

*Centre for Sustainable Electricity and
Distributed Generation*

**Further Analysis for Design of
Offshore Infrastructure**

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Predrag Djapic and Goran Strbac

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Table of Contents

Executive Summary	4
1. Objectives.....	6
2. Maximum Rating of a Single Transformer Offshore Substation.....	6
3. Impact of Reconnection Costs on a Minimum Security Criteria for the Offshore Cable Circuit Design.....	9
4. Key Findings	12
5. References	12

List of Abbreviations

BERR	Department for Business Enterprise and Regulatory Reform
cdf	cumulative distribution function
CF	Capitalisation Factor
CR	Cost of Reconnection after extended outage duration (six months)
DECC	Department of Energy and Climate Change
ECR	Net present value of Expected Costs of Reconnection
EEC	Expected Energy Constrained
MTTR	Mean Time to Repair
NF	Number of Cable Faults per annum
NGET	National Grid Electricity Transmission plc
Ofgem	the Office of Gas and Electricity Markets
OFTO	the Offshore Transmission Operator
pdf	probability distribution function
PR	Probability of Repair time exceeding six months
ROCs	Renewable Obligations Certificates
SEDG	Centre for Sustainable Electricity and Distributed Generation

Executive Summary

This briefing note shows the results of a sensitivity analysis carried out on the two specific questions:

- The appropriate threshold for a transformer capability redundancy requirement to apply in respect of an offshore transmission system. The Ofgem/BERR June 2008 consultation set out the need to further evaluate NGET's recommendation that the threshold should be reduced to 90 MW (from 120MW) [1].
- The robustness of the minimum-security criteria for the offshore cable circuit, taking account of the effect on single circuit offshore connections of an extended period without supplies to the offshore platform.

Maximum Rating of a Single Transformer Connection

This study concluded that a maximum rating of a single transformer offshore substation/platform is about 90 MW for the given dataset. A sensitivity study has been carried out up to the breakeven point where costs of a single transformer and double transformer substations become similar. The five driving factors are analysed: i) marginal platform and plant cost, ii) mean time to repair, iii) failure rate, iv) repair cost, and v) duration of preventive maintenance outage.

It was found out that the most influential factor is mean time to repair (MTTR). If MTTR were reduced from generic six months adopted for large transformers to four months that may be appropriate for smaller transformers, the threshold would increase from 90 to 120 MW¹. The reader should be reminded that, for an exponential distribution, 63% of repairs would be shorter than MTTR and 37% longer.

The required change in the other driving parameters needs to be as follows: marginal platform and plant cost would need to be increased by a further £0.9m which is similar to the cost of a transformer; failure rate would need to be reduced from 3.0 to 1.6 faults per year and per 100 transformers; repair cost would need to increase from £2.5m² to £5.5m; and finally, no impact of the duration of preventive maintenance outages.

Impact of Reconnection Costs on a Minimum Security Criteria for the Offshore Cable Circuit Design

This study estimated the maximum reconnection costs that will necessitate a change in design from a single to a double-circuit subsea cable connection. The reconnection costs are the costs associated with the process of reconnecting offshore generation if

¹ Comment from a manufacturer: This is achievable if a spare transformer is available and a vessel can be booked on a short notice. Furthermore, there are single-transformer offshore substations of about 160 MW in use in Denmark.

² The majority of repair cost is vessel cost that is assumed to be £2m.

it loses connection with grid for a prolonged time, ie beyond six months. It is assumed that there would not be such costs if a wind farm were connected with a double-circuit connection.

This study concluded that the decision in respect of the minimum-security criteria for the offshore cable circuit design was robust provided that the reconnection costs following an extended period without supplies to the offshore platform were below £5.75m.³

³ Advice from a manufacturer: An offshore generator would generally install standby generation facilities within three or four days to provide supplies for an offshore wind farm, if an outage on a single cable circuit connection is likely to be extended.

1. Objectives

This briefing note shows the results of a sensitivity analysis carried out on the two specific questions:

- The appropriate threshold for a transformer capability redundancy requirement to apply in respect of an offshore transmission system. The Ofgem/BERR June 2008 consultation set out the need to further evaluate NGET's recommendation that the threshold should be reduced to 90 MW (from 120 MW) [1].
- The robustness of the minimum-security criteria for the offshore cable circuit taking account of the effect on single circuit offshore connections of an extended period without supplies to the offshore platform

2. Maximum Rating of a Single Transformer Offshore Substation

The base case for a maximum rating of a single-transformer offshore substation is presented in section 9.3.2 of the main report [2]. It has subsequently been recommended that the maximum rating of a single-transformer platform should be limited to 90 MW⁴. In this section, a sensitivity analysis of this maximum rating is examined to test the robustness of the recommendation. A sensitivity study has been carried out up to the breakeven point where costs of a single transformer and double transformer substations are the same. The five driving factors are analysed: i) marginal platform and plant cost, ii) mean time to repair, iii) failure rate, iv) repair cost, and v) duration of preventive maintenance outage.

