Failure Rate, Repair Time and Unscheduled O&M Cost Analysis of Offshore Wind Turbines

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ABSTRACT

Determining and understanding offshore wind turbine failure rates and resource requirement for repair is vital for modelling and reducing O&M costs and in turn reducing the cost of energy. While few offshore failure rates have been published in the past even less details on resource requirement for repair exist in the public domain. Based on ~350 offshore wind turbines throughout Europe this paper provides failure rates for the overall wind turbine and its sub-assemblies. It also provides failure rates by year of operation, cost category and failure modes for the components/sub-assemblies that are the highest contributor to the overall failure rate. Repair times, average repair costs and average number of technicians required for repair are also detailed in this paper. An onshore to offshore failure rate comparison is carried out for generators and converters based on this analysis and an analysis carried out in a past publication. The results of this paper will contribute to offshore wind O&M cost and resource modelling and aid in better decision making for O&M planners and managers.

KEYWORDS

Failure mode, failure rate, offshore wind turbine, reliability.

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1. INTRODUCTION

The reliability of an offshore wind turbine and the resources required to maintain it can make up ~30% of the overall cost of energy [1]. Typically, a higher failure rate and greater repair resource requirement (i.e. material cost and labour) leads to a higher cost of energy. Consequently, wind farm developers try to select wind turbines with low failure rates and those that require the least amount of maintenance resources. Due to accessibility issues, reliability of turbines becomes even more important as offshore wind energy generation increases [2,3]. This paper shows the results of an analysis determining the failure rates and resource requirements for repair of modern multi MW scale offshore wind turbines and their sub-assemblies.

This analysis is based on ~350 offshore wind turbines from a leading manufacturer. All offshore turbines in this analysis are between 3 and 10 years old and are from between 5 - 10 wind farms throughout Europe. The full data set consists of over 1768 turbine years of operational data. For confidentiality reasons the exact number of wind farms/turbines cannot be provided. For the same reasons the exact nominal power, blade size or drive train configuration of the turbine type used in this analysis is also not provided. However it can be stated that it is a modern multi MW scale turbine type with an identical blade size and nominal power in all turbines. It can also be stated that it is a geared turbine with an induction machine. As a guide to the size of the turbine type, the rotor diameter is between 80m and 120m and the nominal power is between 2 and 4MW.

The novelty of this work lies in the large modern population of offshore wind turbines analysed. The analysis of the resources required for repair of offshore wind turbines is also novel as little or no past publications were found with real data in this area during the literature review. Offshore wind farm operation and maintenance (O&M) cost models need resource requirements for repair as inputs to the models. These models can be highly sensitive to the accuracy of this data and that data is not currently in the public domain [4,5]. In some cases onshore input data is used to estimate offshore outputs in these models [2,6]. Inputs such as failure rates, repair times, number of technicians required for repair and average cost of repair are required. This paper is unique in providing each of these inputs based on analysis of this large and modern population of offshore wind turbines. Out of the four input areas mentioned above, failure rates is the area with the most literature available, however this paper is still novel in this area because the majority of the past literature available is for the failure rates of populations of older and smaller onshore turbines [7,8] rather than offshore failure rates based on modern multi MW turbines.

2. Offshore O&M Literature Review

As mentioned in the introduction little or no past literature exists in the area of resource requirement for repair of on or offshore wind turbines. As this paper also includes a failure rate / reliability section, past literature on the reliability of offshore wind turbines was reviewed. As the offshore wind industry is young and turbine manufacturers are generally reluctant to release performance data there is a lack of offshore reliability analyses available in the public domain.

Reference [9] describes an availability analysis on a number of UK offshore wind farms. Each of the wind farms in reference [9] are in the early years of operation, all of which are operational for less than three years. The paper highlights the need for improvements to be made in availability if the economic targets of these wind farms are to be met. However it does not look at wind turbine failure rate or sub assembly failure rate as this paper does, making it difficult to determine which areas to focus on to achieve the required availability improvements.

One other offshore analysis is detailed in paper [10]. This analysis is based on a single wind farm of 36 turbines. The analysis is based on turbine stoppages rather than turbine failures and the paper states that this type of analysis cannot be compared to a failure rate analysis because the stops are defined differently than failures. One of the drivers for this difference is that scheduled operations are included in the turbine stoppage analysis but not in the turbine failure analysis.

There are more onshore reliability analyses in the public domain than there are offshore. These analyses cover the onshore turbine as a whole as well as its subassemblies. However as stated in [11] these analyses are repeatedly based on the same wind turbine populations and failure databases due to the small number of reliability databases in the public domain [12]. Databases like LWK and WMEP in Germany, WindStats in

Germany and Denmark, Reliawind and a population from Sweden [13,14] are the basis for the analysis in the papers described in the following paragraphs.

References [7,8] analyze a population that reaches 6,000 onshore wind turbines at the end of an 11 year period. This population of 6,000 turbines is located in Germany and Denmark and failures have been recorded in the Windstats and LWK database. The Windstats and LWK database is based on the largest population encountered in the literature review; however, it contains turbines as old as 20 years and as small as 200kW. As the population contains these older smaller turbines, questions are raised as to whether the population is representative of modern multi MW turbines.

The WMEP database is used in references [12,15]. The WMEP database contains failure data for up to 1,500 turbines over a 15 year period throughout Germany. A similar onshore failure rate analysis is carried out in [13] on a population consisting of turbines from Sweden. This Swedish database runs from 1997 and builds up to ~ 750 turbines. The work carried out by Reliawind [16] is based on 10 minute SCADA data, work orders, alarm logs and service records from 350 turbines. This is a smaller population than the other onshore databases discussed above but it consists of more modern larger onshore turbines.

3. Population Analysis

The population analysed in this paper builds up to ~350 turbines over a five year period. These turbines come from between 5-10 wind farms. 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% is greater than 5 years old. In total this population provides 1768 turbine years or ~15.5 million hours of turbine operation. Exact population details cannot be provided for confidentiality reasons.

