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Quantifying O&M savings and availability improvements from wind turbine design for maintenance techniques

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Abstract

Design for maintenance has the potential to significantly reduce the cost of offshore wind energy. This paper shows the results of an O&M cost and availability analysis when different design for maintenance techniques are applied to wind turbines. The design for maintenance techniques considered, reduce repair times and the need for jack up vessels as well as introducing redundancy to the power train of the wind turbines. A detailed lifetime O&M cost and availability model is used in this analysis and populated with empirical operational and cost data from a population of ~350 offshore wind turbines from between 5 and 10 offshore wind farms throughout Europe.

A base line availability and O&M cost per MWh are obtained from the model and input data, these inputs are then adjusted based on different design for maintenance techniques. The subsequent outputs from the model using the adjusted inputs allow for the quantification of O&M savings and availability improvements for the different design for maintenance techniques. These design for maintenance techniques may have different effects on different wind turbine types. As a means of investigating this, a comparison of the O&M saving and availability improvements will be carried out for both a DFIG turbine type and a PMG FRC turbine type. For a hypothetical site located 50km offshore using a verified O&M model and empirical operational and cost data this paper shows that the overall combination of these improvements reduces the total O&M cost by ~16% for the DFIG and ~17% for the PMG FRC. It also shows that in both turbine types the largest reduction in O&M costs are seen to come from the elimination of the need for heavy lifting vessels.

1. Introduction

Wind turbine manufacturers, owners and operators all aim to reduce the cost of energy (CoE) from wind turbines. Operations and Maintenance (O&M) cost make up a large percentage of the overall CoE. This is particularly the case offshore where up to 30% of the CoE is known to come from O&M costs [1].

With such a large percentage of the CoE coming from O&M costs, this area has been identified as having significant cost saving potential. As a result it has become one of the focus areas of the CoE reduction efforts form the stakeholders mentioned above. As seen in section 2, areas such as vessel strategies, condition monitoring systems, risk based O&M planning, component redundancy, in-built lifting mechanisms and design for maintenance techniques are all being investigated in industry and academia as a means of reducing the O&M costs and in turn reducing the CoE. The analysis in this paper focusses on in-built lifting mechanisms, reduced repair times from design for maintenance techniques and redundancy in the power train.

A baseline O&M cost and availability scenario was simulated for a hypothetical 100 wind turbine site that is located 50km offshore. This was based on the offshore wind turbine population analysed in reference [2] and the O&M cost model described in [3]. The authors are interested in the effect of different power train technologies on Cost of Energy, so this site was investigated for both doubly fed induction generator (DFIG) turbine types and permanent magnet generator (PMG) with fully rated converter (FRC) turbine types. Model inputs were then adjusted (as detailed in Section 4) to simulate the effect on O&M cost and availability of in-built lifting mechanisms, redundancy and innovations that help reduce repair times for both turbine types. These new O&M costs and availability figures are compared to the baseline figures and to each other for both power train types. Conclusions are then drawn on which of the three areas investigated (in-built lifting mechanisms, redundancy and reduced repair times from design for maintenance techniques) have the greatest potential benefit and on which power train type they have the greatest effect.

2. Literature Review

Offshore wind turbine manufacturers, owners, operators and researchers have investigated a number of different strategies as a means of increasing availability and reducing O&M costs: turbine technology choice and design, improved condition monitoring and diagnostic systems, operational strategies and decision making, better logistics, redundancy, design of enabling technology and design for maintenance techniques. This section reviews past analysis and papers that have looked into these areas.

Vessel costs make up a large part of the overall O&M cost, in particular the heavy lift vessels [4]. Due to the high cost of vessels, operators are interested in reducing these vessel costs through optimizing their vessel use strategies. Some research has been carried out in this area [5] in which a number of different vessel strategies are investigated (fix on fail, batch repair, short term charter, annual charter and purchase) and conclusions are drawn on which strategies are most appropriate for certain sites. Operators are also using condition monitoring systems to try and reduce O&M costs. There are commercial and technical challenges with these systems [6] and researchers have tried to quantify the benefits of these systems in terms of availability improvements [7]. Another possible method of reducing downtime and reducing O&M costs is risk based O&M planning. Using this approach, maintenance is scheduled and carried out based on the risk of components failing. Reference [8] details this approach and states it has potential to reduce downtime when it comes to gearbox and generator failures.

