Reliability of Wind Turbine Technology Through Time

This study attempts to obtain more detailed knowledge of failures of wind turbines (WTs) by using the German “250 MW Wind” test program database. Specific objectives are to show the reliability of some major components and to analyze how their design has advanced through time, what the main failures are, and which technologies have proven to work. Within the program, reports on operation and maintenance are analyzed with respect to WT type, size, and technologies used. This paper presents a comparison of component reliability through time, with respect to their technology. The results show significant differences in reliability for certain subcomponents depending on the size of the WT and especially on the type of power control. For instance, induction generators show half the annual failure rate compared to synchronous generators. The study also includes failures of other components that are affected or added due to the use of the components being analyzed. In general, the results show that failure rates of WTs decrease with time. Most of the data show a short period of “early failures” and later a long period of “random failures.” However, this is not the case for the megawatt class: As technology is introduced into the market, WTs show a longer early failure behavior, which has not yet become stable. Furthermore, large turbines, included in the database analyzed, show a significantly higher annual failure rate of components, per WT. This may be due to the immature technology of the WTs included in the database.

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1 Introduction

Design of wind turbines (WTs) has evolved through time, with the aim of becoming less expensive and producing energy more efficiently. Design changes take place at all technological levels. WT manufacturers have tried a broad variety of possibilities. They have investigated different design topologies, such as vertical or horizontal axis of rotation and upwind or downwind placement of the rotor, and also considered the use of different control strategies or changes in smaller components such as brakes and blade tips.

This evolution of technology for different components is due not only to the experience of what has proven or not proven to work but also to the growth of the wind energy industry. Fossil fuels are becoming less popular, giving opportunities for renewable energies to develop, and consequently WTs are becoming more commercial, producing energy at competitive prices. For the past 15 years, WTs have grown in size and in rated power, and this has been reflected in their design. However, the current development slows down as WTs reach rated powers of 3 MW, 5 MW, and more.

Manufacturers attempting to make WTs more commercial and less expensive have looked into other fields where technology is proven and where, in many cases, components can be obtained off the shelf. However, in some cases, results show lower reliability than expected, mainly because operational conditions for WTs are not known with enough detail. Unsteady operational conditions differ greatly from conditions in other industries. For instance, gearboxes show high failure rates in spite of their commerciality.

The design of the WT seems simple at first sight. The basic structure rarely changes, although there are still different alternatives from the technology point of view. For instance, there are vertical or horizontal axis designs; upwind or downwind rotor placement; 1, 2, 3, or even more blades; stall, active stall, or pitch regulation systems; constant or variable speed operation; synchronous, induction, doubly fed induction generators, direct-drive train; aerodynamic brakes, etc. Some of these concepts have remained, some others have disappeared, or they are just rarely used nowadays.

Despite all these possibilities, the industry has coalesced to a few topologies: WTs are usually horizontal axis, three bladed machines and nowadays they are pitch controlled. Mostly, they are equipped with doubly fed induction generators, and gearboxes convert the rotational speed of the rotor to the speed of the generator. As a second trend, direct driven types are equipped with multipole synchronous generators, which rotate at the same speed as the rotor, in which case a gearbox is not needed. Typically, both concepts use two independent braking systems providing safe operation, where at least one is often an aerodynamic brake. In general, technology has escalated in size with relatively few innovative breakthroughs.

As the role of wind energy within the public energy supply is now becoming more important, it also becomes more important for operation and maintenance (O&M) to determine reliability of WTs as systems and failure rates of single components through time in order to identify the best designs or configurations.

As of today, data have been analyzed regarding the wind turbine as a complete system, without distinguishing between different component technologies, throughout their operational age. There are historical data on the development of components [1,2], which mention some of the WT topologies included in the database. However, this analysis does not consider reliability, especially through time.

There are not many sources of information to study reliability of WT technology through time. Only few databases exist with failure information such as the WMEP [3] and LWK [4] in Germany, one in Denmark published by Windstats Newsletter [5], and according to Ref. [6], one in Finland published by the VTT, and one in Sweden published by Elforsk.


These data have been used often to study reliability of WTs. Still, there are many different aspects to consider other than failure rates. For instance, downtime caused by failures [6,7], effect of icing [8], and wind speed effects [9] on reliability. Other researchers have used these data to analyze reliability of WTs and their components; nevertheless, there is very little literature in reliability of components throughout their years of operation [7,10–13].