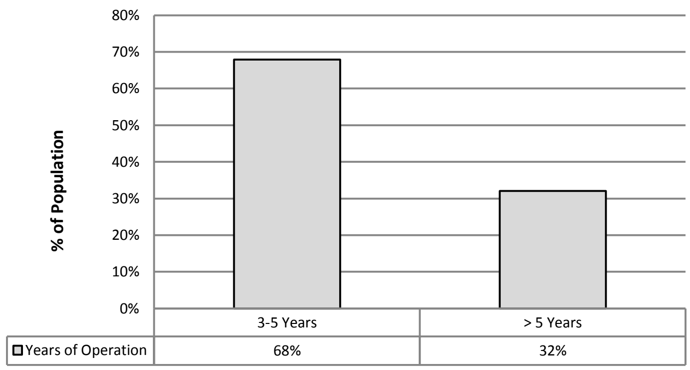


Figure 1. Population Operational Years

4. FAILURE DATA AND DEFINITIONS

4.1 Failure Definition

There is no standardized way for defining a failure in the wind energy industry. This analysis defines a failure as a visit to a turbine, outside of a scheduled operation, in which material is consumed; this is consistent with reference [11]. Material is defined as anything that is used or replaced in the turbine; this includes everything from consumable materials (such as carbon brushes) to replacement parts such as full IGBT units and full generators.

Faults that are resolved through remote, automatic or manual restarts are not covered by this definition of a failure. However, if the faults that are resolved through remote, automatic or manual restarts repeatedly occur and they require a visit to the turbine in which material is used, the failure is then subsequently captured in this type of failure definition, providing the visit is outside of a scheduled service. This definition is somewhat different to that in reference [16], in which a failure is defined as a stoppage of a turbine for one or more hours that requires at least a manual restart to return it to operation.

4.2Failure rates and failure rate categories

This paper provides failure rates in a per turbine per year format as seen in [7, 8, 11]. The formula used to determine failure rate per turbine per year can be seen below. It is the same formula used in [7, 8, 11]:

$$\lambda = \frac{\sum_{i=1}^{I}\sum_{k=1}^{K} n_{i,k}/N_i}{\sum_{i=1}^{I} T_i/8760} \qquad (1)$$

where

λ = failure rate per turbine per year

I = number of intervals for which data are collected

K = the number of subassemblies

$n_{i,k}$ = the number of failures

N_i = the number of turbines

T_i = the total time period in hours

The numerator $\sum_{i=1}^{I}\sum_{k=1}^{K} n_{i,k}/N_i$ is the sum of the number of failures in all periods per turbine. The denominator, $\sum_{i=1}^{I} T_i/8760$, is the sum of all time periods in hours divided by the number of hours in a year.

The failure cost categories are grouped in three ways. These groups are based on the Reliawind categories from [17] in which failures are classified as a minor repair, major repair or major replacement. In this paper any failure with a total repair material cost of less than €1,000 is considered a minor repair, between €1,000 and €10,000 a major repair and above €10,000 a major replacement. These costs are based on material cost only. Travel time and lead time are not included. Presenting the costs in this manner means repair costs are independent of distance from shore. This is useful for the modeling of O&M costs of wind farms at varying distances from shore.

4.3 Method

A similar method to the method used in [11] was carried out for this analysis. As in [11] a leading wind turbine manufacturer provided access to their offshore work order and material usage databases. The work order database is a database in which every piece of work carried out on the turbine is recorded and the material usage database is the database in which every material used on the turbine is recorded.

These two databases were connected with bespoke code created in SQL (a standard language for accessing databases) using work order numbers to match up the work carried out with the material used on the turbine. The data was also cleaned to remove any scheduled operations such as scheduled services or scheduled inspections. These scheduled events may influence the failure rates as poorly maintained turbines may have higher failure rates. The turbines in the population analysed were maintained to the standard recommended by the manufacturer, with services occurring at the recommended intervals.

Once each failure is identified, its total material cost is calculated and the failure is then categorized as a minor repair, major repair or major replacement as described in the previous section. Each failure is then put into a subassembly/component group. The failure group of each work order is determined by reading through the work order long text in which the wind turbine technician provides a brief description of the work carried out.

The number of technicians and repair time required to repair the failure is also determined from the work order database. The average cost of failure is determined by adding the cost of each material used for each work order and calculating the average for each sub assembly. This process can be seen in Figure 2.