The sensitivity analysis specifically looks at how much each of the above factors would need to change for the NGET recommended change (from 120MW to 90MW) not to be valid. In order to understand the analysis, an extract of Table 30 of the main report [2] is presented below. For readability a simplified version of Table 30 (only planned outage duration of 10 hours) is reproduced here as Table 1.

This analysis assumes a single transformer offshore platform as a base case. The additional investment cost and benefits are calculated and then compared. If cost outweighs benefit then a single-transformer substation is preferred, otherwise a double-transformer is the preferred option. In both cases, there is no redundancy in capacity. The double-transformer platform option with redundancy (2x90MVA) is not the preferred option as there is smaller gain compared to the option without redundancy (2x60MVA).

⁴ Rating of wind farms is given in MW, and of transformers and substations in MVA. For the purpose of this report, these can be interchangeably used. For example, 120 MW wind farm will be connected to 120 MVA substation.

Table 1 – Additional cost and benefit of installing two transformers for wind farm of 120 MW

Offshore platform rating (MVA)		1x120	2x60	2x90
Additional investment cost (£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
Total corrective and preventive maintenance cost (£m)		5.05	2.91	1.74
Benefit (£m)		0	2.14	3.31

Firstly, the additional investment cost for a double-transformer (2x60MVA) design instead of a single transformer (120MVA) offshore substation is calculated. This cost of £1.24m is obtained as follows:

- Additional transformers costs is $2 \times 0.75 - 1.16 = £0.34\text{m}$, where £0.75m and £1.16m are costs of a 60 MVA and 120 MW transformer, respectively
- Additional cost of the offshore platform is estimated to be 20% of the offshore platform cost for two transformers, namely $20\% \times (23/1000) \times 120 = £0.55\text{m}$, where £23/kVA is the cost of offshore platform to support the substation with two transformers, and 120 MW is the rating of the substation
- Additional bays cost is $0.25 + 0.1 = £0.35\text{m}$, where £0.25m and £0.1m are costs of 132 kV and 33 kV bays, respectively

Secondly, the benefit of having two transformers (2x60MVA) is calculated. A benefit of £2.14m is calculated as follows:

- Capitalised benefit of $-£0.74\text{m}$ from the difference in repair costs for a single and double-transformer offshore substation. For single transformer offshore substation the expected repair cost is $1/(1/0.03+0.5) \times 2.5 \times 10 = £0.74\text{m}$, where 0.03 1/year is the failure rate, 0.5 years (6 months) is the MTTR, £2.5m is the cost per repair and 10 is the capitalisation factor. For a double-transformer offshore substation, the cost is double.
- Benefit of reducing expected energy constrained (EEC) originating from forced outages is £2.73m and is calculated as follows:
 - Annual energy $95\% \times 120 \times 40\% \times 8760 = 399,456 \text{ MWh}$, where 95% is wind farm availability, 120 MW is wind farm capacity, 40% is the load factor, and 8760 is the annual duration in hours
 - Probability of outages in a single-transformer offshore substation is $1 - 1/(1+0.03 \times 0.5) = 0.014778$; in a double-transformer offshore substation for a single transformer outage is $2 \times 0.014778 \times (1 - 0.014778) = 0.02912$; and the outage of both transformers is $0.014778^2 = 0.000218$

