Understanding Out of Warranty Reliability

Using benchmark data to identify reliability trends for onshore turbines

Contents

This paper examines the relationship between turbine type and reliability. Wind Energy Benchmarking Services reliability data is used to analyse turbines, grouped by technology and nameplate capacity, to identify mean time to failure and mean repair time per failure.

The analysis shows that turbines which use doubly fed induction machine technology encounter failures more often, and experience longer repair times per failure, in comparison with other turbine technologies. The results also suggest no one single trend can be attributed to onshore turbines as a whole as reliability varies by technology and generation capacity. The paper concludes that the adoption of industry wide benchmarking platforms such as that seen for gas turbines and Oil & Gas facilities is a key enabler for better understanding of turbine reliability.

Introduction: The Post Warranty Wind O&M Landscape

The O&M landscape has gone through considerable changes in recent years. Owner Operators and IPP's are increasingly examining a range of O&M options as their assets reach the end of warranty. A recent report by GCube[1] noted that around 1/3 of all wind turbines are now reaching the end of O&M service agreements. Operators, asset managers and those responsible for overall project operations are now assessing the value of independent service providers (ISP's) maintenance contracts. Cost is often cited as an important issue in selecting an ISP vs the OEM end-of-warranty package option[2]. At a time of decreasing subsidies and record low auction prices cost is increasingly significant, a trend expected to continue over the next 3-5 years.

Navigant Research has noted that warranties have now expired on over 50% of the global installed turbine capacity. Make Consulting predict that the global O&M market is set to grow from $9.7bn in 2015 to $19.3bn by 2021.[3] This trend is particularly prevalent in the USA. IHS Energy Research forecast U.S. O&M spending will almost double to $6 billion by 2025 as a direct result of the number of turbines coming out of warranty.[4]

This space has been further complicated by some of the M&A activity in recent years. Vestas $60 million acquisition of Upwind in 2015 has already enabled it to win wind service contracts for 1.75GW of GE Turbines for Berkshire Hathaway[5]. This is of particular significance given the purchasing power of Berkshire Hathaway and shows that even those with the deepest pockets are assessing cost as a major factor in wind farm O&M. Vestas has made further inroads into this sector with the €88 million acquisition of German turbine servicing firm Availon in early 2016.[6] Gamesa's €2.6 million acquisition of B9 Energy in 2015 has now enabled it to bid on rival turbines in the UK and Ireland[7]. Utilities have been doing this for years; Duke Energy acquired Outland Energy Services in 2005 in order to both service its existing fleet and win in excess of 300MW of tenders for non-owned assets[8] . In 2016 Duke Energy joined forces with Siemens to combine service divisions.[9] Many familiar names in wind equipment manufacturing are trying to capture pieces of the O&M market. Among them are Enercon, Gamesa, GE Wind, Goldwind, Nordex, Siemens, Suzlon Group, United Power and Vestas.[10]

Benchmarking & The O&M Contracting Environment

Operators often work in a non-symmetrical environment as during the O&M contract negotiation phase OEMs do not always share historical operating data for assets. This means the negotiation of Energy Yield or Availability Guarantees is loaded in favour of the OEM who has more data at hand to inform contract negotiations than the asset owner. End of Warranty inspections and reviews can provide an engineering context as to the relative reliability issues within a wind farm, but this can be further enhanced by using peer data to understand typical reliability trends at a technology level to set out an initial benchmark and negotiating position.

Participation in a benchmarking programme is critical to enable access to reliability and performance data, knowledge sharing of best practices and the implementation of standards across wind. This was initially demonstrated by the SPARTA offshore programme launched in 2015, which includes all 10 of the UK's offshore wind farm Owner Operators.[11] This is already increasing investor confidence in the wind sector by reducing the levelized cost of energy.

In this paper historical reliability data is used in order to understand expected changes in turbine reliability

1 http://www.gcube-insurance.com/en/news_en/the-end-of-warranty-and-the-wind-maintenance-market/
2 http://analysis.windenergyupdate.com/operations-maintenance/post-warranty-om-how-balance-cost-quality-and-control-services
3 http://www.windpowermonthly.com/article/1414434/siemens-duke-form-servicing-co-op
4 GCube report
5 http://www.windpowermonthly.com/article/1395711/vestas-subsidiary-service-ge-turbines
6 http://www.windpowermonthly.com/article/1380256/vestas-acquires-service-provider
7 http://www.gamesacorp.com/recursos/doc/accionistas-inversores/gobierno-corporativo/junta-general-accionistas/documentacion-2016-ingles/consolidated-annual-accounts-2015.pdf
8 http://www.renewableenergyworld.com/articles/print/volume-17/issue-5/wind-power/the-big-and-booming-business-of-keeping-wind-turbines-spinning.html
9 http://www.windpowermonthly.com/article/1414434/siemens-duke-form-servicing-co-op
10 http://www.renewableenergyworld.com/articles/print/volume-17/issue-5/wind-power/the-big-and-booming-business-of-keeping-wind-turbines-spinning.html
11 https://www.thecrownestate.co.uk/news-and-media/news/2015/pioneering-sparta-system-for-offshore-wind-farms-goes-live/

at the end of warranty period, to identify which turbines are expected to exhibit similar characteristics from year 6 through to year 10 of operation. The data is grouped by technology type and nameplate capacity. The failure data used in this study is provided by Wind Energy Benchmarking Services (WEBS), a secure web-based benchmarking service for onshore wind farms across several Key Performance Indicators (KPIs) associated with wind farm availability, performance, reliability and costs. The data has been obtained from a variety of sources including insurance underwriters and academic research.

Turbine Technology Overview

This paper examines 4 key turbine technologies observed over the last 20 years: Danish Concept, Variable Resistance, DFIM and Direct Drive (see table 1).

Table 1: Characteristic of key turbine technologies

Generic Name	Power Control	Speed	Generator Type	Grid Connection	Gearbox
Danish Concept	Stall or Pitch	Fixed	SCIG	Direct	Spur
Variable Resistance	Active Stall or Pitch	Twin	OSIG	Direct	Spur / Planetary
DFIM	Pitch	Variable	DFIG	Partial Converter	Planetary
Direct Drive	Pitch	Variable	Electro Magnet	Full Converter	None

Danish Concept

Early US-developed turbines were single speed, high RPM machines that were typically erected on concrete towers, but there were disadvantages to this type of design. Many early U.S. wind turbines operated at high rotor speeds. These machines were noisy and trouble-prone.

Denmark was the European pioneer of Wind power. The first grid-connected wind-turbine in Denmark in the seventies was erected in 1975 by Christian Riisager[12]. The other early key adopter in Europe was Germany who has invested more than 3.5 billion Euros in renewable energy R&D since 1990; its overall approach to renewable energy has evolved to place greater emphasis on technology deployment activities[13]. Early European turbines were sophisticated and pitch regulation as the primary method of power control.