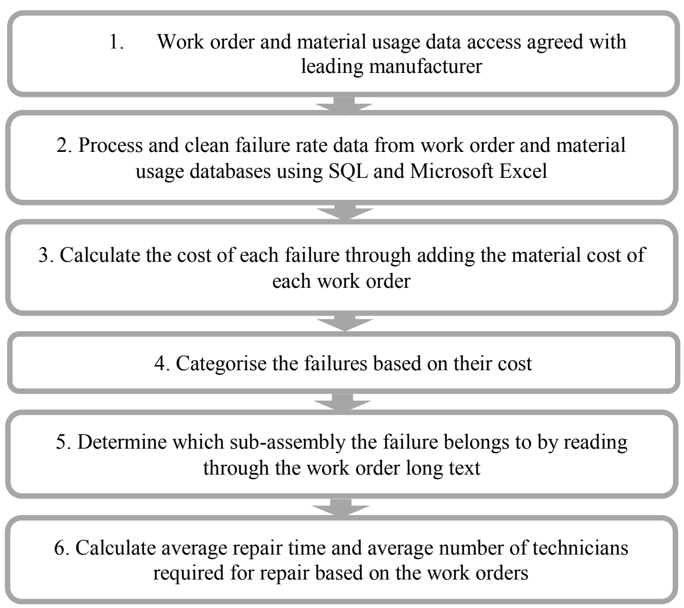


Figure 2. Flow chart of failure rate data analysis

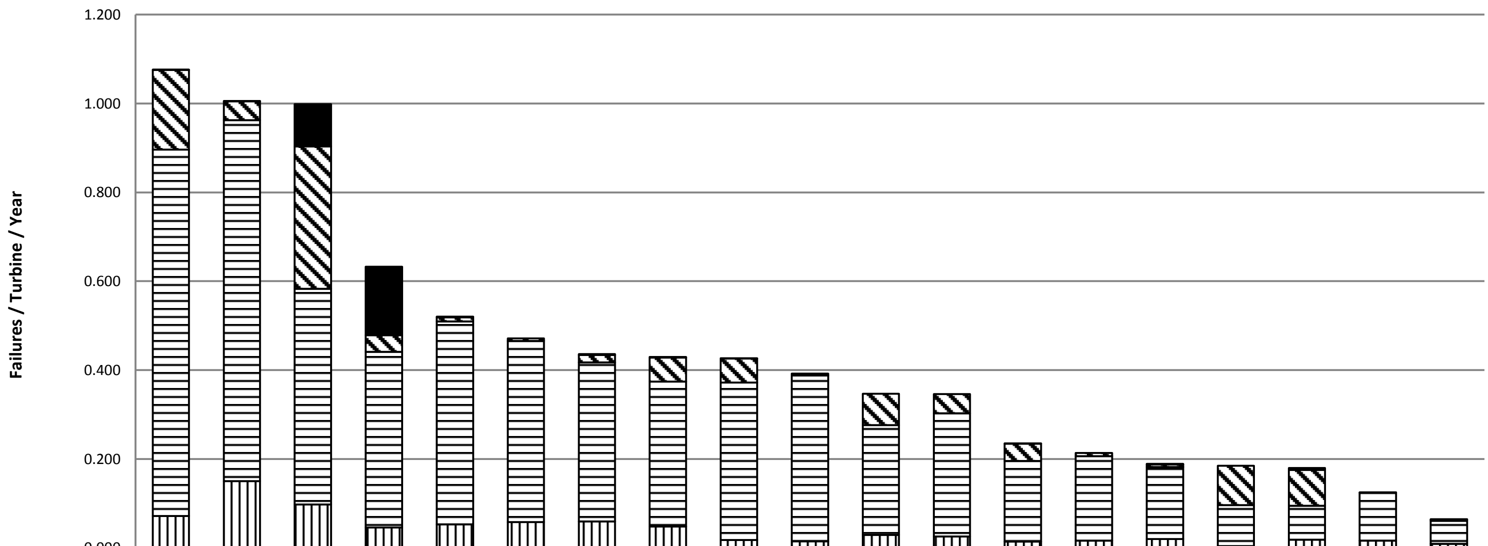
5. RESULTS AND DISCUSSION

5.1 Subassembly/component failure rates and failure category Pareto chart

The average failure rate for an offshore wind turbine from this analysis is 8.3 failures per turbine per year. This consists of 6.2 minor repairs, 1.1 major repairs and 0.3 major replacements. 0.7 failures per turbine per year have no cost data so could not be categorized. Figure 3 shows the breakdown of that failure rate by wind turbine subassembly/component and by failure cost category. The failure cost categories are detailed in section 4.2. In the figure, the vertical hatching represents failures that have no cost data available, the horizontal hatching represents minor repairs costing less than €1,000, the diagonal hatching represents major repairs costing between €1,000 and €10,000 and the solid black sections represent major replacements costing over €10,000.

The biggest contributor to the overall failure rate for offshore wind turbines is the pitch and hydraulic systems. The pitch and hydraulic systems make up ~13% of the overall failure rate. "Other Components" is the second largest contributor to the overall failure rate with ~12.2% of the overall failures. The "Other Components" group consists of failures to auxiliary components which enable the other systems to function such as lifts, ladders, hatches, door seals and nacelle seals. The generator, gearbox and blades are the third, fourth and fifth biggest contributors to the overall offshore failure rates with 12.1%, 7.6% and 6.2% respectively.

When minor repairs alone are considered the pitch and hydraulic systems as well as the "Other Components" group are again the largest contributors making up 26% of the failures for the minor repair category. The lack of major repairs or major replacements in the other components section is explained by the fact that the majority of the repairs are to small lower value components such as repairs to lifts, ladders, hatches and seals. The greatest contributor to the major repairs of the turbine is the generator; here 30% of the failures are in the major failure category. Looking to the third smallest contributor overall, it can be seen that the power supply/ converter has a high percentage of major repairs, this is due to IGBT issues and the cost of replacing an IGBT pack being between €1,000 and €10,000. Generator and gearbox failures make up 95% of all failures in the major replacement category. The gearbox has more failures than the generator at 0.154 failures per turbine per year in comparison to 0.095 failures per turbine per year for the generator.

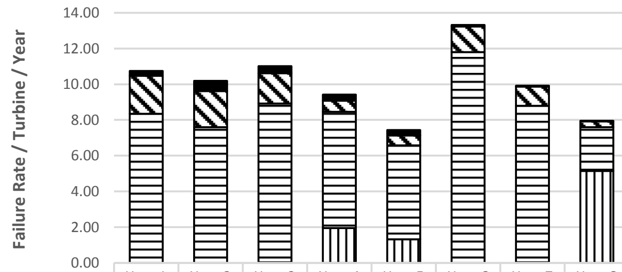


	Pitch / Hyd	Other Components	Generator	Gearbox	Blades	Grease / Oil / Cooling Liq.	Electrical Components	Contactor / Circuit Breaker / Relay	Controls	Safety	Sensors	Pumps/ Motors	Hub	Heaters / Coolers	Yaw System	Tower / Foundation	Power Supply / Converter	Service Items	Transformer
Major Replacement	0.001	0.001	0.095	0.154	0.001	0.000	0.002	0.002	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.005	0.000	0.001
Major Repair	0.179	0.042	0.321	0.038	0.010	0.006	0.016	0.054	0.054	0.004	0.070	0.043	0.038	0.007	0.006	0.089	0.081	0.001	0.003
Minor Repair	0.824	0.812	0.485	0.395	0.456	0.407	0.358	0.326	0.355	0.373	0.247	0.278	0.182	0.190	0.162	0.092	0.076	0.108	0.052
No Cost Data	0.072	0.150	0.098	0.046	0.053	0.058	0.059	0.048	0.018	0.015	0.029	0.025	0.014	0.016	0.020	0.004	0.018	0.016	0.009

