offshore wind farm that is larger than 1320MW. This means that additional response requirements due to wind are assessed for each period (1/2-hr of the year) of the year.
2. Using the annual wind profiles (and corresponding annual demand profile), the additional response requirements are determined for only those periods when the wind output P_i^w is greater than the considered MCGL.
3. The system inertia effects at different loading conditions are included. This results in different response requirements even for same level of power loss at different loading conditions.

Having determined the additional response requirements R_i^w due to wind during all periods (N) when wind level P_i^w exceeds the MCGL, the additional response cost is determined by:

$$\text{Additional Response Cost} = \sum_{i=1}^N \left\{ 0.5 \times \frac{R_i^w}{r_g} \times C_g^\eta \times MSG \right\}$$

Where,

C_g^η is the cost of efficiency loss of the generator (unit) to provide response by operating at MSG (£/MW/hr)

r_g is the total amount of reserve provided by each generator unit at its MSG level (MW)

MSG is minimum stable generation.

10.1 Rating Limit of a Single Converter Block in HVDC Applications

The reliability of the converter units and the maximum allowed frequency of power loss events affect the total capacity of the offshore wind farms and hence the rating

¹⁴ In this analysis we use a GB generation system model developed by SEDG (see “Value of fault ride through capability of wind generation in the UK”, www.sedg.ac.uk), used to support changes in Grid Code requirements associated with wind generation.

of converter blocks. The table below provides the appropriate ratings of the converter blocks against a range of frequency of their failure rates for a permissible range (one to three events) of a power loss event of 1000MW.

Table 50 – Constraints imposed by “infrequent” loss of 1000MW

Frequency of converter failures per year	Maximum allowed frequency of 1000MW loss		
	Once in 1 year	Once in 2 year	Once in 3 year
1	>1500MW	>1500MW	>1500MW
2	>1500MW	>1500MW	<1470MW
3	>1500MW	<1470MW	<1310MW
5	>1500MW	<1310MW	<1200MW
10	<1310MW	<1200MW	<1160MW

It can be observed that for converters with higher reliability (one expected failure per year), the wind farm capacity is not constrained (remains >1500MW). However, for converters with low reliability (ten expected failures per year), the size of wind farms to be connected to a single converter (and the converter rating) is significantly constrained.

A simplified approach is applied to determine the optimal size of the offshore wind farms that can be connected to an onshore grid through a single converter block. A credible power loss of 1000MW is applied as a measure to evaluate the optimal wind capacity that can be transported through the HVDC link. Due to unavailability of sufficient data on the reliability¹⁵ of converter blocks a range of their frequency of failure (1 to 10 failures per year) are investigated. The approach requires an assessment of the probability of wind output from wind farms that exceeds the considered credible loss (see Table 51). This information is then combined with the converter failure frequency and permissible level of power loss to estimate the optimal capacity of wind farms or the rating of the converter block that can transport the wind energy securely to the onshore grid.

Table 51 – Probability that the output of a wind farm of a given capacity is above 1000MW level

Wind Capacity (MW)	Probability
1050	0.00
1160	0.03
1260	0.08
1370	0.12
1470	0.16
1580	0.20

¹⁵ CIGRE task force report provides a higher failure rate of the existing HVDC CSC converter units in several countries while such data is not available for VSC technology.

Example:

For
 Converter reliability = 5 failures/year
 Permissible level of power (1000MW) loss = 2 per year
 Probability of failure = $1/5 \times 1/2 = 1/10 = 0.10$

The appropriate size of wind farm can be determined through interpolation of the capacity sizes (table 16) around probability level of 0.1, which indicates that:

$$\begin{aligned} \text{Size of wind capacity} &= (0.10-0.08)/(0.12-0.08) \times (1370-1260) + 1260 \\ &= 1310 \text{ MW} \end{aligned}$$

10.2 Rating Limit of a Single Circuit

The objective of this study was to perform a cost benefit analysis to assess the economic suitability of providing additional response provision in order to manage instantaneous loss of a large offshore wind farm, greater than 1320MW, connected through a single offshore HVDC circuit.