Danish designs such as the Vestas V27 (now collectively known as Danish Concept) operating at more modest rotor speeds were more reliable[14]. One and two bladed designs were popular in the early days as they made turbines lighter and kept cost down, as well as being advantageous with regards to noise and sound considerations. The acoustic impact of three bladed turbines is lower than that of two bladed, which have to be operated at a higher tip speed ratio to get the maximum power coefficient. The optical impression of three blades is also more favourable as their rotation appears less irregular because of their circular design[15].

Variable Resistance

Variable Resistance machines, such as the Vestas V82, used a pole switchable generator using active stall control, without a power converter. These were introduced across a variety of different models. These machines were normally capable of running at twin fixed speeds, rather than across a continuous range. These turbines take their name from the variable resistance rotor, rather than the generator type.

The superior grid fault ride through capabilities (due to the presence of the power converter) was a critical factor in the adoption of DFIM over the variable resistance concept. By 2001 Doubly Fed Induction Machine (DFIM) turbines were being installed at a significantly higher rate than Variable Resistance turbines.

12 http://www.windsofchange.dk/WOC-75-77.php
13 http://www.globalchange.umd.edu/energytrends/germany/2/
14 Gipe, P. (1995) Wind Energy Comes of Age. Wiley and Sons.
15 http://proceedings.ewea.org/annual2012/allfiles2/1554_EWEA2012presentation.pdf

DFIM

DFIM turbines, as first introduced in 1996 with the Tacke TW1.5s, utilised full pitch control and a variable speed generator utilising a partial power converter. These turbines featured variable speed motors and were able to better ride-through low voltage grid faults, a common issue with single or twin speed turbines. A crowbar protection system is used to make wind turbines more resistant to voltage dips and increase their ability to ride-through grid faults[16]. This would become the dominant design for the next 10 years and is still prevalent today. DFIM turbines were also more efficient than their fixed or twin speed predecessors, being approximately 2-3% more efficient.

Direct Drive

A high speed generator requires the use of a gearbox to step up the rotor rpm from low speed to high speed. However, a low speed generator does not require a gearbox and experts argue that use of a low speed generator in a direct drive turbine can reduce the overall mass of the drive train to that of a gearbox-plus-generator in a conventional wind turbine of equivalent size. Direct Drive turbines are also attractive for low wind speed sites. Electro Magnet or Permanent Magnet Generators (PMG) have been used since 1992, with many early designs from the German OEM Enercon, such as the Enercon E33. It has been demonstrated that a Direct Drive design can provide an overall increase in efficiency since it produces more power at part load operation than achieved by a conventional generator, which reaches peak efficiency at full load[17]. There are drawbacks to using such technology; notably the cost of extracting rare-earth metal. Though attractive for its high magnetic flux, material such as neodymium is expensive to extract due to the required energy intensive processing, and its supply is concentrated mainly in China[18]. As a result alternative solutions are being developed by turbine and generator manufacturers. Fuelled by high rare earth prices and market volatility, turbine drive systems comprising a two-stage gearbox and medium-speed PMG are becoming more prevalent for both onshore and offshore wind[19]. Data for hybrid turbines was not available for this study.

16 Abdelaziz, A., Y., Ibrahim, A., M., Asim, A., M., and Razek, A., H., A., A. (2013) DYNAMIC BEHAVIOUR OF DFIG-BASED WIND TURBINES DURING SYMMETRICAL VOLTAGE DIPS. Electrical and Electronics Engineering: An International Journal (ELELIJ) Vol 2, No 2, May 2013

17 http://www.windpowermonthly.com/article/962701/getting-gear-magnets

18 http://www.renewableenergyfocus.com/view/29640/how-to-get-the-best-offshore-wind-turbine-reliability

19 http://www.windpowermonthly.com/article/1148239/abb-shifts-focus-medium-speed-drive-systems

Data

Table 2: Data fills for turbine nameplate capacity vs technology

Nameplate Capacity	Danish Concept	Variable Resistance	DFIM	Direct Drive
≥1MW	0	791	387	260
<1MW	2993	2646	177	689

When the number of operational years of data according to technology and nameplate capacity are analysed, some gaps within the data are apparent. There is no data available for Danish Concept turbines ≥1MW as this technology was superseded by Variable Resistance and DFIM turbines as the nameplate capacities of turbines exceeded the 1MW mark. The data fills required to analyse both <1MW and ≥1MW turbines for Variable Resistance turbines are available, however for Direct Drive turbines, data is available out to ten years for <1MW turbines only.

Table 3: turbine fills for year of operation vs technology

Year of Operation	Danish Concept	Variable Resistance	DFIM	Direct Drive
1 to 5	1081	1341	290	450
6	199	279	69	60
7	259	262	64	60
8	259	243	62	60
9	220	231	41	40
10	158	242	21	60

While data is available for Direct Drive turbines ≥1MW, this data does not stretch to Year 10 of operation so this group has been omitted from the analysis. All Direct Drive data is for electro magnet type machines only. There is not enough data on operational permanent magnet machines out to Year 10 yet to complete the analysis at this time.

Results

Figure 1: MTTF of all technologies

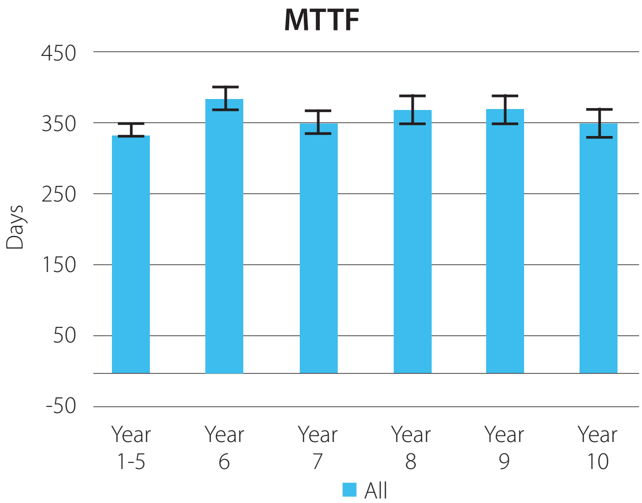
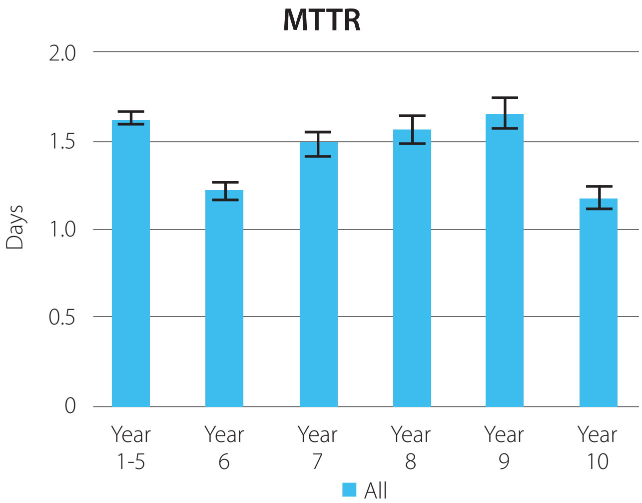