Figure 3. Failure rate Pareto chart for subassembly and cost category

5.2 Overall failure per year of operation

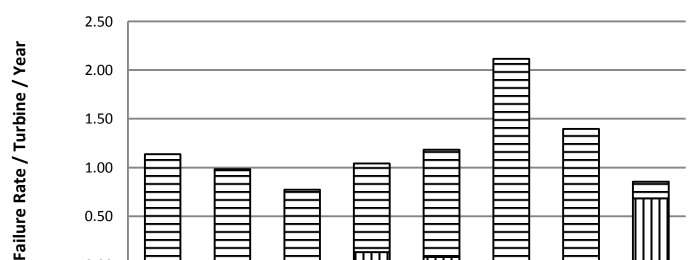
Figure 4 shows the failure rates per year of operation. It can be seen that the failure rate has a slight downward trend in the first 5 years. This downward trend is slower than the failure rate drop shown in past papers [11]. There is a failure rate spike in year 6 before another downward trend. Further investigation into this increased failure rate in year six showed a spike in pitch and hydraulic failures.



	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
Major Replacment	0.28	0.56	0.39	0.34	0.31	0.09	0.05	0.03
Major Repair	2.13	2.02	1.70	0.62	0.56	1.43	1.07	0.32
Minor Repair	8.34	7.60	8.89	6.50	5.24	11.80	8.76	2.45
No Cost Data	0.00	0.00	0.03	1.95	1.33	0.00	0.03	5.14

Figure 4. Failure rate and failure category per year of operation

Past papers have mentioned that wind turbines and their components may fail in a similar manner to the failure trend suggested by the bathtub curve [7, 11]. This is not clearly evident in Figure 4. The reason for this is that turbine sub-systems with higher failure rates, such as the pitch and hydraulic system, do not follow the bathtub curve, as seen in Figure 5. However, some turbine components, such as the converter and electrical components show more of a resemblance to a bathtub curve as seen in Figure 6. However the systems that follow the bathtub curve are outnumbered by the systems that do not, resulting in the overall turbine failure graph shown in Figure 4.



	1	2	3	4	5	6	7	8
Major Replacement	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Major Repair	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Minor Repair	1.14	0.97	0.77	0.91	1.10	2.11	1.39	0.17
No Cost Data	0.00	0.00	0.00	0.13	0.08	0.00	0.01	0.68

Figure 5. Pitch/hydraulic system failure rate and failure category per year of operation

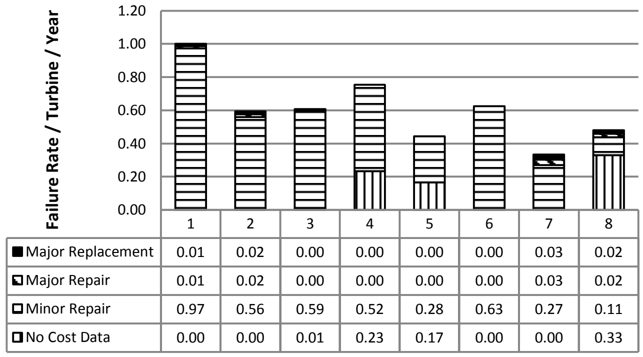


Figure 6. Converter/Electrical component failure rate and failure category per year of operation

5.3 Detailed analysis on top 3 failure modes

As seen in Figure 3 the top three subassemblies contributing to offshore failures are the pitch/hydraulic systems, other components and the generator. As a means of identifying the vital few failure modes from the trivial many, the following graphs show the top five failure modes in each subassembly.

Figure 7 shows that oil and valve issues make up about 30% of the overall pitch/hydraulic failures with a further 20% consisting of actuator, sludge and pump repairs or replacements. Oil issues consist of failures like leaks, unscheduled oil changes and unscheduled oil top ups. Sludge issues consist of failures in sensors and leaks. The majority of valve, accumulator and pump issues are resolved through valve, accumulator and pump replacements.

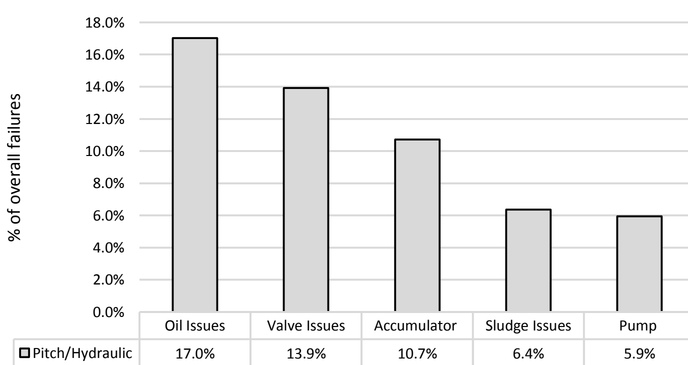


Figure 7. Pitch/hydraulic failure modes

Figure 8 shows that door hatch and skylight issues are the largest contributor to the "other components" failure group with approximately 25% of all failures in this area. The remaining 4 issues in the top 5 are covers, bolts, lighting and repairs to the lift, each of which contribute ~ 5% to the overall failure rate.