Redundancy – when some of the major sub-systems and components are duplicated – could be another method of improving availability of the turbine and potentially reducing the O&M costs of wind turbines. In this analysis it is generators and converters that are duplicated. References [9] and [10] suggest that as wind turbines move offshore, redundancy could contribute to reducing O&M costs. However, duplicating some sub-systems, like gearboxes for example, may prove unrealistic due to functionality restrictions, weight, space and capital cost restrictions [9]. This analysis will focus on the O&M cost saving by duplicating the generator and converters of the wind turbine however, it does not consider the extra capital costs related to including the extra or modified generator. Extra costs may also be incurred in the tower and nacelle due to increased weight and space requirements.

This paper also looks at the effect of reducing the need for heavy lift vessels (HLVs) through the use of in-built lifting equipment. Wind turbine manufacturers can build cranes into the nacelles of their turbines as detailed in the offshore turbine in [11] or provide tower cranes as seen in [12]. The aim of these in-built lifting mechanisms is to reduce the need for the hiring of HLVs which can have long waiting times and day rates of the order of £100k [3]

The final focus area for this paper is reduced repair times delivered through the use of design for maintenance techniques. Reference [13] provides an overview of design for maintenance techniques that could be used on wind turbines in order to reduce the repair times. These techniques aim to make repair easier and more efficient for the wind turbine technicians which in turn is hoped will allow them to carry out their repairs in a shorter period of time. The types of design for maintenance techniques discussed in [13] are: the use of fasteners where possible so the number of required tools are minimized; the provision of adequate space for maintenance around the components that need to be maintained so technicians can carry out their work unobstructed; the design of equipment in such a way that it can only be maintained in the correct way allowing for faster repair and for technicians with different expertise to complete the repair; position maintenance points close to each other; the design for the use of standard tools and the provision of visual inspection ports where possible.

3. Analysed Population, Model Overview and Analysis Methodology

3.1 Analysed Population

The population used in this analysis is the same as used in [2]. In this analysis it is used to obtain input operational and cost data for the model described in Section 3.2, to model the base case O&M costs and availability. The population builds up to ~350 turbines over a five year period. These turbines are all of the same turbine type and manufacturer and come from between 5 and 10 offshore wind farms throughout Europe. Exact turbine numbers, wind farm numbers, rotor size or rated power cannot be provided for confidentiality reasons; however it can be stated that all turbines in the population are multi MW offshore turbines with a rotor size between 80 and 120 meters and a rated power between 2 and 4 MW. The years of installation for the population are shown in Figure 1. It can be seen that 68% of the population analysed is between three and five years old and 32% are over 5 years old. In total this population provides ~15.5 million hours of turbine operational data, equivalent to 1768 turbine years of operational data.

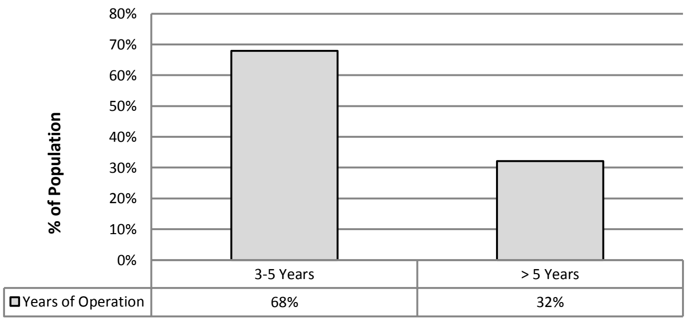


Figure 1. Wind turbine population operational years showing a bias towards turbines in the early operational period of the dataset [2]

3.2 Model Overview

The O&M model used to simulate the O&M costs and availability in this analysis is a model that was developed by the University of Strathclyde. A detailed description of this model can be found in [14] and a case study verifying its performance against similar models is detailed in [3]. This model determines O&M costs and availability through calculating accessibility and power production of the wind farm by using a multivariate auto-regressive climate model and a Markov Chain Monte Carlo failure model. The inputs required to obtain these outputs are detailed in Section 4.