Few publications attempted to compare the data provided in all these databases [6,7,11,13]. However, they all face the same challenge of comparing different topologies, placed in different sites, and with information collected in different ways. The results are usually failure rates in general, and when provided per component. They look at their reliability without comparing different types of technologies used [13]. In other cases, they present failure rates of the whole WT, per year of operation [6,9,11,13]. Some of these studies provide life curve analysis of WTs [11].

In general, literature is consistent in their conclusions about the lack of availability of data and the diversity of methods for data collection. Additionally, similar remarks on development of technology have come up in literature, such as the effect of introducing new models in the market increasing mean failure rates in these databases [6,13]. In particular, references such as Ref. [12] show reliability analysis of generators and converters, but mostly oriented to direct-drive use, and without analyzing the reliability throughout operational age.

This paper presents a further step in the reliability analysis of WTs. Sixty-three thousand maintenance reports collected through the German program “250 MW wind” have been studied, focusing on the maintenance information provided on a yearly basis. Specifically, failure rates per year of operation and per WT are presented, emphasizing trends of technology of different components.

2 Approach

The study evaluates operational information from the German 250 MW Wind test program. This program includes a Scientific Measurement and Evaluation Program (WMEP), which is comprised of data on operational experience of WTs for a period of up to 15 years.

2.1 Database German “250 MW Wind” Program. Since 1989, the German government has promoted the 250 MW Wind program in order to obtain statistically verifiable data on wind energy use in Germany. More than 1500 turbines with approximately 350 MW rated power installed were incorporated in this measure [3].

The 250 MW Wind program has benefited from the obligation of each participant to take part in the Scientific Program WMEP over a period of at least ten years. Thus, the WMEP, carried out by ISET, collects continuously data from each individual turbine. The acquisition of data is made by means of a logbook for each turbine, containing manual documentation of the operators. The operators report using customized forms and send the reports directly to ISET. These reports are collected in logbooks containing the following information:

- standard project data, e.g., technical data, location information, grid connection, etc.
- disruptions, malfunctions, repair and maintenance measures, affected components, and downtimes.
- monthly figures of energy production and consumption by regular readings of calibrated electricity meters
- O&M costs

Up until the end of 2006, operators sent in around 63,000 reports concerning maintenance or repair, approximately 89,000 quarterly reports on monthly energy yield, and around 14,000 annual reports concerning the operating costs of their plants.

2.2 Data Analysis. Reports on O&M contain information about the type of maintenance performed, affected component(s), date of occurrence, and downtime period. All information is stored in a database; thus, all the operational experience can be evaluated by filtering and combining data using individually defined criteria.

Maintenance is classified by the different types of repair, with the objective of focusing on unforeseen events and damages. Each failure event is recorded per year of operation, differentiating occurrences at each of the three periods of the operational life defined by the bathtub curve: "infant mortality" or "early" failures, "constant" or "random failures," and "wear-out" failures. The first year of operation used for this paper begins after commissioning, usually within three months.

Evaluating operational experience to gain knowledge on how reliable a machine or a facility works typically leads to figures such as mean time between failures (MTBF) and failure rates. According to the definition of these figures, the reports on O&M are systematically evaluated by dividing more recent WTs from older and smaller ones or by separating pitch-controlled WTs from stall regulated, etc.

Manufacturers improved their machines either by enlarging existing types by some percentage of rotor diameter or by changing technology and introducing a new model. Within the study, WTs of one manufacturer with more or less the same technology, just slightly differing in diameter and rated power, are put together in WT groups and evaluated accordingly. The number of WTs within these groups differs from each other, making it difficult to process the data and to interpret results.

In the following sections, a comparative analysis of the maintenance reports is shown, focusing on failures and incidents of the WTs as complete systems and on failure of major components. An incident is defined as a malfunction of the WT system, i.e., standstill, reduced power output, noise, etc., which required an unplanned maintenance activity. Also, it should be stated that with one maintenance activity, several failures may be corrected. On the other hand, failures represent any malfunction of a component that was repaired. A repair may have been performed with an unplanned maintenance activity or during a regular preventive maintenance activity.