- Finally, the EEC cost for a single-transformer substation is $0.014778 \times 399456 \times (40+30) \times 10 / 1e6 = \text{£}4.13\text{m}$ and for a double-transformer offshore substation is $(0.02912 \times 16.5\% + 0.000218) \times 399456 \times (40+30) \times 10 / 1e6 = \text{£}1.40\text{m}$, where $\text{£}40/\text{MWh}$ and $\text{£}30/\text{MWh}$ are average annual energy cost and ROC value respectively, 10 is the capitalisation factor, and 16.5% the factor for the diversified profile from Figure 14 of main report [2]. The benefit is then $\text{£}4.13\text{m} - \text{£}1.40\text{m} = \text{£}2.73\text{m}$
- Benefit of reducing the EEC cost originating from planned outages lasting on average 10h per annum is $\text{£}0.15\text{m}$ and is calculated as follows:
 - Average energy during 10 hours in summer is $95\% \times 120 \times 24\% \times 10 = 273.6 \text{ MWh}$, where 24% is the load factor during three summer months
 - EEC cost for a single-transformer substation is $273.6 \times 100\% \times (35+30) \times 10 / 1e6 = \text{£}0.18\text{m}$; and for a double-transformer offshore substation is $273.6 \times 7.55\% \times (35+30) \times 10 / 1e6 = \text{£}0.03\text{m}$, where the factor 7.55% is read from Figure 23 of the main report [2]

This means that a double-transformer offshore substation is overall cheaper than a single one by $\text{£}0.90\text{m}$.

A sensitivity analysis comparing a single (120MVA) and double-transformer offshore substation (2x60MVA) has been carried out to find break-even points where the additional investment cost is the same as total benefits. The results of the analysis are as follows:

- Marginal offshore platform and plant costs would need to increase by a further $\text{£}0.9\text{m}$ (which is in the range of transformer cost);
- Mean time to repair (MTTR) would need to reduce from 6 to about 4 months;
- Failure rate would need to reduce from 0.03 to 0.016^5 per year, or
- Repair cost would need to increase from $\text{£}2.5\text{m}$ to $\text{£}5.5\text{m}$ for the recommended change (from 120MW to 90MW) not to be valid.
- The recommended change is robust to all reductions to the duration of preventative maintenance outages.

Therefore, the most influential factor in this case is MTTR. It should be noted that the value of MTTR could be managed by an OFTO by keeping a spare transformer onshore and by having ability to book a vessel at short notice⁶.

⁵ It should be noted that a failure rate for an onshore transformer of 0.02 per year is used.

⁶ Comment from a manufacturer: This is achievable if a spare transformer is available and a vessel can be booked at short notice. Furthermore, there are single-transformer offshore substations of about 160 MW in use in Denmark.

3. Impact of Reconnection Costs on a Minimum Security Criteria for the Offshore Cable Circuit Design

This study estimates the maximum reconnection costs for which the proposed security criteria for offshore cable connections would not be valid. In this context, the reconnection costs are the costs associated with the process of reconnecting offshore generating plant if it loses connection with grid for a prolonged time, ie beyond six months. It is assumed that there would be no such costs resulting from a single circuit outage condition, if an offshore wind farm was connected with a double-circuit connection.

Figure 1 shows costs associated with alternative connection designs for a wind farm of 350 MW and 25 km cable connection(s). It can be seen that for a non-diversified profile the cheapest solution is a single 800mm² 220kV cable connection. In addition, the cheapest solution with two cables is a double circuit 500mm² 132 kV connection. In this case, the advantage of a single-cable connection is £5.9m. The calculation is repeated for various wind farm capacities, and cable lengths and results presented in Table 2 and Table 3 for non-diversified and diversified wind profiles, respectively.