Figure 2: MTTR of all technologies



Figures 1 and 2 show the mean time to failure and the mean time to repair respectively for all technology types. Initial analysis of all turbine technologies provides a baseline trend for all turbine technologies. An initial improvement is observed in reliability post warranty with the MTTF lengthening and MTTR shortening in year 6, indicating less frequent and less complex failures. However, while the MTTF remains relatively stable in subsequent years, the MTTR increases each year through years 7, 8 and 9 which suggests the occurrence of increasingly complex failures that take longer on average to repair. This is followed by a dramatic decrease in MTTR in year 10, which suggests that the majority of more complex failures have been addressed by the end of year 9.

Danish Concept Turbine Reliability

Figure 3: MTTF of <1MW Danish Concept turbines

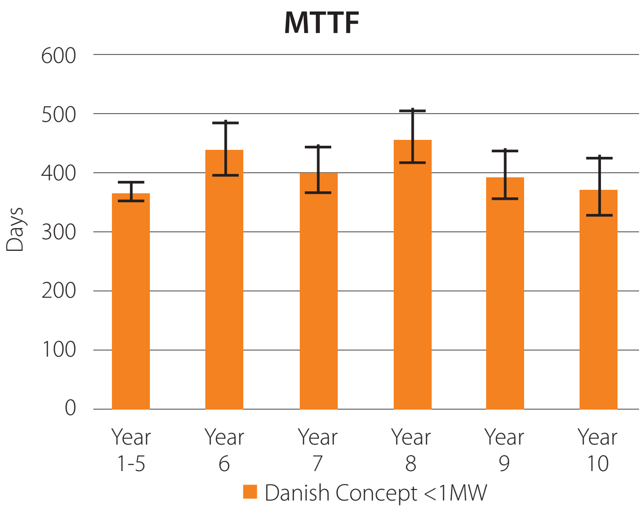
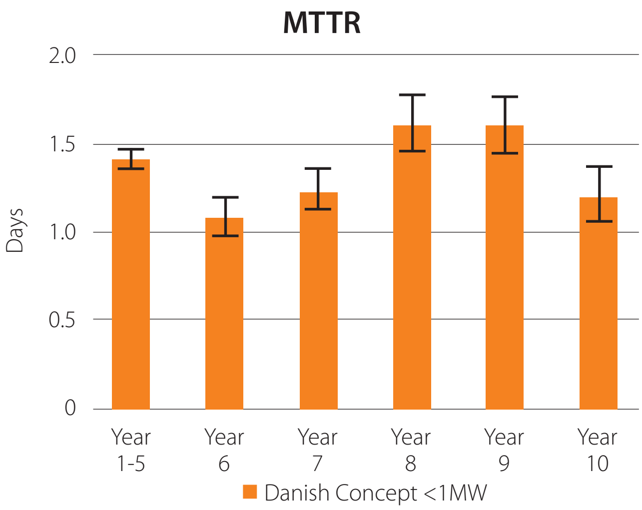


Figure 4: MTTR of <1MW Danish Concept turbines



The data for the <1MW Danish Concept machines in figures 3 and 4 shows that the MTTF increases in the post-warranty period, which indicates that the majority of issues are covered within the warranty period. In year 6 the MTTF increases and MTTR decreases, indicating both fewer and less severe failures. However for subsequent years 7 and 8, MTTR lengthens which indicates that more severe and time consuming repairs are being carried out. We also see that the variance associated with both MTTF and MTTR is tightly bound, indicating consistency across the fleet, which is to be expected when examining a mature turbine technology.

Variable Resistance Turbine Reliability

Figure 5: MTTF of <1MW Variable Resistance turbines

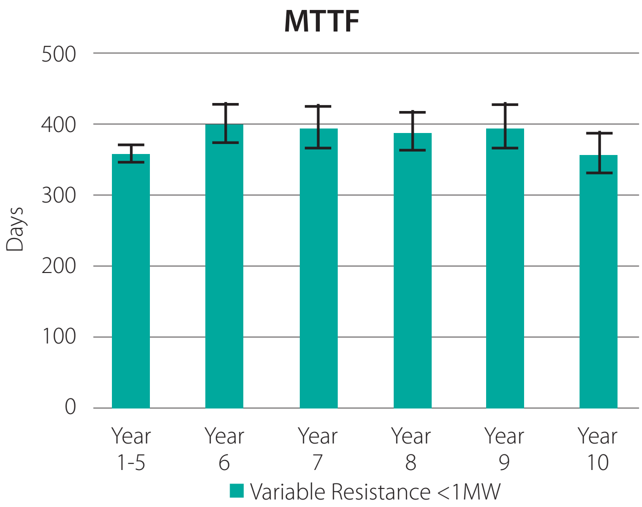
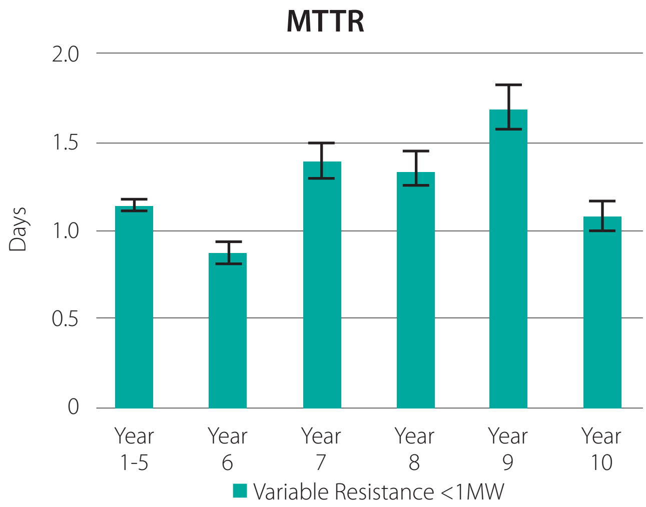


Figure 6: MTTR of <1MW Variable Resistance turbines



The <1MW Variable Resistance turbines exhibit different characteristics from the Danish Concept turbines of similar nameplate capacity. As shown in figures 5 and 6 we see a slight lengthening of MTTF post-warranty period, which indicates that reliability has improved, however there is a much greater variance in the MTTR. After an initial drop in MTTR in Year 6, there is an increase in MTTR of up to 50% in years 7 to 9, an indication that more complex repairs are being carried out in those years, before MTTR returns to in-warranty levels in Year 10. Again we see relatively low variance associated with these estimates, indicating consistency across the fleet.