The term “failure rate” is used throughout this paper as the “annual number of failures per WT.” “Incident rate” is used as the “annual number of incidents per WT.” Additionally, the minimum and maximum values and confidence bounds of the data used are provided in the figures only for the cases in which it is considered to add value for a better interpretation.

3 Analysis

3.1 General Development of Reliability. Usually, WTs are designed to operate for a period of 20 years. However, no final statement can be made yet concerning the actual life expectancy of modern WTs, as until now, little operational experience of such a period is available. Nevertheless, changes in reliability with increasing operational age can provide indications of the expected lifetime and the amount of maintenance required. Reliability can be expressed as failure rate. The principle of its development is well known in other technical areas. Early failures often mark the beginning of operation. This phase is generally followed by a longer period of random failures, with a statistically constant rate, until it starts increasing with operation age (wear-out failures) due to wear and damage accumulation [14,15]. The total life period and the individual phases are naturally distinct for different technical systems. For WTs, hardly any experience is available in this respect.

Figure 1 shows the annual number of component failures per WT depending on their operational age, with the corresponding confidence bound for each year data. These confidence bounds represent a range between which 95% of the failures lie [15,16]. These data correspond to all events reported for nearly 1500 WTs,
during the entire 250 MW Wind test program, and without discriminating based on size or technology. Operators were required to report for ten years. However, some operators kept providing the reports on a volunteered basis after the tenth year. This is why data are presented for 15 years. Unfortunately, the confidence bound of those past years are very wide, with which conclusions cannot be made. Nevertheless, these data are considered of great value since reliability information for periods of 15 years is rarely found in the WT industry.

The results show two different scenarios: One in which technology seems mature and shows random failures, and the other one in which high early failures occur mostly in the first year of operation. This is mainly because the types of WTs involved in the program differ not only in the size but also in the maturity of the system itself. In some cases, the WTs enrolled correspond to new models entering the market. These WTs suffered many failures during the first years of operation (early failures). Later, in Sec. 3.2, few special cases will be analyzed.

Figure 2 shows the annual rate of exchange of main components per WT. During the ten years of the program, a total of 947 parts were replaced involving 538 WTs. These 947 parts account for almost 1400 failures reported. The figure shows that blades and generators are more often exchanged than other components. This is an expected result, especially for blades for which repair methods are not easily performed on-site.

In order to better understand the reliability of the different technologies, three categories of rated power are created. The first one with WTs less than 500 kW of rated power, which includes a broad range of topologies, manufacturers, and sizes; then the second category with WTs rated between 500 kW and 1000 kW; and finally, a third generation of WTs with a rated power of 1 MW and above. As expected, there are significant data collected for older WTs (Categories 1 and 2), and not so much for the megawatt scale WTs.

Figure 3 shows the amount of incidents per WT that required an unplanned maintenance activity, depending not only on their operational age but also on their rated power. As stated above, one incident can involve one or more component failures. Figure 3 also shows that WTs usually interrupt operation unexpectedly at least once and up to five times a year, while conventional power plants usually do not stop unexpectedly.

It has to be stated that the columns represent different samples of turbines. The first years of operation are achieved by all turbines in the program, while going right in the graph, the samples get smaller. These numbers can be seen in Table 1. After the tenth year, the number of turbines reduces significantly due to the end of the program. As mentioned earlier, some owners and operators continued providing maintenance reports on a volunteer basis. Thus, the right columns are assumed to be less trustworthy.

Incident occurrences or unplanned maintenance visits of older turbines below 1 MW were especially high during the first year of operation and reduced to a somewhat lower level for the following years of operation. In contrast, the group of megawatt WTs shows significantly higher incident rates, which seem to decline slightly by increasing age and to increase again after the sixth year. However, as seen from Table 1, the samples of eight and nine year old megawatt turbines are very small. The reliability of megawatt turbines with advanced operational age will become clear only with time.

For each technical system, it can be expected that failure rates increase sometime after a longer period of lower rates driven by random failures. This behavior is expected for WTs too. Even though there are not enough data collected for the lifetime of WTs, it seems that at least for WTs under 1 MW, the wear-out failures do not start before the 11th year of operation (Fig. 3). However, it is not yet confirmed that the slight increase in the failure rate of smaller turbines is a hint on wear-out failures.