3.3 Analysis Methodology

O&M cost and availability was simulated for two hypothetical wind farms located 50km offshore using the data gathered from the population described in Section 3.1 and the O&M cost model described in Section 3.2. These simulations are used as base case scenarios for O&M costs and availability figures. The inputs from the previous simulation are then adjusted as described in Section 4 to represent in-built lifting mechanisms, redundancy and reduced repair times for both turbine types. The model was then run taking into consideration these new inputs. This provided simulated O&M cost and availability outputs for in-built lifting mechanisms, redundancy and reduced repair times for both turbine types. These new outputs for both turbine types are then compared to the baseline O&M costs and availability figures and conclusions are drawn. This work flow can be seen in the flow chart in Figure 2.

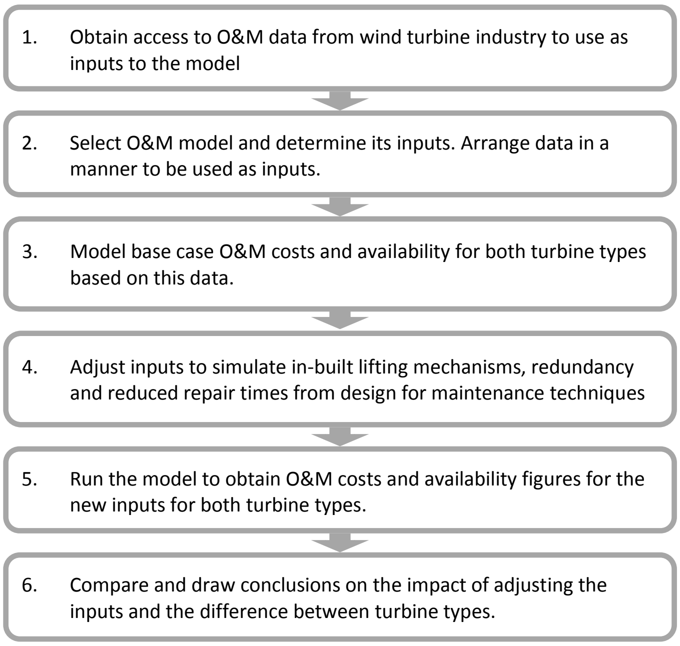


Figure 2. Flow chart showing work carried out

4. Input parameters and variation for scenarios

The model was used to examine a number of scenarios. Some of the input parameters were kept consistent for all scenarios; others were varied to describe the innovation used in that scenario. These are the major consistent input parameters used in all of the scenarios:

- Wind data, wave height data and wave period data for the hypothetical site of 100 wind turbines 50km offshore. This was obtained from the FINO offshore research platform [15] in the North Sea, located 45km north of Borkum Island. This climate data is in the public domain and inputted to the model in hourly averages.
- Vessel cost and operational data. The inputs required for the model that relate to vessel operation and costs came from [2] and [3]. Reference [3] provides the vessel cost and operational figures based on the data and expertise of an offshore wind farm developer.
- Power curve, failure rate, repair time, required technicians and average failure cost data. For one of the turbine types this data was obtained from the analysis of the population detailed in Section 3.1. For the other turbine type this data was estimated by adjusting the power curve, failure rate and average failure cost data for the other power train type based on [16].

Once the O&M cost and availability were modelled for the base cases using these parameters common to all scenarios, the following adjustments were made to inputs to capture the in-built lifting mechanisms, redundancy and reduced repair times from design for maintenance techniques:

- **In-built lifting mechanisms** and tower cranes have been discussed in literature and advertised in wind turbine manufacturer's promotional documents. In-built lifting mechanisms and tower cranes have the potential to reduce the need for HLVs for major replacements on the wind turbine. As a means of capturing this potential in the inputs to the model, the requirement for the use of these jack up vessels has been reduced by 25%, 50%, 75% and 100% based on the of varying degrees of capability of 4 hypothetical lifting mechanisms. This will provide O&M cost and availability outputs for both wind farms and show the effectiveness of these different lifting mechanisms (each of which have their own capital costs).
- **Redundancy.** The idea of including redundancy in the wind turbine power train has been encountered in other papers. As a means of capturing power train redundancy in this analysis, two generators and two power converters for each turbine have been included in the model. Failure rates have been split between the two converters and generators and power production has been split 50% between each generator and converter so if one of the converters or generators fail the wind turbine still produces 50% of its rated power. The split of failure rates by 50% because the rated power is halved is based on reference [16] for the converters and reference [17] for the generators. For the converters reference [16] suggests that a converter three times larger than another converter will have a failure rate ~ 3 times larger so the assumption is made that a converter half the size will have half the failure rate. An onshore generator roughly half the rated power of the generator used in the population shown in section 3.1 shows a failure rate of roughly half [17] when the onshore to offshore fudge factor from reference [2] is applied. The authors acknowledge that this method for estimating offshore failure rates is not ideal and may not hold for all generator types. Future work will aim to improve these assumptions by obtaining further offshore failure rate data for generators and converters of different power ratings.
- **Reduced repair time due to design for maintenance techniques.** It has been suggested that the design for maintenance techniques discussed in the literature review can reduce repair times. As a means of quantifying these repair time reductions in terms of O&M cost savings and availability improvements the repair time inputs to the model were reduced by 10% and 20% for both turbine types. Using an example of the generator major replacement these 10% and 20% reductions mean a drop repair times from ~81 hours to ~73 and ~65 hours respectively.

5. Results and Discussion

This section shows the results of modelling the availability, direct O&M costs (staff costs, repair costs, transport costs) and total O&M costs (staff costs, repair costs, transport costs and lost production costs) for each turbine type in the hypothetical wind farm described in Section 4. In the following graphs:

- The "Baseline" is the modelled results for the DFIG turbine and the PMG FRC turbine obtained from the empirical data.

- "Redundancy Con", "Redundancy Gen" and "Redundancy Both" are the modelled results from adjusted empirical input data to simulate redundancy in the converter, generator and both combined.
- "Repair time 10%" and "Repair time 20%" are the modelled results from adjusted empirical input data to simulate reduced repair time from design for maintenance techniques.
- "HLV reduced 25%" is the modelled results from adjusted empirical input data to simulate reduced requirement for HLV by 25% due to the use of in-built lifting mechanisms. The HLV requirement is also shown when it is reduced by 50%, 75% and not required at all.
- "All Improvements" are the modelled results from adjusted empirical input data to simulate all of the above improvements with repair times *reduced by 10%* and *HLV usage by 50%*.

Figure 3 shows that for the DFIG turbine type the greatest single improvement to the availability is achieved through the introduction of redundancy in the power train. This improves availability by ~1%. Reducing repair times by 10% through Design for Maintenance (DFM) techniques improves availability by 0.57% and reducing the need for HLVs by 50% improves availability by 0.44%. As a means of showing how much revenue would be lost by a 1% availability loss a rough estimate of the cost of lost production was obtained using a similar method to that used in reference [18]. In this method an annual lost production cost is obtained by using the availability difference and a production estimate for an average 3.6MW offshore wind turbine [19] and the ROC rate of £45/MWh with two ROCs/MWh for offshore [3]. This gave a value of ~130 MWh a year or ~£11,500 a year for the 1% loss of availability.

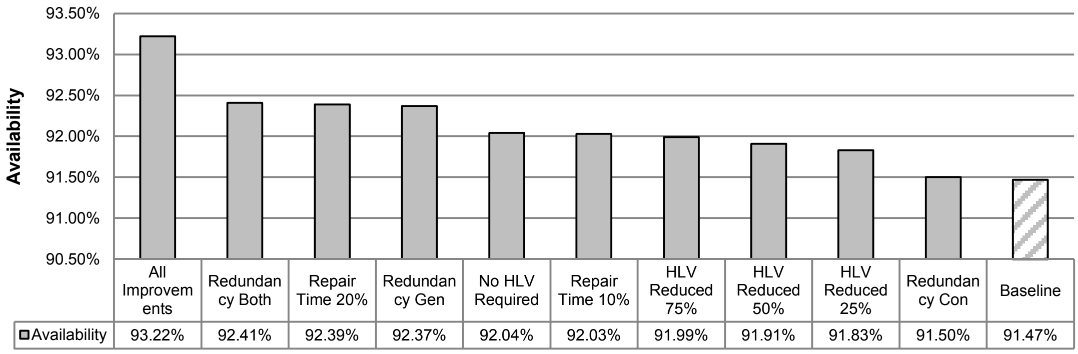


Figure 3. DFIG availability with simulated improvements showing "Baseline" has the lowest availability and "All Improvements" have the highest.