Data:

1. Annual half-hourly generic GB wind data depicting diverse and non-diverse wind farms was used. Both wind power output profiled represents 1500MW wind farm with a 40% load factor.
2. Historical demand data of half-hourly averaged loads was used
3. Maximum credible generation loss (MCGL) in the system was considered to be 1320MW
4. Response providing units are assumed to have the characteristics as given in Table 52.

Table 52 – Characteristics of response providing units

Generic size of the unit providing response service	500	MW
Minimum stable generation (MSG) level of the unit	250	MW
Response provision by the unit at MSG	50	MW
Fuel cost of the unit at full output	40	£/MWh
Fuel cost of the unit at MSG	48	£/MWh
Efficiency losses of the unit at MSG	20	%

It should be noted that the assumptions listed in table present an upper bound on additional response cost. The results of the evaluations of the response costs are presented in Table 53.

Table 53 – Additional annual response costs

Wind farm capacity [MW]	Annual additional cost of response [m£]
1395	0
1421	0.04
1447	0.12
1474	0.23
1500	0.43

These additional response costs are compared with the cost of installing additional line (double circuit instead of single circuit) presented in Table 54.

Table 54 – HVDC single and double circuit costs (1500MW)

Total cost (m£)		Distance (km)			
No cables	Cable size (mm ²)	25	50	75	100
1	2000	343	390	436	483
2	1000	365	417	469	522
Cost difference (m£)		22	27	33	39

Comparisons of the capitalized costs of the additional response provision (£4.3m in Table 53) and an additional HVDC circuit over a distance of 25km (£22m in Table 54) for a 1500MW offshore wind farm clearly indicates that the cost of additional response for handling losses above 1320MW is 5 times smaller than the cost of additional circuit. This result suggests that it would be justifiable to increase the MCGL for offshore wind farms above 1320 MW.

11. An Example

Let us explore the options for connecting a wind farm of 300 MW to the onshore transmission system. A single platform with two transformers will be constructed. The distance to the shore connection requires that each cable is 50 km long. Find out the optimal direct connection arrangement.

Solution

Required transformers rating is

$$S_{Ts} \geq X \cdot P_{WF} = 0.95 \cdot 300 = 285 \text{ MVA}$$

Therefore, two transformers of 150 MW are chosen and cost of platform and plant is:

$$PPC = 5 + (1 + 0.2(2 - 2))(20 + 25)/1000 \cdot 2 \cdot 150 = \text{£}18.5\text{m}$$

Various options in terms of voltage, number, and size of cables are investigated. Costs of cables per each case are given in the following Table

Voltage kV	Number	Size mm ²	Rating MVA	Unit cost m£/km	Length km	Capability MW	Cost m£
132	1	1000	217	0.59	50	216	29.5
132	2	500	169	0.42	50	168	42
220	1	500	279	0.59	50	273.5	29.5
220	1	630	308	0.625	50	301.5	31.25

Cost of compensation is given in the following Table

Voltage kV	Num ber	Size mm ²	Compensation (MVA _r)		Unit cost (m£/MVA _r)		Cost m£
			Offshore	Onshore	Offshore	Onshore	
132	1	1000	0	20.9	0.025	0.015	0.3135
132	2	500	0	21.8	0.025	0.015	0.6540
220	1	500	0	54	0.025	0.015	0.8100
220	1	630	0	60.4	0.025	0.015	0.9060

Estimation of cost of losses

The estimated cost of transformer losses is

$$CTL = 2 \cdot \left[\frac{1}{20} + \frac{(0.95 \cdot 300 / (2 \cdot 1))^2}{150^2} \cdot \delta \right] \cdot \frac{0.6}{100} \cdot 150 \cdot 8760 \cdot 750$$

which for non-diversified wind generation profile CTL is £3.70m and for diversified CTL is £3.06m.