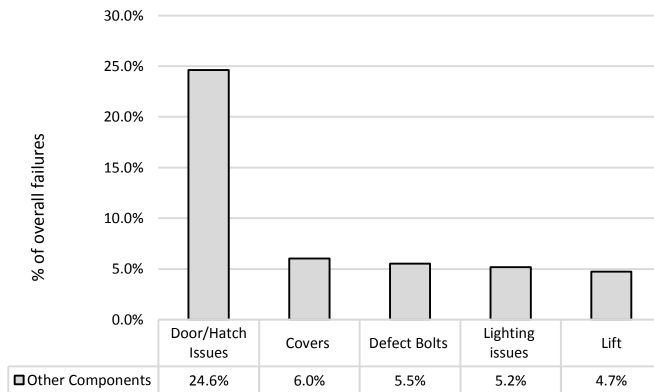


Figure 8. Other Components failure modes

Figure 9 shows that slip ring issues are the largest contributor to the generator failure group with approximately 31% of all failures in this area. The remaining 4 issues in the top 5 are bearing issues, problems with the generator grease pipes, issues with the rotor and fan replacements.

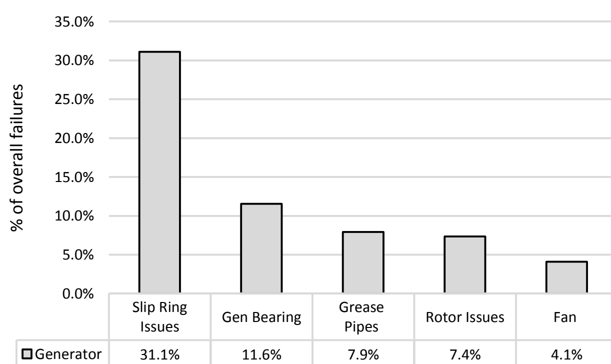


Figure 9. Generator failure modes

5.4 Wind speed and onshore to offshore comparison

The average failure rate and average wind speed for each of the turbines in this population is plotted in Figure 10. In the past this has been shown for onshore turbines and components [15, 18] but not for offshore turbines. Reference [18] shows a trend for onshore turbines to have a higher failure rate in higher wind speeds. It contains a similar graph to Figure 10 in which the slope of the line is 0.08 showing a relatively weak correlation. It can now be seen from Figure 10 that offshore there is also an overall trend for turbines that are sited in areas with higher wind speeds to experience higher failure rates. The slope of the line in Figure 10 is 1.77 showing a stronger correlation. When compared to the slope of 0.08 from [18] it is obvious that higher wind speeds have a greater impact on failure rates offshore compared to onshore. A similar analysis was carried out for turbulence intensity, however no clear trend was observed.

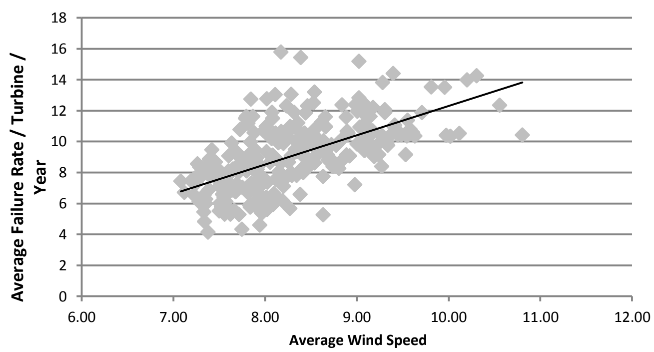
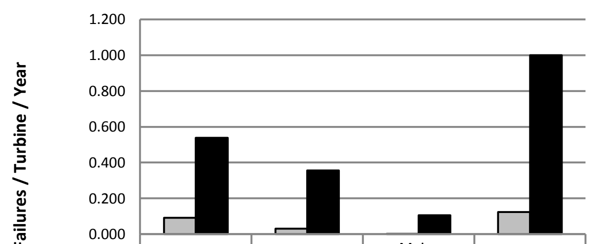


Figure 10. Average failure rates vs. average wind speed

Generator and converter failure rates from a similar reliability analysis for onshore wind turbines are available in reference [11]. Figures 11 and 12 use the onshore failure rates from [11] and the offshore failure rates for the generator and converter from this paper to compare the difference between onshore and offshore failure rates.

Figure 11 shows the onshore generator failure rates in grey and the offshore generator failure rates in black. It can be seen that overall the onshore failure rate is approximately eight times less than the offshore failure rate. This higher failure rate for offshore is evident across each of the 3 failure cost categories, minor repair, major repair and major replacement. There are a number of possible explanations for the lower onshore failure rate. One may be that offshore sites have a higher average wind speed than onshore sites and as seen in Figure 10 this in turn leads to a higher failure rate. The average wind speeds from all offshore sites in this paper is 8.2 m/s. The average wind speed from a similar number of onshore sites in Germany (where the majority of the onshore failure rate population in Figures 11 and 12 comes from) is 6.3m/s [19]. Based on Figure 10 this would see a 33% increase in onshore to offshore failure rates due to wind speeds alone.

Another reason could be that onshore turbines are maintained to a better standard due to easier access which in turn reduces failures. Other reasons for the difference in Figures 11 and 12 could be down to the difference in populations analysed. Both populations have a different number of operational years and rated powers. The offshore population has a higher rated power than the turbines in the onshore populations and it is known that larger turbines have a higher failure rate [20]. Based on extrapolating the failure data from Figure 5 in reference [20] it was calculated that the difference in rated power for the onshore and offshore populations in this comparison would lead to a greater offshore failure rate of 27%. The harsher environment offshore may also contribute to the difference in failure rate from onshore to offshore. For components outside the nacelle such as blades and towers this will most likely be the case. Manufacturers have tried to mitigate the harsher environment by hermetically sealing the nacelle to protect components like the generator and converter. However, these components may be exposed when the maintenance and repairs are being carried out.