Figure 7: MTTF of ≥1MW Variable Resistance turbines

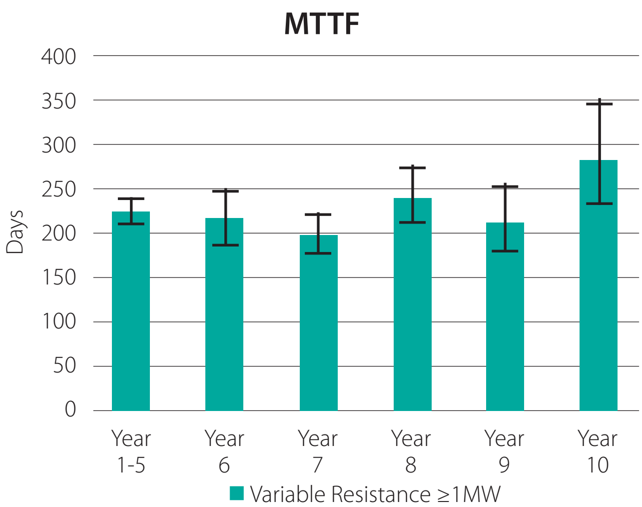
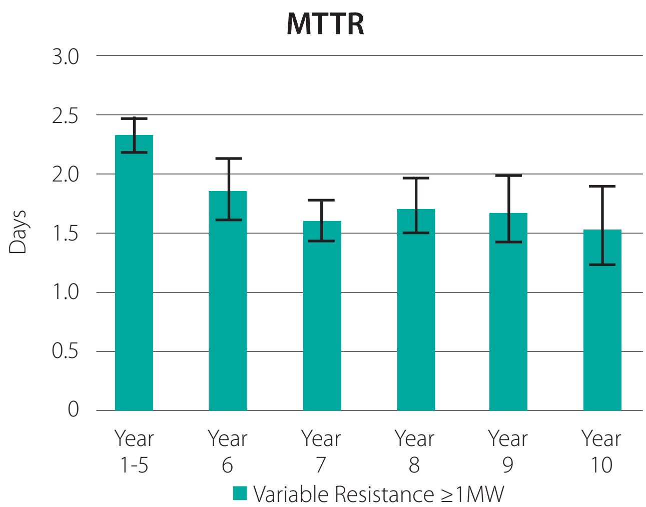


Figure 8: MTTR of ≥1MW Variable Resistance turbines



The trends observed for the <1MW Variable Resistance turbines do not continue when we observe the data for ≥1MW turbines shown in figures 7 and 8. For these turbines two significant trends are observed. While MTTF shows some variance post-warranty period, there is a broad trend of increasing MTTF over this period. This indicates improvements in reliability as the turbines continue operation. This is complemented by a decrease in the MTTR over the same period. So not only are turbines failing less frequently on average, but they are also taking less time to repair, indicating less severe forced outages. This could be attributed to improvements in the R&D and manufacturing process as turbine OEMs grow more comfortable with the Variable Resistance technology and begin to identify potential improvements.

DFIM Turbine Reliability

Figure 9: MTTF of <1MW DFIM turbines

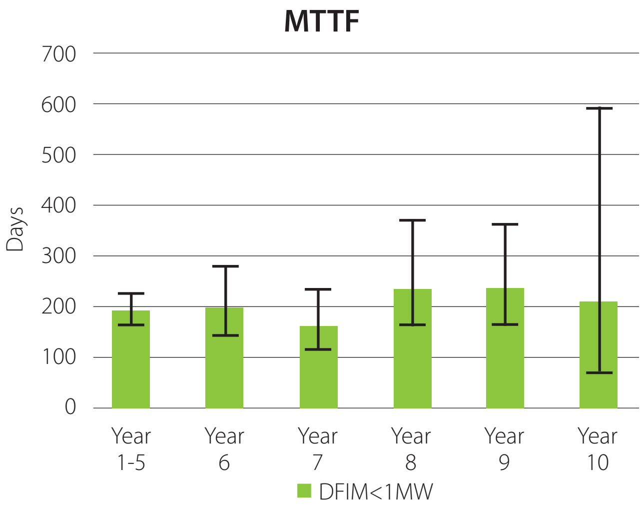
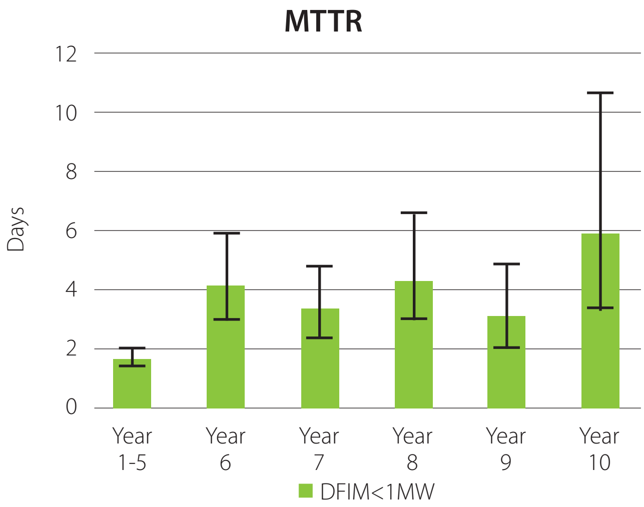


Figure 10: MTTR of <1MW DFIM turbines



In examining the data for <1MW DFIM turbines, an altogether different trend is observed compared to Danish Concept and Variable Resistance turbines. DFIM <1MW turbines have a broadly static MTTF across the first 10 years of operation as shown in figures 9 and 10. However within the data there is a wide range of values, which suggest greater variance in the observed MTTF from turbine to turbine or project to project. The most striking trend with these turbines is the increase in MTTR both at the end of the warranty period and over the following 5 years. By year 10 each repair is taking on average three times as long as during warranty, indicating an increasing severity of failures which may lead to complete component replacement rather than repair.