The estimated cost of cables losses is

$$CCL = 1 \cdot n_c \cdot r_c \cdot 50 \cdot \left(\frac{0.95 \cdot 300}{V \cdot 1} \right)^2 \cdot \delta \cdot 8760 \cdot 750$$

and presented in Table 55.

Table 55 – Cable losses.

Voltage	Number	Size	Resistance	Profile	Loss load factor	Cost
kV		mm ²	Ω/km		%	m£
132	1	1000	0.0275	Non-diver	29.1	12.25
				Diversified	23.1	9.73
	2	500	0.0493	Non-diver	29.1	10.98
				Diversified	23.1	8.72
220	1	500	0.0489	Non-diver	29.1	7.84
				Diversified	23.1	6.23
	1	630	0.0391	Non-diver	29.1	6.27
				Diversified	23.1	4.98

Table 56 shows total costs for transformers and cables losses.

Table 56 – Transformers and cables losses.

Voltage	Number	Size	Profile	Total losses cost
kV		mm ²		m£
132	1	1000	Non-diver	15.95
			Diversified	12.78
	2	500	Non-diver	14.68
			Diversified	11.78
220	1	500	Non-diver	11.54
			Diversified	9.28
	1	630	Non-diver	9.97
			Diversified	8.04

Table 57 shows reliability parameters used to calculate EEC in this example

Table 57 – Transformers and cables reliability parameters.

	Transformers	Cables
Failure rate	0.03 1/year	0.08 1/year, 100km
Mean time to repair	6 months	2 months

Availability is calculated as:

$$A = \frac{1}{1 + FR[1/year] \cdot \frac{MTTR[months] \cdot 30[days/month] \cdot 24[hours/day]}{8760[hours/year]}}$$

where:

A availability

FR failure rate in 1/year

MTTR mean time to repair in months

This gives the result that transformer availability is 0.9854 while availability of 50 km of cable is 0.9935.

For the case of one 132 kV cable of 1000 mm² a capacity outage probability table is shown in Table 58. It also shows a constrained energy for a diversified wind generation profile.

Table 58 – Capacity outage probability table.

Capacity in (MW)	Probability	Energy constrained (MWh)	Expected energy constrained (MWh)
216	0.96471	33350	32173
150	0.02854	164848	4698
0	0.00674	998640	6691
Total	1.0000	Total	43609

Table 59 shows the EEC costs.

Table 59 – EEC cost.

Voltage kV	Number	Size mm ²	Profile	EEC	EEC cost
				MWh	m£
132	1	1000	Non-diver	108232	81.17
			Diversified	43609	32.71
	2	500	Non-diver	10934	8.20
			Diversified	6470	4.85
220	1	500	Non-diver	19084	14.31
			Diversified	11517	8.64
	1	630	Non-diver	14666	11.00
			Diversified	11440	8.58

Cost of transformers corrective maintenance is

$$MC_T = [2/(1/0.03 + 6 \cdot 30 \cdot 24/8760) \cdot 2.5] \cdot 10 = \text{£}1.478m$$

while cost of cable corrective maintenance is

$$MC_c = [1/(1/0.04 + 2 \cdot 30 \cdot 24/8760) \cdot 0.5] \cdot 25 = \text{£}0.199m$$

which gives total cost of corrective maintenance of

$$MC = MC_T + MC_c = \text{£}1.68m$$

for one cable and

$$MC = MC_T + 2 \cdot MC_c = \text{£}1.88m$$

for two cables.

The total cost is given in Table 60.

Table 60 – Total cost.