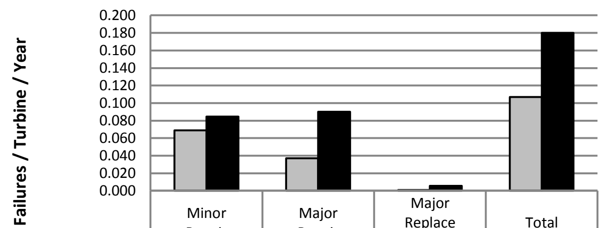


	Minor Repair	Major Repair	Major Replace ment	Total
Generator (Onshore)	0.091	0.030	0.002	0.123
Generator (Offshore)	0.538	0.356	0.105	0.999

Figure 11. Onshore vs. offshore generator failure rates

If it is the case that the points discussed above are the driver for the far great failure rate for electro-mechanical components like a generator, these points do not seem to have such a high impact on purely electrical components such as the converter shown in Figure 12. The onshore converter is again shown in grey and the offshore converter is shown in black. It can be seen that the total difference in failure rate for the converter is less than the total difference in failure rate for the generator. Overall there are ~40% more failures for the offshore converters than there are for the onshore converters.

When combined the reasons stated in the previous paragraphs for the difference in onshore to offshore failure rates equal ~ 60%. This is 20% more than the observed difference in the converter but far less than what is observed for the difference in onshore and offshore generators. This leads the authors to believe that there are certain components in a turbine that the step from onshore to offshore affects more than others. It must also be considered that other unquantified factors are driving the difference in generator failure rates when they are moved from on to offshore.



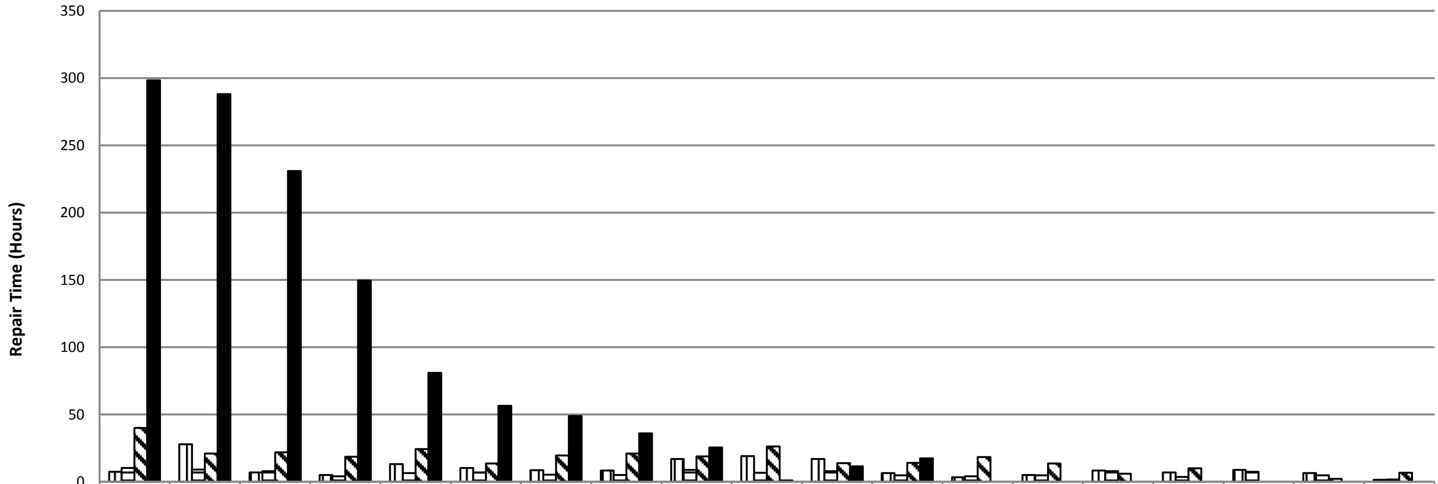
	Minor Repair	Major Repair	Major Replace ment	Total
Converter (Onshore)	0.069	0.037	0.001	0.107
Converter (Offshore)	0.084	0.090	0.006	0.180

Figure 12. Onshore and offshore converter failure rates

5.5 Average Repair times per failure category

The average offshore repair time can be seen in Figure 13. In this analysis the offshore repair time is defined as the amount of time the technicians spend in the turbine carrying out the repair. Unlike downtime it does not include travel time, lead time, time added on due to inaccessibility and so on.

As expected it can be seen that the highest repair times occur in the major replacement category shown in black in Figure 13. The top three average repair times occur in the hub, blades and gearbox. It should be noted that even though the hub and blades have very high repair times for major replacement, the effect on overall availability will be quite low due to the fact that their failure rate (shown in Figure 3) is low. In terms of availability it is more likely that the gearbox and generator will have a greater impact due to the fact that their failure rate for major replacements and repair time for major replacements are towards the higher left sides of both graphs.