Figure 4 shows direct O&M costs for the turbines with DFIGs. These include staff costs, repair costs and transport costs. It can be seen that reducing the need for HLVs by 50% reduces O&M costs by £1.83 / MWh, reducing repair times through DFM techniques reduces O&M costs by £0.24 / MWh and redundancy in the power train reduces O&M costs by £0.17 / MWh. Redundancy does not reduce overall O&M costs but reduces the O&M cost per MWh because it allows the turbine to continue producing at 50% which produces more power than would be the case without redundancy meaning cost per MWh reduces even though overall O&M costs do not. In the following graphs the All Improvements group does not reduce O&M costs by the largest amounts because all improvements model HLV reduction at 50% and reduced repair times at 10%. Elimination of HLV altogether and even reducing it by 75% reduces O&M costs so much that those groups are reduced below the All Improvements group.

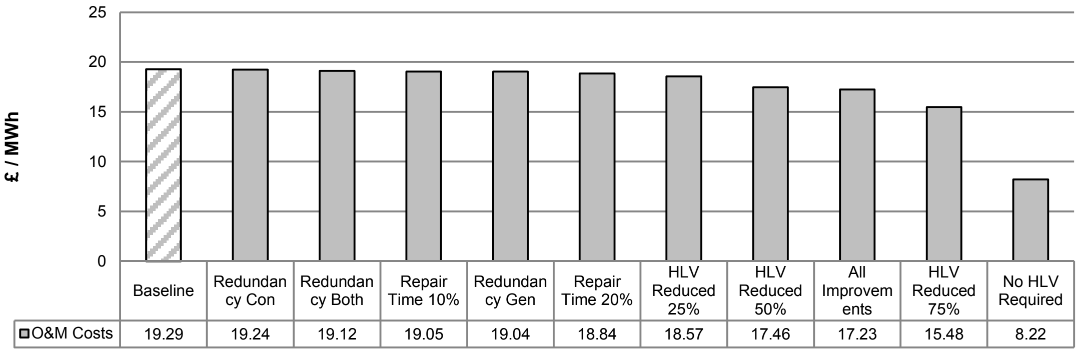


Figure 4. DFIG direct O&M costs with simulated improvements showing “Baseline” has the highest O&M costs and “No HLV” has the lowest.

Figure 5 shows total O&M costs, that is the aggregate of the cost of lost production (due to turbine downtime) and the direct O&M costs for the DFIG turbine type. It can be seen that reducing the need for HLVs by 50% reduces total O&M costs by £2.50 / MWh, redundancy in the power train leads to a reduction of £1.82 / MWh and reducing repair times through DFM techniques leads to a reduction of £1.18 / MWh.