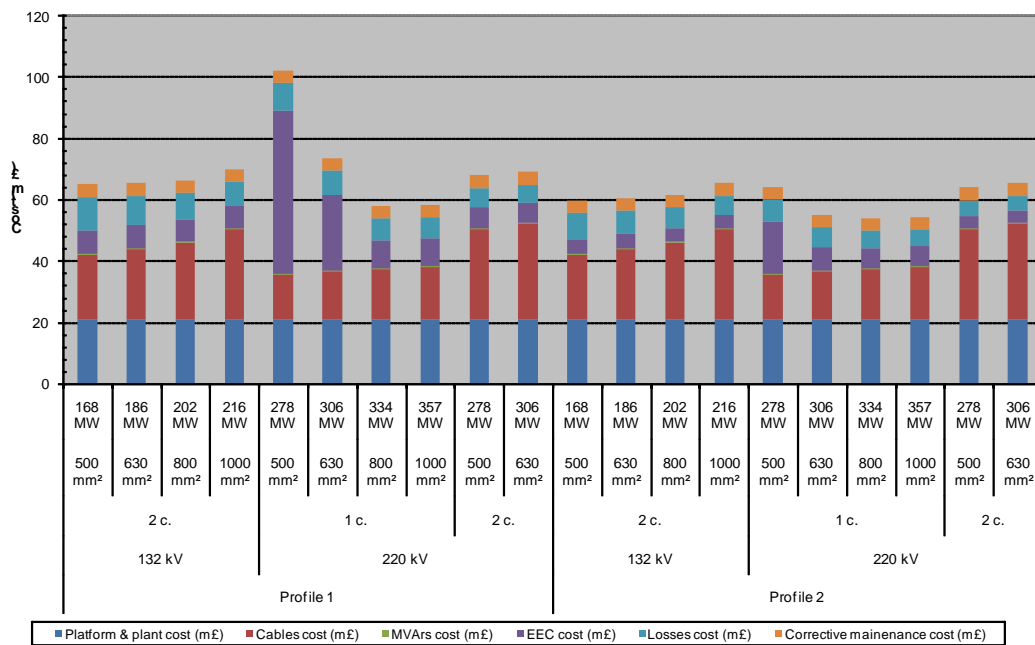


Figure 1 – Cost of alternative connection designs for a wind farm of 350 MW and 25 km cable connection(s). Label at x-axis from bottom is profile (1 being non-diversified and 2 diversified), cable rated voltage, number of cables, cable cross section and cable capability.

Table 2 – Benefit of a single-cable connection for a non-diversified wind profile

Wind farm capacity (MW)	Distance (km)			
	25	50	75	100
410			1.8	1.3
408			3.4	3.0
406		1.3	4.9	4.7
400		5.3	9.3	9.5
392	1.1	9.1	13.1	15.0
350	7.3	14.4	20.4	27.4
300	6.5	12.8	19.0	25.5
200	6.6	13.6	20.5	27.7
100	9.4	19.2	29.0	38.9

Table 3 – Benefit of a single-cable connection for diversified wind profile

Wind farm capacity (MW)	Distance (km)			
	25	50	75	100
474				4.1
470			2.8	6.5
456		1.6	10.1	14.5
434	0.7	8.5	13.9	17.4
400	6.4	13.2	19.2	24.4
350	5.9	11.7	17.3	23.0
300	5.8	11.6	17.2	22.8
200	7.1	14.6	22.2	29.8
100	9.6	19.4	29.3	39.4

A net present value of expected costs of reconnection can be calculated as $ECR = CF \times NF \times PR \times CR$, where: CF – capitalisation factor, NF – average number of cable faults per year, PR – probability that the actual repair time will exceed six months (three times MTTR), and CR – cost of reconnection after extended outage duration.

Given that the actual probability distribution function is not known, then in order to estimate PR it should be assumed. In this study, an exponential distribution is assumed⁷. Figure 2 shows probability and cumulative density functions for exponential distribution of repair time with MTTR of two months. It can be seen, from cumulative distribution function, that the frequency of repair time being above MTTR is 37% and being above three times MTTR (in this case six months) is 5%. Therefore, probability that a cable repair will last more than six months and the offshore platform without supplies for six or more months⁸ (PR) is 5%.

⁷ It should be noted that a uniform distribution for repair time cannot be constructed as average value should be 2 months and it should extend at least to 6 months.

⁸ Advice from a manufacturer: An offshore generator would generally install standby generation facilities within three or four days to provide supplies for an offshore wind farm, if an outage on a single cable circuit connection is likely to be extended.

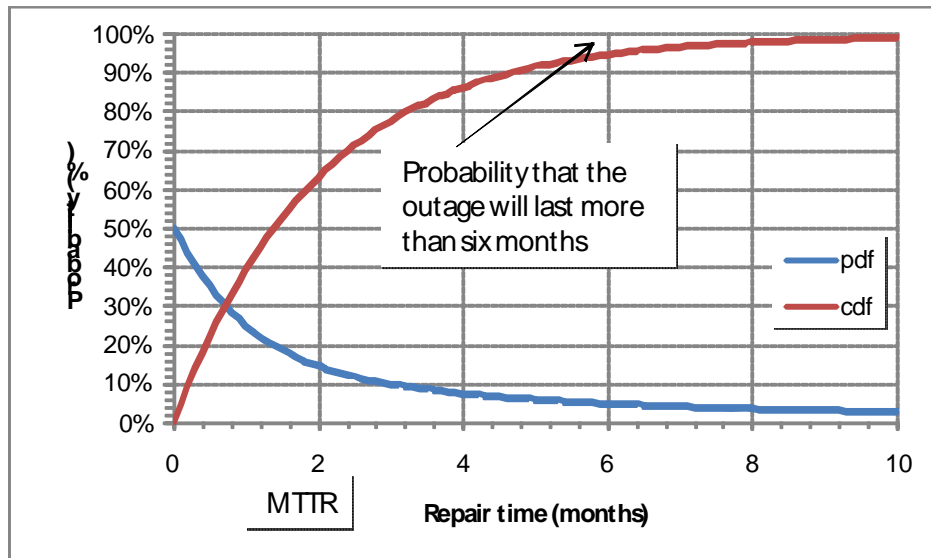


Figure 2 – Probability and cumulative density functions for exponential distribution of repair time with mean time to repair of 2 months