V	N	Size	Profile	PPC	CC	QC	LC	EECC	MC	Total
kV	o	mm ²		m£	m£	m£	m£	m£	m£	m£
132	1	1000	Non-diver	18.5	29.5	0.31	15.95	81.17	1.68	147.1
			Diversified	18.5	29.5	0.31	12.78	32.71	1.68	95.5
	2	500	Non-diver	18.5	42	0.65	14.68	8.20	1.88	85.9
			Diversified	18.5	42	0.65	11.78	4.85	1.88	79.7
220	1	500	Non-diver	18.5	29.5	0.81	11.54	14.31	1.68	76.3
			Diversified	18.5	29.5	0.81	9.28	8.64	1.68	68.4
	1	630	Non-diver	18.5	31.25	0.91	9.97	11.00	1.68	73.3
			Diversified	18.5	31.25	0.91	8.04	8.58	1.68	69.0

Notes:

PPC platform and plant costs

CC cables costs

QC compensation costs

LC losses costs

EECC expected energy curtailed cost

MC corrective maintenance cost

The optimal solutions are shown in bold. It can be seen that the final solution is dependent on the footprint of wind farm. For a small wind farm footprint, i.e. the non-diversified wind generation profile can be assumed, the optimal solution is with one 220 kV 630 mm² cable. In the other case, if diversified wind profile can be assumed, the optimal solution is with one 220 kV 500 mm² cable.

12. Key Findings

In this report, a cost-benefit based methodology was presented that is employed to determine an optimal design of the offshore transmission grid to connect offshore wind farms to onshore electricity networks. This methodology is used for the development of the new GBSQSS for Offshore Transmission Networks, as a part of the activities carried out by the GBSQSS sub-group of OTEG.

The developed cost benefit analysis was employed to find optimal trade offs between the following two broad categories of costs:

- cost of offshore transmission system investment, that is composed of:
 - costs of undersea cable network
 - cost of platform with associated equipment (transformers, reactive compensation and switchgear)
 - cost of onshore circuits and substation and reactive compensation
 - capitalised cost of corrective maintenance and
- capitalised cost of expected constrained energy due to preventive and corrective maintenance and losses over the period of the asset life.

Based on evaluating the above two cost components for a spectrum of feasible offshore transmission system configurations with different levels of redundancy, we have identified optimal designs for undersea cable network and offshore platforms (including compensation both onshore and offshore), for a range of wind farms with ratings up to 1500 MW and for a range of offshore combined and open cycle gas turbines (GTs) with ratings up to 200 MW and various distances ranging from 25 km to 100 km. Furthermore, optimal designs of onshore circuits with length ranging from 1 to 50 km and onshore substations have been identified.

Specific recommendations

The detailed cost-benefit analysis suggested that the design of offshore network systems could be separated into four main sections:

- the offshore platform (i.e. the AC transformer circuits and HVDC converters on the offshore platform);
- the offshore cable network (i.e. the transmission cable circuits linking the onshore network and the offshore platform);
- the onshore circuit if necessary
- the onshore substation if necessary

Each of the four sections can be considered separately for single and multiple generation plants connections. However, coordination of preventive maintenance activities across offshore assets has to be considered simultaneously.

It should be noted from the results presented that each of the key input parameters has been tested to find the value at which the conclusion changes. A number of the key items of the input data to the cost benefit analysis have been tested (average repair times, cost of wind or gas turbines energy curtailed, etc.) to investigate at what

level these would change the design recommendations of the cost benefit analysis. A comprehensive set of more than 35,000 sensitivity studies was performed to propose the optimal design and to demonstrate the robustness of the recommendations made.