Figure 11: MTTF of ≥1MW DFIM turbines

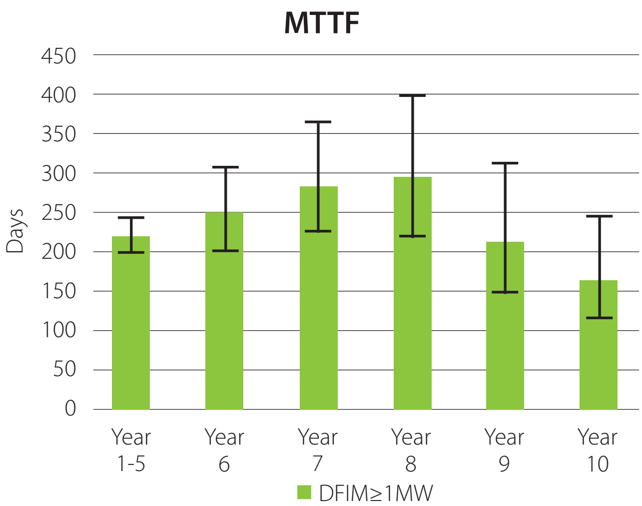
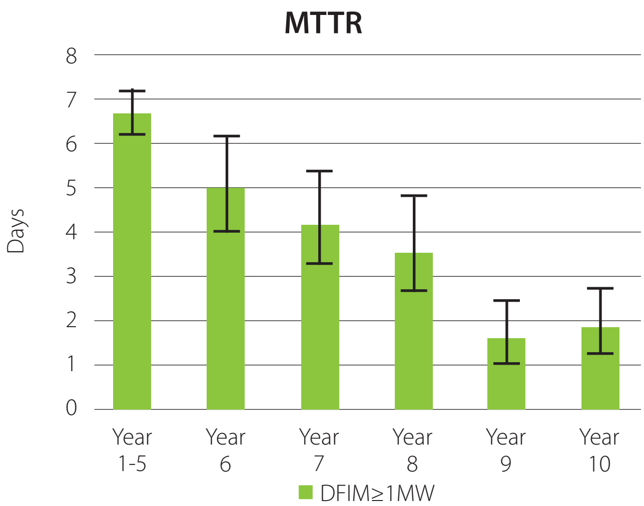


Figure 12: MTTR of ≥1MW DFIM turbines



The trend of increasing MTTR observed for the <1MW DFIM turbines, is reversed for the ≥1MW variants. Figure 12 shows MTTR steadily decreases following the end of warranty, which indicates that the most severe issues impacting these turbines are typically ironed out by the time they reach the tenth year of operations. We also see more uniform variance of the MTTR compared to a wide variance on the <1MW turbines, which indicates that the reliability of these units is less variable. The MTTF shows an improvement post warranty until year 8, but then starts to considerably worsen in years 9 and 10. This, coupled with a decrease in MTTR, indicates that these turbines start to suffer from multiple minor faults in years 9 and 10 of operations.

Direct Drive Turbine Reliability

Figure 13: MTTF of <1MW Direct Drive turbines

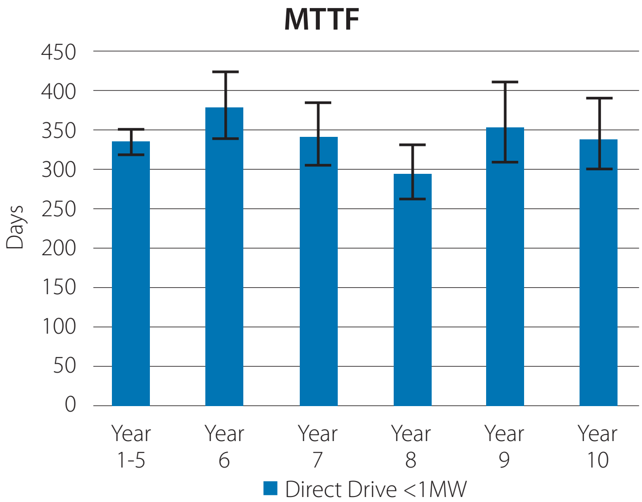
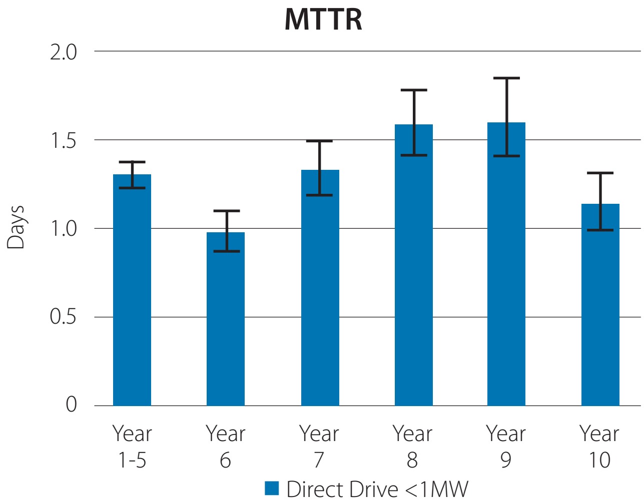


Figure 14: MTTR of <1MW Direct Drive turbines



Direct Drive machines were hailed as revolution when they were first introduced as they were designed to eradicate what many experts saw as the Achilles heel of wind turbines, the gearbox. However, direct drive turbines still exhibit similar characteristics to Danish Concept and Variable Resistance machines of similar size, typically suffering roughly 1 failure per turbine per year. As with the Variable Resistance machines, after an initial drop in MTTR in Year 6, we then observe an increase in MTTR of up to 50% which indicates more complex repairs in Years 7 to 9 before reverting to in-warranty levels in Year 10, (see figures 13 and 14). The variance of the MTTR is greater than for Variable Resistance turbines which demonstrates that there is less consistency across the fleet.