The estimated break-even cost of reconnection (CR) where the overall costs for a single and double-cable connections are the same for wind farm of 350 MW is elaborated below. It should be noted that capability of a single cable of 220 kV is also about 350 MW as shown in Table 6 of main report [2]. This example is done for four cable lengths, 25, 50, 75 and 100 km:

- If the cable length is 25 km then the minimum cost of reconnection which will justify a double circuit cable connection design is £5.9m (see Table 3). This is compared with capitalised net present value of expected cost being $ECR = 10 \times 2 \times 5\% \times CR$, where 2 is the failure rate for a 25 km cable circuit. Therefore, if CR is greater than £5.9m, two cables are justified
- If the cable length is 50 km, the minimum cost of reconnection which will justify a double circuit cable connection design is £11.7m and a capitalised net present value of expected cost is $ECR = 10 \times 4 \times 5\% \times CR$. Therefore, if CR is greater than $11.7/2 = £5.85m$, two cables are justified
- Similarly if the cable length is 75 km and if CR is greater than $17.3/3 = £5.77m$, a double circuit cable connection design would be justified
- Finally if the cable length is 100 km and if CR is greater than $23/4 = £5.75m$, a double circuit cable connection design would be justified

Therefore, it can be concluded that there would be no impact of reconnection costs on minimum-security criteria for the offshore cable circuit design if the reconnection costs due to an extended period without supplies to the offshore platform are below £5.75m.⁹ It should be noted that this threshold for CR is practically independent from cable length.

⁹ Advice from a manufacturer: An offshore generator would generally install standby generation facilities within three or four days to provide supplies for an offshore wind farm, if an outage on a single cable circuit connection is likely to be extended.

4. Key Findings

Maximum Rating of a Single Transformer Connection

It was found out that the most influential factor is mean time to repair (MTTR). If MTTR were reduced from six to four months, then the recommended reduced threshold of 90MW would not be valid and a threshold of 120MW would be more appropriate¹⁰. The reader should be reminded that for an exponential distribution 63% of repairs would be expected to happen before MTTR and 37% after.

A similar conclusion is drawn for each of the following of the other driving parameters: an increase of the marginal offshore platform and plant cost by a further £0.9m (which is similar to the cost of a transformer); a reduction of failure rate from 3.0 to 1.6 faults per year and per 100 transformers, and an increase of the repair cost from £2.5m¹¹ to £5.5m. This study concluded that the recommended change is robust to all reductions to the duration of preventative maintenance outages.

Impact of Reconnection Costs on a Minimum Security Criteria for the Offshore Cable Circuit Design

This study estimated the maximum reconnection costs that will change design from a single to a double-circuit subsea cable connection. The reconnection costs are the costs associated with the process of reconnecting offshore generation if it loses connection with grid for a prolonged time, beyond six months. It is assumed that there would not be such costs if a wind farm were connected with a double circuit connection.

This study concluded that there would be no impact of reconnection costs on minimum-security criteria for the offshore cable circuit design if the reconnection costs due to an extended period without supplies to the offshore platform were below £5.75m.¹²

5. References

- [1] Offshore Electricity Transmission – A Joint Ofgem/BERR Regulator Policy Update, Ofgem Ref: (84/08), BERR (URN 08/730), June 2008
- [2] P Djapic and G Strbac, Cost Benefit Methodology for Optimal Design of Offshore Transmission Systems, Centre for Sustainable Electricity and Distributed Generation (SEDG), July 2008, BERR URN 08/1144

¹⁰ Comment from a manufacturer: This is achievable if a spare transformer is available and a vessel can be booked on a short notice. Furthermore, there are single-transformer offshore substations of about 160 MW in use in Denmark.

¹¹ The majority of repair cost is vessel cost of £2m.

¹² Advice from a manufacturer: An offshore generator would generally install standby generation facilities within three or four days to provide supplies for an offshore wind farm, if an outage on a single cable circuit connection is likely to be extended.