Offshore transmission network design for wind farms

The following recommendations for offshore transmission system for wind farms are drawn:

- Minimum number of submarine cables with no redundancy. The total capacity of cables can be lower than the maximum export capacity of wind farms connected (see X factor in table below)
- Maximum rating of single transformer substation for offshore platform is 90MW. Minimum rating for multi-transformer substations is 50% of the wind farm rating and there is no impact of preventive maintenance
- Design of 132 kV overhead lines for wind farms to 400 MW is given in Table 61. For wind farms up to 1100 MW it is double circuit and above that is two double circuits. Design of 220 kV overhead lines are given in Table 62. Design of onshore underground cables will follow design of offshore subsea cables. However, there might be benefit of connecting two subsea cables to one onshore underground cable.
- Maximum rating of single transformer substation for onshore substation is 120-180MW

Table 61 – Results for 132kV onshore overhead lines (with generic maintenance of OH lines)

Length (km)	Wind farm capacity (MW)		
	150	250	400
1	SC	DC	DC
10	SC	SC/DC	DC
25	SC	SC	DC
50	SC	SC	SC/DC

- SC – Single circuit
- DC – Double circuit

Table 62 – Results for 220kV onshore overhead lines (with generic maintenance of OH lines)

Length (km)	Wind farm capacity (MW)				
	400	600	800	1000	1060
≤2	DC	DC	DC	DC	DC
≤4	SC	DC	DC	DC	DC
≤8	SC	SC	DC	DC	DC
≤25	SC	SC	SC	DC	DC
≤50	SC	SC	SC	SC	DC

As the diversity of wind power output was considered to potentially have an impact on the design of cable network, two extreme wind profiles are used:

- a non-diversified profile, characteristic for relatively small wind farms occupying relatively small geographical areas, and
- a diversified profile, characteristic for relatively large wind farms occupying relatively large areas. In this case, due to the dispersed locations of the wind generators, statistically there is a relatively low probability that full output of all individual wind generators will be available at any given time.

Offshore platform

The quantitative assessments demonstrated that offshore platform capacity should be about 95% of the maximum export capacity of the wind farm connected. Furthermore, for wind farms with a capacity of 90MW or greater, following an outage (planned or unplanned) of any offshore platform transformer, there should be, at a minimum, 50% of the installed platform transformer capacity remaining.

Offshore Cable Network

For cable networks, the total optimal capacity installed can be lower than the maximum export capacity of the wind farm connected, due to the cost of installing offshore transmission assets to full capacity (X factor in table below). For the non-diversified wind profile (appropriate for relatively small wind farms, occupying small geographical areas) the installed network capacity should be above 95% of the maximum output of the wind farm, while in the case of a diversified wind profile (appropriate for relatively large wind farms occupying relatively large areas) the installed network capacity should be above 90% of the maximum output of the wind farm. In cases where this value requires an additional cable to be installed, consideration should be given to installation of network capacity below 95% for a non-diversified profile and below 90% for diversified profiles. The optimal values of the X factor will be a function of the distance as shown in the table below.

X factor (%)	Cable length (km)
--------------	-------------------

Wind farm profile	Condition - Increase in	25	50	75	100
Non-diversified wind profile	Cable rating	>95			
	Number of cables	>91	>88	>86	>84
Diversified wind profile	Cable rating	>90			
	Number of cables	>85	>82	>79	>77

For wind farms connected through HVDC technology, following an outage (planned or unplanned) of any single offshore platform DC converter module, the loss of power infeed is proposed not to exceed the existing onshore Normal Infeed Loss Risk (1000MW). However, it would be economically efficient to connect wind farms of 1500MW (maximum considered) to a single offshore transmission circuits.

Onshore overhead lines and cables design

Onshore overhead lines are preferable solution due to high cost of onshore cables. Design of 132 kV overhead lines for wind farms up to 400 MW is given in Table 61. For wind farms up to 1100 MW it is double circuit and above that is two double circuits. Design of 220 kV overhead lines are given in Table 62. Please note that data of just a single size conductor for 220 kV overhead lines is available.

If cables are to be used, the design should follow one developed for offshore (the obtained data revealed that underground cables are much more expensive than equivalent undersea cables). However, there might be a benefit of connecting two subsea cables to a system of single-core onshore underground cable. The more detailed study was not conducted due to lack of timely available data.