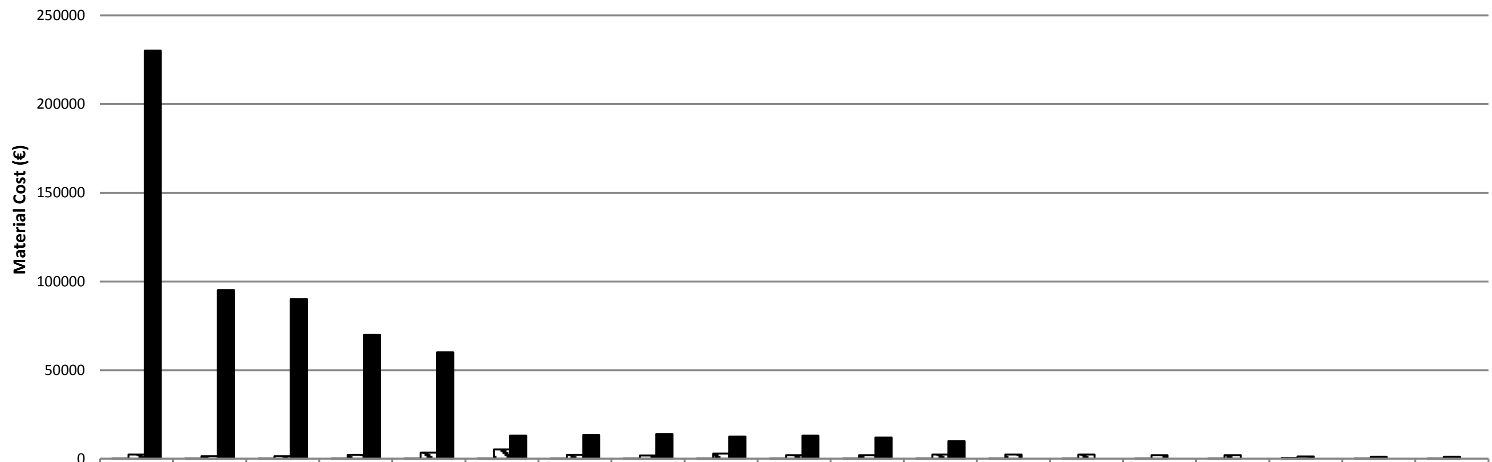
	Hub	Blades	Gearbox	Contactor / Circuit Breaker / Relay	Generator	Power Supply / Converter	Yaw System	Other Components	Pitch / Hyd	Transformer	Controls	Electrical Components	Grease / Oil / Cooling Liq.	Heaters / Coolers	Sensors	Pumps/Motors	Service Items	Tower / Foundation	Safety
No Cost Data	8	28	7	5	13	10	9	8	17	19	17	7	3	5	8	7	9	6	2
Minor Repair	10	9	8	4	7	7	5	5	9	7	8	5	4	5	8	4	7	5	2
Major Repair	40	21	22	19	24	14	20	21	19	26	14	14	18	14	6	10		2	7
Major Replacement	298	288	231	150	81	57	49	36	25	1	12	18	0	0	0	0	0	0	0

Figure 13. Pareto chart of average repair times for each sub-assembly/component

5.6 Average Repair costs per failure category

Figure 14 shows the average repair costs for each sub-assembly and severity category. The average costs are shown in Euros and include the cost of materials only. They do not include labour costs or compensation costs paid to the operator for downtime. It can be seen that the chart is dominated by the average costs of the major replacements. The average cost of major repairs and particularly minor repairs are far less significant in this graph because they are so small in comparison to the average cost of major replacements.

The gearbox has the highest average cost per failure with a major replacement costing €230,000 on average. The fact that the gearbox has a high major replacement failure rate and repair time also suggests that it will be one of the largest contributors to the overall O&M costs for the offshore turbine. The second and third highest average costs are the hub and blades respectively. Even though these components have high average costs of repair and high repair times, the fact that their major replacement failure rate is so low means that their contribution to the overall annual O&M cost will be relatively low in comparison to the gearbox and generator.



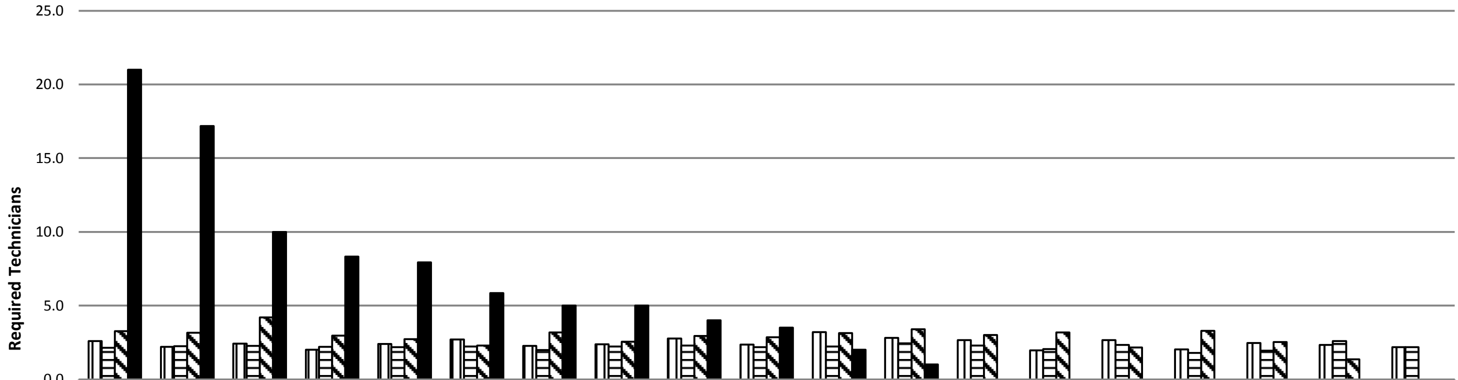
	Gearbox	Hub	Blades	Transformer	Generator	Power Supply / Converter	Contactor / Circuit Breaker / Relay	Pitch / Hyd	Yaw System	Controls	Electrical Components	Other Components	Sensors	Safety	Pumps/ Motors	Grease / Oil / Cooling Liq.	Heaters / Coolers	Service Items	Tower / Foundation
Minor Repair	125	160	170	95	160	240	260	210	140	200	100	110	150	130	330	160	465	80	140
Major Repair	2500	1500	1500	2300	3500	5300	2300	1900	3000	2000	2000	2400	2500	2400	2000	2000	1300	1200	1100
Major Replacment	230000	95000	90000	70000	60000	13000	13500	14000	12500	13000	12000	10000	0	0	0	0	0	0	0

Figure 14. Pareto chart of average repair cost for each sub-assembly/component

5.7 Average number of technicians required per failure category

The average number of technicians required for repair is the average of the number of technicians that recorded time working on repairing a failure to a subassembly/component in one of the three failure categories. When calculating the O&M costs for the year the average number of technicians required for repair can be used to determine the labour costs when modelling overall O&M costs.

From Figure 15 it can be seen that the blades, gearbox and hub require the most technicians when a failure occurs. Once again it is the gearbox that will contribute more than the blades and hub to the annual labour costs due to its higher failure rate. It can be seen that up to twenty technicians are used in some of the major replacements; however this does not necessarily mean that twenty technicians are working on the repair for the full repair time. A more likely scenario is that there is a smaller core team of technicians that work throughout the repair time and there are additional technicians that register smaller amounts of time in supporting roles on the repair job.