Turbine Type Reliability Comparison

Figure 15: MTTF comparison of all <1MW turbine technologies

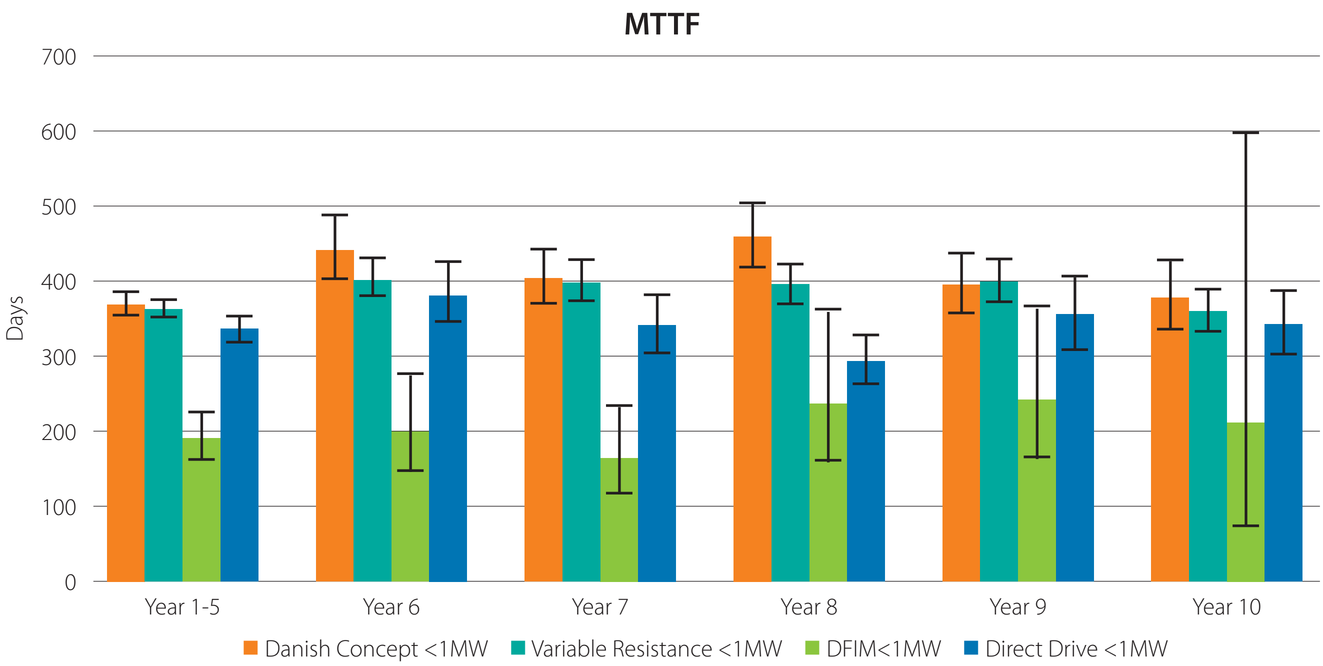
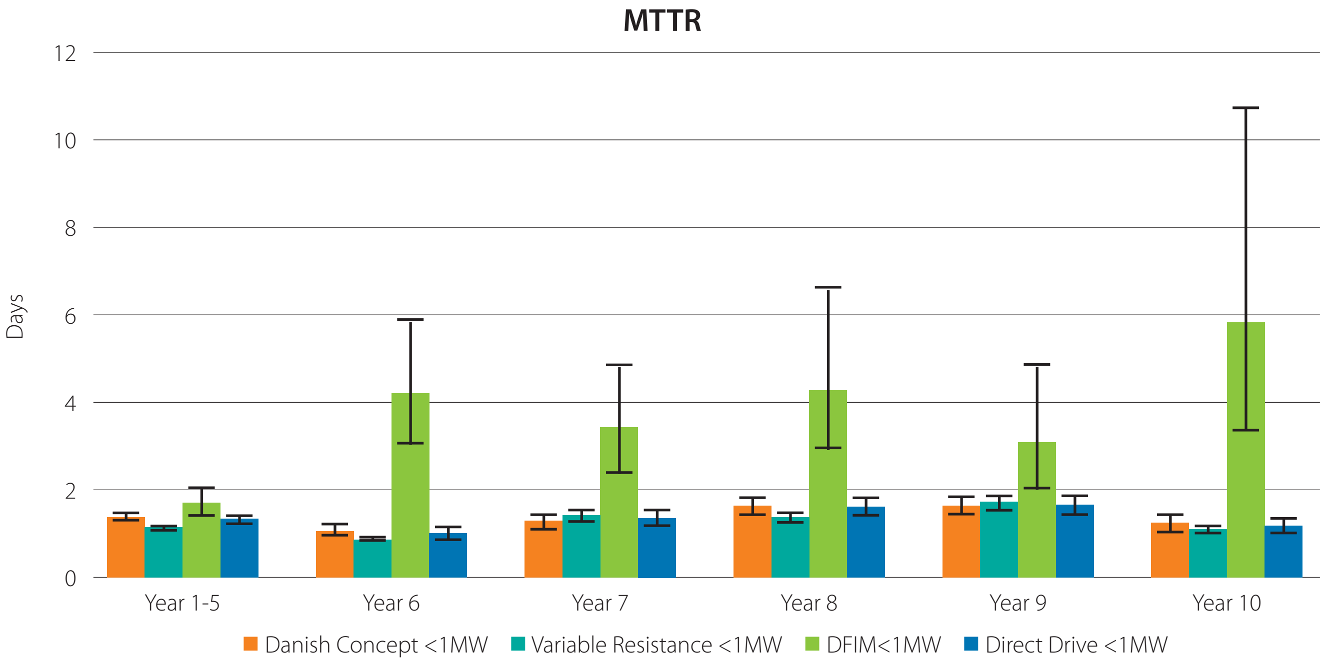


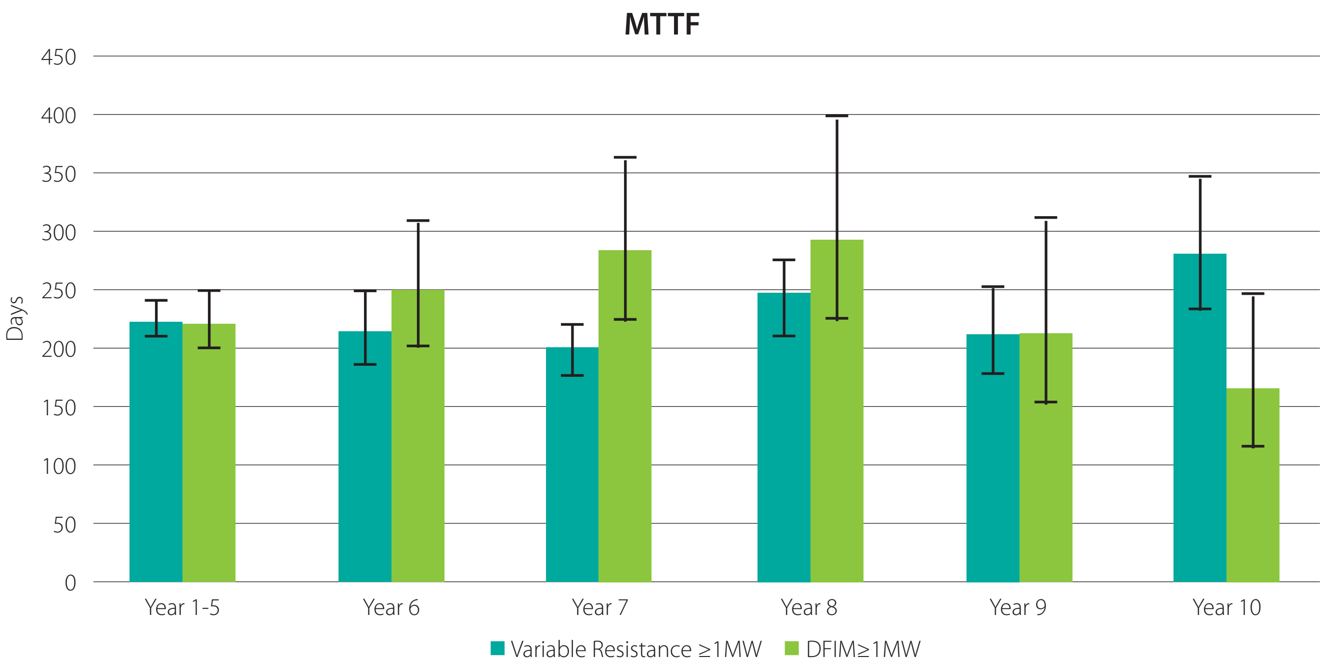
Figure 15 compares the different <1MW turbine technologies side by side. The MTTF of the Direct Drive machines is consistently lower than the Danish Concept and Variable Resistance machines of the same size, which conversely means they are failing more frequently. This runs counter to the argument that these machines should be more reliable due to the lack of a gearbox. The worst performing technology in terms of MTTF are DFIM turbines, typically experiencing an MTTF of around half of the best performing technology year on year.