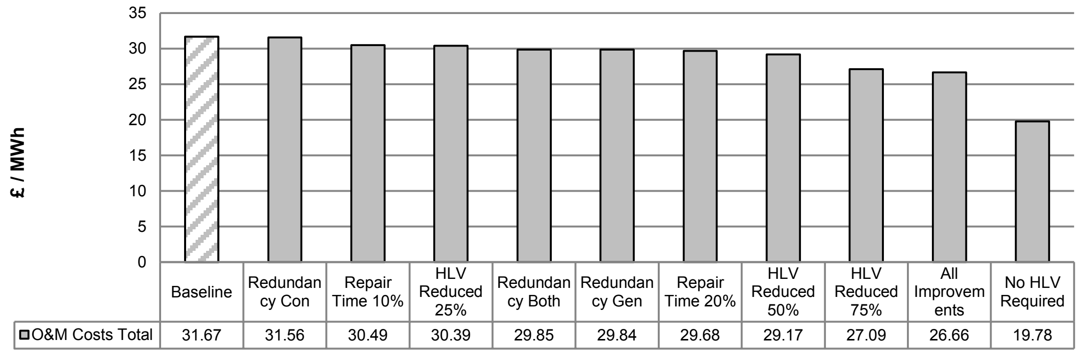
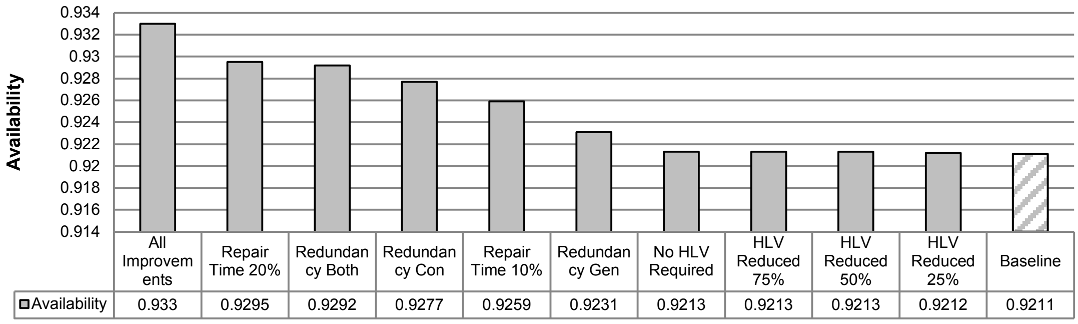


Figure 5. DFIG total O&M costs with simulated improvements showing “Baseline” has the highest O&M costs and “No HLV” has the lowest.

Figures 6-8 show the same analysis but for the PMG FRC turbine type. Figure 6 shows that for the PMG FRC turbine redundancy in the power train improves availability by 0.81%, reducing repair times by 10% (through DFM techniques) improves availability by 0.48%.

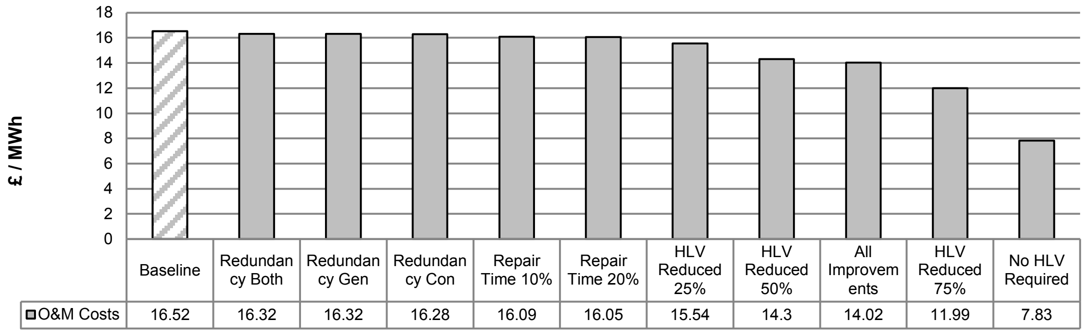
It can be seen that reducing the need for HLVs does not show improvements in the availability. This can be explained due to the increased dependency on CTV vessels resulting in the use of these resources becoming constrained. However, due to crew transfer vessel (CTV) usage costing significantly less than HLV usage, the benefits of the reduced HLV usage are captured in the O&M cost graphs in figure 7 and 8. Unlike the PMG FRC turbine, slight availability gains can be seen from the reduction in use of the HLVs for the DFIG turbines in figure 3. The reason for this is there is there are more frequent failures that require a HLV for repair with the DFIG turbine than there are with the PMG turbine. As a result, the greater reduction in the need for a HLV for the DFIG shows greater impact on the DFIG availability due to the elimination of the longer mobilisation time for the HLV in comparison to the mobilisation time for the CTV.



	All Improvements	Repair Time 20%	Redundancy Both	Redundancy Con	Repair Time 10%	Redundancy Gen	No HLV Required	HLV Reduced 75%	HLV Reduced 50%	HLV Reduced 25%	Baseline
Availability	0.933	0.9295	0.9292	0.9277	0.9259	0.9231	0.9213	0.9213	0.9213	0.9212	0.9211

Figure 6. PMG FRC availability with simulated improvements showing “Baseline” has the lowest availability and “All Improvements” have the highest.