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\begin{array}{|c|c|c|c|c|}
\hline
\text{Number of turbines} & 1st year & 9th year & 11th year & 13th year \\
\hline
\text{P}^* \leq 500 \text{ kW} & 1115 & 1004 & 334 & 100 \\
\text{500 kW} \leq \text{P}^* \leq 1 \text{ MW} & 218 & 173 & 59 & — \\
1 \text{ MW} \leq \text{P}^* & 31 & 6 & — & — \\
\hline
\end{array}
\]

\( ^* \text{P} \) is the rated power.
3.2 Special Wind Turbine Models. The significantly higher incident rates of the megawatt WT demand a closer look at the component failures causing all these incidents. While most of the WT types show similar development and similar numbers of damaged components per year, some types show significant differences. It was found that for some models, high component failure rates dramatically decreased with time, while others showed a high failure rate of subcomponents randomly developing over time. This is mainly due to the immature stage of their development at the time of data collection. Nevertheless, it is interesting to see how these turbines behaved.

One example of the megawatt class is depicted in Fig. 4. It shows a high frequency of damages of different subcomponents and a very significant improvement as well. It is a type of standard topology using stall control, fixed rotor speed, gearbox, and induction generator. The development shows quite clearly poor reliability due to early failures. In this special case, the high failure rates were mainly driven by problems with the rotor, electrical, and control systems. After six years, the problems, at least with the control system, seem to be solved, but the overall failure rates remain comparably high. Nevertheless, Fig. 4 represents a small group of three individual turbines belonging to the same type.

Another example of a megawatt turbine included in the program is depicted in Fig. 5. This one stands out due to its extremely high failure rates. However, it shows randomly shaped development of reliability. This turbine is also of a standard topology.

Different components drive the failure rate. As depicted, the failures do not occur at an early stage, but rather randomly, keeping overall failure rate at high level. Also, this WT is represented by three individual turbines only.

In the end, besides high failure rates of components, no general explanation for high incident rates of turbines of the megawatt was found.

3.3 Differences Between Stall and Pitch. Pitch control is used to increase efficiency and to reduce stress for mechanical parts of the drive train. However, adding a system like pitch control also means adding possibilities for failures.

Figure 6 shows a comparison of component failure rates of stall-controlled WTs to that of pitch controlled. It indicates that pitch-controlled WTs tend to have significantly more component failures than stall-controlled ones.

Specifically, reliability of certain components of stall- and pitch-controlled turbines can deviate from each other quite significantly. Especially, the rotor system (without blades) of pitch-controlled WTs naturally tends to increase failure rates. On the other hand, gearboxes, hydraulic systems, and mechanical brakes of stall-controlled WTs tend to increase failure rates as well, but at a much lower level. Figures 7–9 show data for hydraulic systems, rotors, and mechanical brakes, respectively, for both stall-and pitch-controlled turbines.

Stall-controlled WTs normally use a hydraulic system for driving tip brakes. In some cases, the hydraulics are used for other purposes, such as yawing and mechanical braking. In some cases of pitch-controlled WTs, hydraulic systems are used as pitch drives, and also in some models with “active-stall” power control. In all cases regarding the reports in the 250 MW wind program, the hydraulic system consists of pumps, tubes, and pipes, as well as valves and cylinders.

One main difference between stall- and pitch-controlled WTs regarding their reliability may be seen in the additional subcom-
ponents such as pitch drives and blade bearings. Here, failure rates of the rotors of both technical concepts are compared without counting failures of the blades, but only regarding hub, pitch drives, bolted joints, blade bearings, and some additional accessories. It is clear that the rotor failure rate for pitch-controlled WTs exceeds that for stall-controlled by about 0.2–0.25 failures per year and turbine, which corresponds to about 85% of its value.

The additional subcomponents for pitch control seem to increase the failure rate for these WTs. On the other hand, it was found that mechanical brakes are more often repaired in stall-controlled WTs. This advantage for pitch control may be caused by the possibility to first reduce forces and torques in the rotor by pitching and only in a second step activate the mechanical brake.

Figures 6–9 depict, on one hand, the differences between stall- and pitch-controlled turbines, and on the other hand, the development of failure rates during the years of operation. While Fig. 6 shows that failure rates are particularly high in the first year of operation, this cannot be stated for subcomponents such as mechanical brakes and rotors (without blades) of pitch-controlled WTs (Figs. 8 and 9). Also, no hint can be found for an increase in annual faults with increasing age.