Figure 16: MTTR comparison of all <1MW turbine technologies



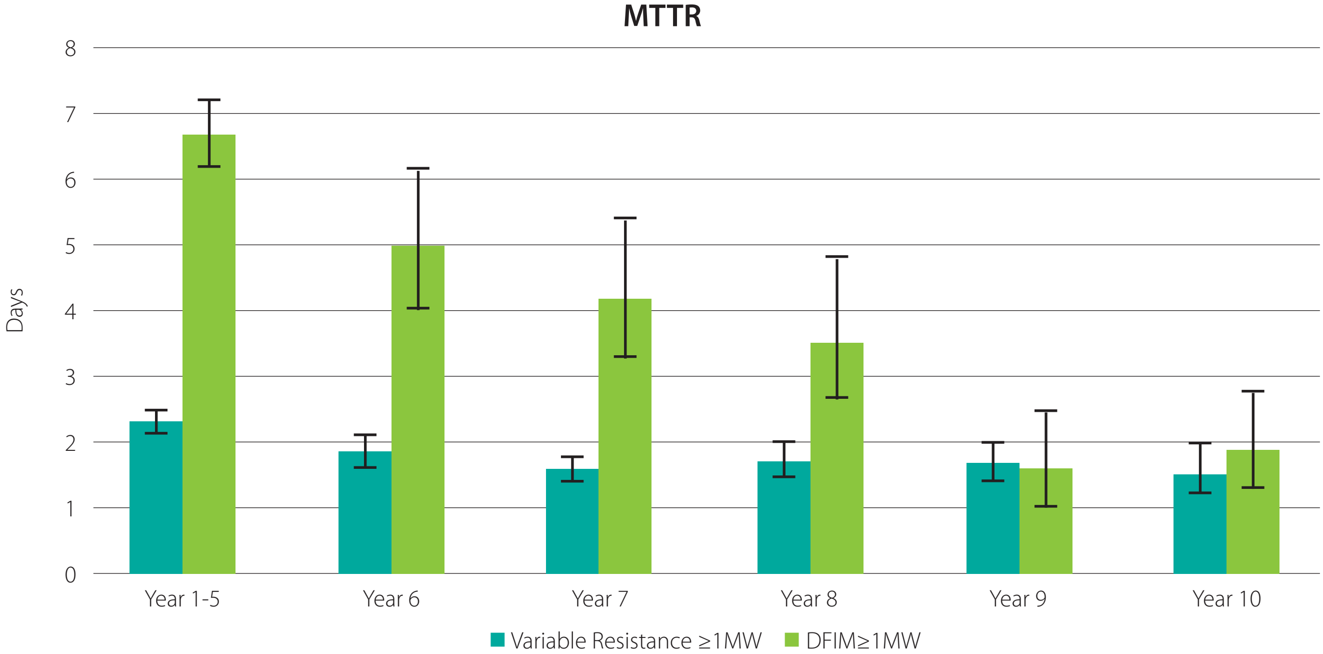
The DFIM reliability trend is sustained when we compare the MTTR of the turbines side by side, as shown in figure 16. Not only are the DFIM turbines experiencing much lower MTTF's than other technologies, but, post-warranty period, the MTTR the shows a dramatic increase to twice as long as any other technology, rising to three times as long as the other technologies by Year 10. In comparison, operators of DFIM turbines are faced with out-of-warranty forced outages on a more frequent basis, which then take far longer to repair. This becomes a major factor in unavailability due to forced outages and could result in DFIM turbines showing lower availability than other technologies before other factors such as weather stoppages or grid unavailability is taken into account.

Figure 17: MTTF comparison of all ≥1MW turbine technologies



When comparing the MTTF of ≥1MW turbines, we only have two technologies available for comparison. No clear trends on MTTF emerge when comparing the two technologies, however the MTTF for Variable Resistance turbines has a lower range every year than the DFIM turbines. This indicates more predictability to the failures of Variable Resistance turbines which aids O&M planning and inventory management in comparison with the less predictable DFIM turbines. Year 10 is an exception as the range of the estimates for failures on Variable Resistance turbines increases significantly in this year, (see figure 17).

Figure 18: MTTR comparison of all ≥1MW turbine technologies



When comparing the MTTR of the same two technologies for larger >1MW turbines, a much clearer trend is observed. Figure 18 shows that Variable Resistance turbines have a significantly lower MTTR than >1MW DFIM turbines. Variable Resistance turbines also demonstrate relatively consistent MTTR's with low variance associated with estimates, while DFIM turbines again show a higher variance adding to the argument that these turbines suffer from less predictable failure trends. Both turbine technologies demonstrate a significant reduction of MTTR over the first 10 years of operation. While this occurs for the DFIM turbines on a larger scale, the Variable Resistance turbines also display this trend, which is a good thing for project owner operators and asset managers as this means less severe, and less costly, repairs as the turbine technology matures.

Conclusions

Our analysis has found DFIM <1MW turbines have the longest repair times post warranty. Without strong benchmarking capabilities, insights like this are harder to detect and asset managers will miss out on the benefits of greater reliability and targeted maintenance planning, which benchmarking can offer.

Each turbine technology type and nameplate capacity grouping demonstrates a wide variety of different trends post-warranty. Some turbines, most notably the ≥1MW Variable Resistance turbines, appear to be continuously improving in the first five years post-warranty. Other turbines, such as the <1MW DFIM technology, appear to be steadily declining, particularly with respect to MTTR. Turbines such as the <1MW Danish Concept and <1MW Variable Resistance machines, show an initial improvement before then reversing and reverting to in-warranty levels by Year 10 of operations. The results show that attempting to predict turbine performance based on an assumed constant MTTF or MTTR is likely to lead to severe errors in O&M strategy and asset management. These errors, particularly regarding the effective deployment of labour and spares inventory management, have the potential to compound into increased expenditure in fixing and maintaining turbines unless identified and corrected early.