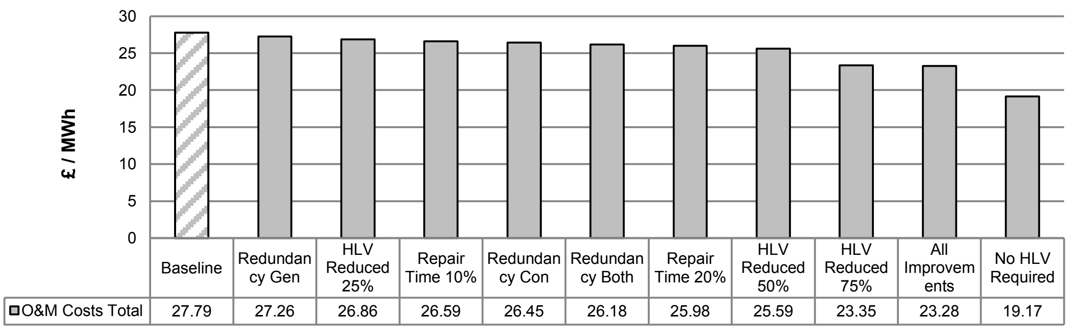
Figure 7 shows the direct O&M costs for the PMG FRC turbine type. It can be seen that reducing the need for HLVs by 50% reduces O&M costs by £2.22 / MWh, reducing repair times through DFM techniques reduces O&M costs by £0.43 / MWh and redundancy in the power train reduces O&M costs by £0.20 / MWh.



	Baseline	Redundancy Both	Redundancy Gen	Redundancy Con	Repair Time 10%	Repair Time 20%	HLV Reduced 25%	HLV Reduced 50%	All Improvements	HLV Reduced 75%	No HLV Required
O&M Costs	16.52	16.32	16.32	16.28	16.09	16.05	15.54	14.3	14.02	11.99	7.83

Figure 7. PMG FRC direct O&M costs with simulated improvements showing “Baseline” has the highest direct O&M costs and “No HLV” has the lowest.

The total O&M costs including lost production costs for the PMG FRC turbine can be seen in Figure 8. It can be seen that these are lower than the baseline for the DFIG. Figure 8 shows reducing the need for HLVs by 50% reduces O&M costs (including lost production costs) by £2.20 / MWh, redundancy in the power train leads to a reduction of £1.61 / MWh and reducing repair times through DFM techniques leads to a reduction of £1.20 / MWh.



	Baseline	Redundancy Gen	HLV Reduced 25%	Repair Time 10%	Redundancy Con	Redundancy Both	Repair Time 20%	HLV Reduced 50%	HLV Reduced 75%	All Improvements	No HLV Required
O&M Costs Total	27.79	27.26	26.86	26.59	26.45	26.18	25.98	25.59	23.35	23.28	19.17

Figure 8. PMG FRC total O&M costs with simulated improvements showing “Baseline” has the highest total O&M costs and “No HLV” has the lowest.

6. Conclusion

For a hypothetical 100 turbine site 50km offshore, significant improvements in availability and O&M costs have been simulated based on real turbine failure data and an offshore accessibility model.
The greatest improvement in availability for the PMG FRC turbines comes from repair times being reduced by 20% due to design for maintenance techniques. This is not the case for the DFIG turbines as the greatest improvement in availability is seen from introducing redundancy to both the generator and the converter. In both turbine types the largest reduction in O&M costs (both excluding and including lost production costs) is seen to come from the elimination of the need for heavy lifting vessels. The overall combination of each of these improvements (with HLV reduction at 50% and repair time reduction at 10%) reduces the total O&M cost by ~16% for the DFIG and ~17% for the PMG FRC. Eliminating the need for a HLV in both turbine types reduces the total O&M cost to ~£19/MWh in both cases. The total O&M costs for the DFIG turbine (Figure 5) drop below the total O&M cost for the PMG baseline turbine (Figure 8) if HLV usage is reduced by 75% or greater, or if power train redundancy, reduced repair time of 10% and reduced HLV usage by 50% are all applied together.