	Blades	Gearbox	Hub	Contactor / Circuit Breaker / Relay	Generator	Power Supply / Converter	Other Components	Yaw System	Pitch / Hyd	Electrical Components	Controls	Transformer	Heaters / Coolers	Grease / Oil / Cooling Liq.	Sensors	Safety	Pumps/ Motors	Tower / Foundation	Service Items
No Cost Data	2.6	2.2	2.4	2.0	2.4	2.7	2.3	2.4	2.8	2.4	3.2	2.8	2.7	2.0	2.7	2.0	2.5	2.3	2.2
Minor Repair	2.1	2.2	2.3	2.2	2.2	2.2	2.0	2.2	2.3	2.2	2.2	2.5	2.3	2.0	2.3	1.8	1.9	2.6	2.2
Major Repair	3.3	3.2	4.2	3.0	2.7	2.3	3.2	2.6	2.9	2.9	3.1	3.4	3.0	3.2	2.2	3.3	2.5	1.4	0.0
Major Replacement	21.0	17.2	10.0	8.3	7.9	5.9	5.0	5.0	4.0	3.5	2.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 15. Pareto chart of average number of technicians required for repair for each sub-assembly/component

6. COMPARISON TO INPUT PARAMETERS CURRENTLY USED

Prior to this paper, inputs for O&M modelling have been estimated using "expert knowledge" informed by limited operational data [21]. Reference [21] is a comparison between a number of different O&M models that all use the same inputs derived from the expert knowledge of a wind farm developer/operator. Table 1 shows the input parameters from that paper.

	Manual Reset	Minor Repair	Medium Repair	Major Repair	Major Replacement	Annual Service
Repair Time	3 hours	7.5 hours	22 hours	26 hours	52 hours	60 hours
Required Technicians	2	2	3	4	5	3
Vessel Type	CTV	CTV	CTV	FSV	HLV	CTV
Failure Rate	7.5	3	0.275	0.04	0.08	1
Repair Cost	0	£1,000	£18,500	£73,500	£334,500	£18,500

Table 1. O&M modelling inputs from reference [21]

For comparison purposes Table 2 shows the inputs from [21] alongside the empirical results from this paper. The empirical results from this paper are re-grouped to form similar groups to [21]. This paper did not focus on Manual Restarts of Annual Service so they were not included in this comparison. Medium repair and Major Repair from Table 1 were combined to allow for a comparison with the Major Repair figures from this paper. It can be seen that the inputs from expert knowledge in [21] are closer to the empirical figures for Repair Times and Required Technicians than they are for Failure Rates and Repair Costs. A driver for the difference in failure rate for the expert knowledge figures and the empirical data could be due to a different method of defining a failure. This paper defines a failure as any visit to a turbine outside of a scheduled operation in which a material is consumed. As there is no standardized way of defining a failure in the wind energy industry the failure definition in [21] is most likely different to the definition used in this paper, which in turn leads to the difference in failure rates. Even if failure rates are defined in the same way they will differ from population to population as turbines from different manufacturers will have varying failure rates due to the different technologies, suppliers and quality standards used.

A driver for the difference in cost of failure could again be due to a different way of defining the failure cost. In this paper the failure cost is solely the cost of the materials used for repair. The higher costs of the failures in [21] could be due to the experts including other costs in the cost of repair such as transport cost, labour cost, storage costs and/or using older cost data from [22]. For comparison the costs from this paper have been converted from Euro to Great British Pound based on an exchange rate of €1 to £0.77.

	Minor Repair		**Major Repair**		**Major Replacement**	
	This Paper	Ref. [21]	This Paper	Ref. [21]	This Paper	Ref. [21]
λ (/ Turbine / Year)	6.81	3.00	1.17	0.31	0.29	0.08
Repair Time (Days)	6.67	7.50	17.64	24.00	116.19	52.00
Req. Technicians	2.61	2.00	3.44	3.50	9.14	5.00
Repair Cost	£140	£1,000	£1726	£46,000	£40,906	£334,500

Table 2. O&M modelling inputs from this paper and reference [21] compared

6. CONCLUSION

This paper is unique in providing all of the input requirements to model the O&M costs of an offshore wind farm. The failure rates, failure costs, average repair times and average number of technicians required for repair from this paper combined with an offshore accessibility model allow for the calculation of offshore wind farm O&M costs. Novel results from this paper show that:

- The average failure rate for an offshore wind turbine levels out at approximately 10 failures per turbine per year by a wind farm's third operational year. With ~80% of those repairs being minor repairs, ~17.5% major repairs and ~2.5% major replacements.
- The subassemblies/components that fail the most are the pitch/hydraulic system, the other components group and the generator. The biggest failure modes in these groups are oil issues for pitch /hydraulic, door/hatch issues for other components and slip ring issues for generators.
- As with onshore there is a trend of rising average failure rates with rising average wind speeds. Offshore shows a stronger correlation meaning that there is a higher failure rate with higher wind speeds offshore than there is onshore.
- Generators and converters have a higher failure rate onshore than they do offshore. The onshore to offshore failure rate difference is greater in generators than in converters. Although and increased wind speeds, age of turbines and size of turbines go some way to explain the differences there is still some differences which perhaps are due to loading or scheduled O&M.
- The hub, blades and gearbox have the highest repair times, repair costs and number of technicians required for repair out of all the components in an offshore wind turbine. However as the major replacement failure rate is so low for the hub and blades they are not likely to contribute as highly as the gearbox or generator to the overall O&M costs.

Further work could use inputs from the analyses carried out in [11] along with the inputs from this paper, combined with the O&M models described in [21] to determine O&M cost, downtimes, availability and resource requirements for repair for offshore wind turbines with different drive train types.

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