Each technology evaluated here clearly exhibits differing reliability trends. So how can we manage this problem? Our research finds evidence that benchmarking is the answer. Unless operators are willing to share data, knowledge and best practices, then each project will essentially exist in an information vacuum. Operators of larger fleets, such as utilities, have the benefit of being able to conduct internal benchmarking to better understand turbine reliability. However, even for these operators the ability to learn from industry peers and the opportunities for improvement this brings cannot be ignored. The Oil & Gas industry have been using the OREDA platform to perform benchmarking for years. Likewise, the Gas Turbine industry has been benchmarking itself for a long time using the SPS ORAP platform. Unless the Wind Industry seizes the opportunities to change, they will struggle to reach the same point of market maturity as Oil and Gas or the Gas Turbine industries.

In a time of decreasing subsidies and record low auction prices for onshore wind, can the Wind Industry afford to operate with such uncertainty around asset reliability? Over the next five years, time, as ever, will tell.

Appendix: Methodology

The failure data used in this research is provided by Wind Energy Benchmarking Services (WEBS). WEBS is a secure web-based benchmarking service for onshore wind farms across several Key Performance Indicators (KPIs) associated with wind farm availability, performance, reliability & costs. The data has been obtained from a variety of sources, including insurance underwriters and academic research.

To carry out the statistical analysis several underlying assumptions were made:

1. All data entries that appear as extreme outliers are data-errors and should be omitted from the analysis. All data is reviewed for censoring, truncation, duplication, misspellings, inconsistent formatting and statistical bias prior to analysis.
2. Outage duration is independent of time to failure.
3. Components fail independently of each other so components can be modelled individually.

Distributional assumptions were then made, firstly that the failures follow a Poisson process where h_{FR}(age) is the failure rate:

$$\text{noEvents}=Y\sim\text{Poisson}(h_{FR}\,(\text{age}))$$

$$h_{FR}\,(\text{age})=\lambda_{FR}\,\exp(\beta_{age})$$

Where age denotes the age group, giving possible values of β_{age} as $\beta_{1\text{-}5}$, β_6, β_7, β_8, β_9, β_{10}. We use $\beta_{1\text{-}5}$ as the reference group, and we assume a relationship over the age years by using a normal random walk:

$$\beta_{1\text{-}5}=0$$

$$\beta_6 \sim Normal(0,\tau^{-1})$$

$$\beta_i \sim Normal(\beta_{i-1},\tau^{-1}) \;\; \forall i>5$$

Where τ is a nuisance parameter. The model also assumes that an outage duration X for a single event has an exponential distribution, with a hazard rate similar to that of the time-to-failure:

$$X\sim\exp(\,h_{OD}\,(\text{age}))$$

$$h_{OD}\,(age)=\lambda_{OD}\,\exp(\alpha_{age}\,)$$

We also use a normal random walk for the age profile:

$$\alpha_{1\text{-}5}=0$$

$$\alpha_6 \sim Normal(0,\tau^{-1})$$

$$\alpha_i \sim Normal(\alpha_{i-1},\tau^{-1}) \;\; \forall i>5$$

With the same τ as that of the time-to-failure, which can be interpreted as a "global smoothing parameter" for the age profile.

When the durations are summed then the distribution of observed total outage duration Z is given by:

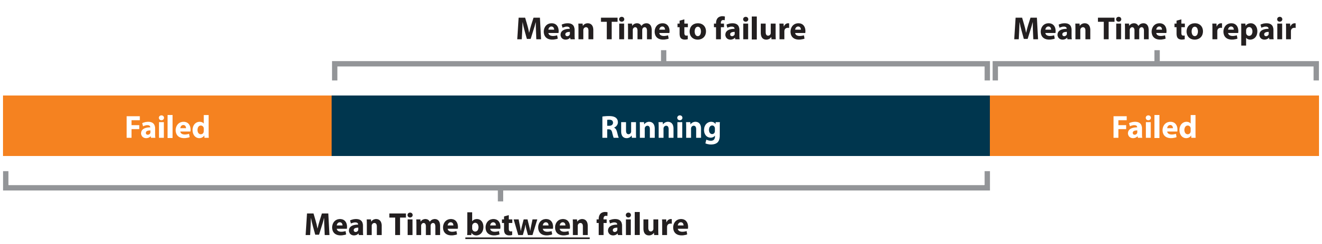
$$\text{duration} = Z = \sum_{j=1}^{Y} X_j \sim\text{Gamma}(Y, h_{OD}\,(age))$$

The parameters that require estimation are λ_{fr} and λ_{od} and all of the and parameters. The model's probabilistic assumptions are first defined, thus a likelihood can be constructed and used to estimate the required parameters. The parameters are estimated using a Bayesian approach utilising Markov Chain Monte Carlo (MCMC) simulation.

A Bayesian approach requires a prior distribution for the parameters λ_{fr} and λ_{od} that require estimation. These are derived from expert beliefs and other published work within academia. Lognormal prior distributions are used they are of a suitably appropriate shape and allow for intuitive translation between expert beliefs and the distributions parameters.

MCMC is a numerical method to explore the parameter space and derive a posterior distribution. The MCMC algorithm takes in all observations (observed failure data) and samples each data point, using each data point to influence and converge to a stable solution for the posterior distribution.

Figure 19: Relationship between MTTF, MTTR and MTBF



There are two key reliability metrics that are calculated as part of the analysis. The Mean Time to Failure (MTTF) illustrates the average running time of a turbine from the point at which it is generating electricity to the point at which a forced outage results in the turbine being taken offline. The Mean Time to Repair (MTTR) is then used to show the average amount of downtime per failure. Mean Time Between Failure (MTBF) is used in some areas to measure reliability; this can be approximated as the sum of MTTF and MTTR. In this paper we do not address MTBF.

We have separated the peer groups of turbines according to turbine technology and generating capacity, less than 1MW and greater than or equal to 1MW. For each peer group, we analyse MTTF and MTTR in the same way. Using the samples from the posterior distribution produced by the MCMC, we then take a median estimate of the MTTF and MTTR respectively. A 95% confidence interval (or uncertainty of our estimate) is also calculated by using the 2.5% and 97.5% percentiles to generate the positive and negative error around the median. This is used to illustrate the uncertainty of the estimate and also the spread of the underlying data used for each peer group.

Appendix: List of Abbreviations

Table 4: List of Abbreviations

Abbreviation	Description
DFIM	Doubly Fed Induction Machine
ISP	Independent Service Provider
KPI	Key Performance Indicator
LCOE	Levelized Cost of Energy
M&A	Mergers and Acquisitions
MCMC	Markov Chain Monte Carlo
MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MW	Megawatt
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
ORAP	Operational Reliability Analysis Program
OREDA	Offshore and Onshore Reliability Data
OSIG	OptiSlip Induction Generator
PMG	Permanent Magnet Generator
R&D	Research and Development
RPM	Revolutions per Minute
SCIG	Squirrel Cage Induction Generator
SPARTA	System Performance, Availability and Reliability Trend Analysis
SPS	Strategic Power Systems Inc.
US or USA	United States [of America]
WEBS	Wind Energy Benchmarking Services Ltd.