7. References

[1] Dinwoodie I, McMillan D, Revie M, Lazakis I, Dalgic Y. Development of a Combined Operational and Strategic Decision Support Model for Offshore Wind. in Proc. DeepWind Conf., Trondheim, Norway, Jan. 24–25, 2013

[2] Carroll J, McDonald A, McMillan D. Failure Rate, Repair Time and Unscheduled O&M Cost Analysis of Offshore Wind Turbines. Submitted to Wiley Wind Energy Journal, Jan 2014.

[3] Dinwoodie I, Endrerud OEV, Hofmann M, Martin R, Sperstad IB. Reference Cases for Verification of Operation and Maintenance Simulation Models for Offshore Wind Farms. Wind Engineering, Volume 39, No. 1, 2015 PP 1–14

[4] Carroll J, Dinwoodie I, McDonald A, McMillan D. Operational Performance and O&M Costs of Offshore Wind Turbines with PMG and DFIG Drive Trains. Submitted to Wiley Wind Energy Journal, Feb 2014.

[5] Dinwoodie I, McMillan D. Heavy Lift Vessel Strategy Analysis for Offshore Wind. In Proc EWEA 2013, Vienna

[6] Yang W, Tavner P, Crabtree C, Feng Y, Qiu Y. Wind turbine condition monitoring: technical and commercial challenges. Wind Energ.2014; 17:673–693

[7] Carroll J, May A, McDonald A, McMillan D. Availability Improvements From Condition Monitoring Systems and Performance Based Maintenance Contracts. Submitted to EWEA Offshore 2015, Copenhagen

[8] Sorensen J. Framework for Risk-based Planning of Operation and Maintenance for Offshore Wind Turbines. Wind Energ. 2009; 12:493–506

[9] Echavarria E, van Bussel G, Tomiyama T. Finding Functional Redundancies in Offshore Wind Turbine Design. Wind Energ.2012; 15:609–626

[10] Holierhoek J et al. Procedures for testing and measuring wind turbine components; results for yaw and pitch system and drive train. Wind Energ.2013; 16:827–843

[11] Igba J, Alemzadeh K, Henningsen K, Durugbo C. Effect of Preventative Maintenance Intervals on Reliability and Maintenance Costs of Wind Turbine Gearboxes. Wind Energ. (2014)

[12] Vestas Promotional Material. V112-3MW Offshore. Available at: www.vestas.com/Files/Filer /EN/Brochures/Productbrochure_V112_Offshore_UK.pdf

[13] Mulder W, Blok J, Hoekstra S, Kokkeler F. Design for maintenance. Guidelines to enhance maintainability, reliability and supportability of industrial products. University of Twente (2012). Available at: http://www.utwente.nl/ctw/opm/staff/ME/MulderW/DesignForMaintenance_Design Guidelines.pdf

[14] Dalgic Y, Dinwoodie I, Lazakis I, McMillan D, Revie M. Optimum CTV fleet selection for offshore wind farm O&M activities. 2014. Paper presented at ESREL 2014, Wroclaw, Poland.

[15] BMU and PTJ, FINO 1 Meteorological Dataset 2004 – 2012, http://fino.bsh.de, last accessed 1/12/2014

[16] Carroll J, McDonald A, McMillian D. Reliability Comparison of Wind Turbines with DFIG and PMG Drive Trains. IEEE Trans. Energy Convers., vol. PP, pp. 1–8, Dec. 2014

[17] F. Spinato, P. J. Tavner, G.J.W van Bussel and E. Koutoulakos, “Reliability of wind turbine subassemblies,” IET Renew. Power Generation, vol. 3, no. 4, pp. 1–15, Sep. 2009.

[18] J. Carroll, A. McDonald, J. Feuchtwang and D. McMillian, “Drivetrain Availability of Offshore Wind Turbines,” in Proc. Eur. Wind Energy Conf., Barcelona, Spain, Mar. 10–13, 2014.

[19] EWEA. Wind Energy Statistics and Targets. Accessed on 18/02/2015. Accessed at: http://www.ewea.org/uploads/pics/EWEA_Wind_energy_factsheet.png