Onshore substation design

The available dataset included only a single (typical) rating of transformer per transformation. Data revealed that the costs of 300MVA (400 or 275/132 kV) are similar to costs of 1100MVA (400/220 kV) transformers. It is recommended that number of transformer in 400/220 kV substation are a single 1100 MVA transformers for up to 640MW of wind power and double above 640 MW. Three transformers are not justified within the scope of wind farm up to 1500 MW. For transformation to 132 kV it is recommended a minimum number of transformers of 240 MVA without redundancy.

Offshore transmission network design for GTs

The recommendations for the optimal design of offshore transmission networks for GTs are as follows:

- Design of offshore substations for GT capacity up to 100 MW a single transformer offshore substation and for capacity greater than 100 MW minimum rating of individual transformers in multiple transformer offshore substations with full (N-1) redundancy
- Design of submarine link: single cable
- Design of onshore link: single circuit

- Design of onshore substation: single transformer

The impact of preventive maintenance is also analysed including coordination of maintenance of different network assets. It has been concluded that for design of offshore infrastructure for GT generation there is no impact of preventive maintenance outages.

13. References

ILEX Energy and Strbac, G. (Oct. 2002), Quantifying the system costs of additional renewables 2020, http://www.dti.gov.uk/energy/develop/080scar_report_v2_0.pdf

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14. Appendix – Equipments and Cost Data

The information for cost calculation is available on the GBSQSS sub-group webpage¹⁶. For completeness, they are repeated here together with the interpolated and/or extrapolated values.

Two **wind farm** profiles are used: non-diversified and diversified. Both profiles have 40% load factors. Availability of wind power is assumed 95%.

Assumed average value of **cost of energy** is £75/MWh. Two extreme values are also investigated £50/MWh and £100/MWh.

HVAC platform cost consists of fixed cost of £5m per platform and variable costs of £20/kVA if two transformers are on a platform. If just one transformer is on a platform variable cost is reduced to 80%. For more than two transformers variable cost is increased for 20% for each additional transformer. Please note that the total rating power of all transformers on the platform remain the same. Cost of AC plant is £25/kVA if two transformers are on a platform. Similarly, to the cost of plant is increased by 20% for third and each successive transformer or decreased by 20% for just one transformer on a platform. For clarity, the previous note still applies. The repair cost of transformers is £2.5m.

The electrical parameters of AC transformers are as follows: load losses 0.6%, losses factor (load losses / no-load losses) 20 and reactance 15%. Maximum rating of an AC transformer is assumed 500 MVA

HVDC VSC platform and plant cost consists of fixed costs £25m per platform and variable costs of £110/kW for two converters on a platform. The cost is linearly adjusted for different number of converters while total rated power is kept unchanged. It is increased for 20% for third and further 20% per each successive converter and decreased for 20% for just one converter on a platform. HVDC VSC converter average repair cost is £0.5m per repair.

The load and no-load losses of HVDC VSC converters are each 0.8%.

Cost of offshore **compensation** is £25/kVAr and onshore £15/kVAr.

Cost of AC cables are given in Table 63 and of HVDC in Table 64. Electrical parameters of AC cables are given in Table 65 and of HVDC in Table 66. Cable maintenance cost is £0.5m.

¹⁶ <http://www.dti.gov.uk/energy/sources/renewables/policy/offshore-transmission/offshore-transmission-experts-group/page31187.html>

Table 63 – HVAC cables cost.

Voltage (kV)	Cable size (mm ²)	Cables cost (£/m) – 3 core or set of three single core		
		Supply	Lay and Bury	Total
132	500	240	180	420
	630	275	185	460
	800	310	190	500
	1000	390	200	590
220	500	390	200	590
	630	415	210	625
	800	440	220	660
	1000	460	230	690
400	800	860	540	1400
	1000	995	555	1550
	1200	1130	570	1700
	1400	1265	585	1850
	1600	1400	600	2000
	2000	1535	615	2150

Table 64 – HVDC cables cost.

Voltage (kV)	Cable size (mm ²)	Cables cost (£/m) – set of two DC single core (VSC)		
		Supply	Lay and Bury	Total
150	1000	310	360	670
	1200	360	370	730
	1400	405	380	785
	1600	450	390	840
	2000	500	400	900
300	1000	440	415	855
	1200	510	430	940
	1400	575	440	1015
	1600	640	450	1090
	2000	710	465	1175

Table 65 – Electrical parameters of HVAC cables

Voltage kV	Cable size mm ²	No cores	AC resistance	Inductance mH/km	Capacitance nF/km	Steady state rating	
			mΩ/km			A	MVA
132	500	3	49.3	0.387	192	739	169
	630	3	39.5	0.372	209	818	187
	800	3	32.4	0.364	217	888	203
	1000	3	27.5	0.351	238	949	217
220	500	3	48.9	0.437	136	732	279
	630	3	39.1	0.415	151	808	308
	800	3	31.9	0.4	163	879	335
	1000	3	27	0.386	177	942	359
400	800	1	31.4	0.54	130	870	603
	1000	1	26.5	0.52	140	932	646
	1200	1	22.1	0.49	170	986	683
	1400	1	18.9	0.47	180	1015	703
	1600	1	16.6	0.46	190	1036	718
	2000	1	13.2	0.44	200	1078	747

Table 66 – Electrical parameters of HVDC cables

Voltage	Cable size	DC resistance	Steady state rating	
			kV	mm ²
150	1000	22.4	1644	493
	1200	19.2	1791	537
	1400	16.5	1962	589
	1600	14.4	2123	637
	2000	11.5	2407	722
300	1000	22.4	1644	986
	1200	19.2	1791	1075
	1400	16.5	1962	1177
	1600	14.4	2123	1274
	2000	11.5	2407	1444

Reliability parameters used in calculation are summarised in Table 67.

Table 67 – Reliability parameters

Element	Failure rate	Mean time to repair*
Transformers	0.03 (1/year)	3 and 6 months
Converters	0.12 (1/year)	1 month
Cables	0.08 (1/year, 100km)	2 months

* It is assumed that each month has 30 days

Costs of ‘small’ transformers are given in Table 68.

Table 68 – Cost of ‘small’ transformers

Transformer rating (MVA)	30	45	60	90	120
Base cost (m£)	0.420	0.490	0.600	0.740	0.930

14.1 Update of Equipment and Cost Data

14.1.1 New Cost Data

Table 69 – AC submarine cables costs

Voltage (kV)	Cable size (mm ²)	Cables cost (£/m) – 3 core		
		Supply	Lay and Bury	Total
132	500	335	300	635
	630	385	300	685
	800	495	300	795
	1000	560	300	860
220	500	515	300	815
	630	550	300	850
	800	675	300	975
	1000	700	300	1000

Table 70 – AC underground cables costs

Voltage (kV)	Cable size (mm ²)	Cables cost (£/m) – 3 core		
		Supply	Lay and Bury	Total
132	500	335	300+255	890
	630			
	800	495	300+322	1117
	1000			
	1200	495+130	300+300?	1268
220	500	515	300+300	1115
	630	550	300+300	1150
	800	675	300+300	1275
	1000	700	300+300	1300

Table 71 – Base cost of 132 /33 kV transformers

Transformer rating (MVA)	30	45	60	90	120
Base cost (m£)	0.530	0.610	0.750	0.930	1.160

14.1.2 Further CBA dataset for Inclusion of Preventive Maintenance

General

Energy cost

Winter - £45/MWh
Summer - £35/MWh
ROC value - £30/MWh

Wind farm output

Load factor during forced outages – 40%
Load factor during planned outages – 24%

Limits to analysis

Up to 100km from the 1st onshore substation
Up to 50km onshore OHL section
Up to 1500MW wind farm capacity
Up to 200MW gas turbine capacity

Transformers

Offshore transformers (for revised work)

Losses: load 0.6%, no-load 0.03%
Failure rate 3%
Mean Time To Repair 6 months
Repair cost per fault - £2.5m
Cost - £29/kVA (for two transformers on a platform)
20% additional cost for third and each successive transformer
20% decrease in cost for just one transformer on a platform
Platform cost - £5m per platform plus
£23/kVA (for two transformers on a platform)
20% additional cost for each additional transformer

Onshore transformers

Failure rate 2% - (**Source** - CIGRE WG 12.05 concluded the average failure rate for units installed on systems operating at voltage lower than 700 kV)
Mean time to repair 2 months (**Source** - National Grid)
Maintenance requirements – 5 days per annum (**Source** - National Grid)
Electrical parameters; (**Source** - National Grid)
400/220 - X=1.6% R=0.02% on 100MVA base (assumed the same as 400/275 unit)
400/132 - X=8% R=0.14% on 100MVA base
220/132 - X=9% R=0.16% on 100MVA base (assumed the same as 275/132 unit)
Cost; (**Source** - National Grid)
400/220 (assumed the same as 400/275 unit) £2.7m (1100MVA which is Maximum permissible)
400/132 £2.5m (240MVA – Maximum permissible 460MVA)
275/132 £2.1m (240MVA – Maximum permissible 460MVA)
0.12% of cost per MVA change in rating above 240MVA up to maximum permissible
HV bay for transformer, to include CB: (**Source** - National Grid)
400kV – £1.8m
220 / 275kV - £1.6m

Overhead lines

Electrical parameters;
R = 2.9×10^{-3} % on 100MVA base
X = 0.386% on 100MVA base
Reliability;

(220 assumed same as 275, 275 and 400 very similar)
 Single cct faults – 0.6714 / 100cct km / yr
 Double cct faults - 0.02659 /100km/yr
 M.T.T.R. – 56 hours (figure does not include all those that closed on DAR)
 132kV (**Source** – As agreed with onshore TOs)

Fault type	Fault rate /100km p.a.	Repair cost (£k)	M.T.T.R. (worst case)
Minor(insulator damage, damage to arcing horns etc)	0.09	20	20hrs
Semi major (conductor damage, broken conductor etc)	0.01	40	36hrs
Major (tower damage etc)	0.01	400	72hrs

Cost;

(400 / 275 / 220 all assumed the same) (**Source** - National Grid)
 Towers – £360k each spaced 400m apart
 Conductor - £300k per cct km
 400kV conductor – single cct rating would be above 1500MVA continuous in summer therefore assume cost covers this due to limit in analysis.

275kV / 220kV – single cct rated at 1250MVA continuous in summer.
 Conductor system and towers could be the same for both voltages therefore tower cost kept the same, assume costs are for the ratings as given i.e. 1500MVA at 400, 1250MVA at 220/275. These costs are for standard sized conductors therefore these would normally be used in each case.

132kV; (**Source** – As agreed with onshore TOs)
 Single Circuit OHL per km (i.e. a wood pole type): £450k (150MVA); £600k (250MVA) or £900k (400MVA)
 Double Circuit OHL per km: £700k (150MVA); £950k (250MVA) or £1250k (400MVA)
 If Double Circuit OHL per km is built with one circuit strung the typical costs are £600k (150MVA); £850k (250MVA) or £1100 (400MVA)
 Incremental cost for the second circuit to be strung on a Double Circuit with one circuit existing per km is £150k (150MVA); £200k (250MVA) or £250 (400MVA).

Cable Sealing ends – Approx £150k for 132kV, £300k for 275kV £500k for

400kV

Onshore cable costs

132kV

Cable Size (mm ²)	Urban (£k/km)	Rural (£k/km)
500	1137	890
800	1364	1117
1200	1516	1268