3.4 Generators and Full Power Converters. Most of the WTs involved in the 250 MW Wind test program use an induction generator instead of synchronous generator in their topology.

The sample of WTs in the WMEP database is smaller for synchronous generators than for induction generators, 27% versus 73%, respectively. Of the WTs using synchronous generators, 23% use direct-drive train. Furthermore, out of the WTs using induction generators, only 0.1% corresponds to a double fed induction generators (DFIGs), and so it is not considered as an additional group.

Figure 10 shows clearly higher failure rates for WTs using synchronous generators. These exceed the failure rates of WTs using induction generators by about 0.15–0.3, corresponding to about 40% of its value. The data for induction generators show an early failure stage especially for the first year, decreasing during the first and third year. Then, the data show a constant or “random” failure stage until the end of the ten year period. On the other hand, for the synchronous generators, there is an increase in faulty events after the first year. This behavior is maybe due to the fact that the direct-drive concept was being introduced into the market. For the past years, the data show a tendency to decrease, indicating the evolution of the concept as perhaps initial phase problems were solved. However, looking at the data, 31% average of the annual failure rates correspond to direct-drive WTs, and as mentioned above, they only represent a 23% of the sample size.

Figure 11 shows the same data of Fig. 10, except that Fig. 11 presents an additional differentiation for the synchronous generators. This group is divided between the use of a direct drive and the use of a gearbox. Failure rates of WTs using induction generators are still the lowest among all. As it can be seen, the WTs using gearbox and synchronous generators show a random failure for the ten year period. The data for direct drive confirm in a way the hypothesis expressed above. The unclear behavior of the WTs using synchronous generators depicted in Fig. 10 is similar to the
one of WTs using direct drive in Fig. 11.

A comparison of failure rates of generators and power electronics is shown in Figs. 12 and 13, respectively.

Figure 12 shows higher failure rates for synchronous generators, as expected based on previous figures. The failure rate of synchronous generators is about 0.22. This is considerably higher compared to a 0.06 for induction generators. Nevertheless, the amount of generator failures is not so significant compared with other components such as power electronics. This is maybe due to failures that are difficult to repair or nonrepairable, leading to higher rate of exchange of components, such as for generators, as shown in Fig. 2.

A distinction is made in Fig. 12 with respect to direct-drive generators. These show early failures per WT during the first operational year, and later random failure rates until the end of the ten year period. This implies that the direct-drive generator is not directly responsible for the general WT failure rates represented in Figs. 10 and 11. In contrast, synchronous generators in WTs with gearboxes show a steeper increase in failure rates during the first four years, decreasing randomly until the end of the ten year period. In other words, it appears that the reliability of other components is affected by the use of direct drive.

Direct drive WTs do not represent a large population in the database; therefore, for this case, large confidence bounds are found. The same applies for the synchronous generators but results in smaller confidence bounds. This does not change the fact that these data show induction generators as more reliable systems.

Figure 13 shows failure rates of power electronics, making a distinction on the type of generator used. It is clear that power electronics have significantly higher faulty events in systems using synchronous generators compared to systems using induction generators.

Power electronics used in WTs with induction generators show a technology in a “constant failure” stage. The failure rate is about 0.47. In contrast, data do not show a defined behavior for failure rates of power electronics in WTs using synchronous generators. Moreover, data show higher failure rates for this group with an annual average value of 1.03. This corresponds to more than the double of failure rates of power electronics in WTs using induction generators. Specifically, failure rates of power electronics in WTs with direct drive are the highest among all and do not show a defined behavior either.

To give a better understanding of the data analyzed, Fig. 14 presents an overview of the annual failure rates per WT during the ten year period. Maximum, minimum, and mean values, as well as confidence bounds are presented for the overall data. Same values are shown for the main cases individually, such as total failure rates for WTs using synchronous generator, induction generator, pitch system, and stall control. The confidence bounds of the data are small. The wider range is for data of WTs using synchronous generators, as expected due to the lower percentage of the sample size. The maximum and minimum values show some special cases that fall relatively far from the mean value. This can be concluded by comparing them with the tight confidence bounds found.

4 Results

Throughout the years, there have been different attempts to innovate on certain components, such as flexible hub, downwind turbine, two-bladed rotors, direct-drive train, aerodynamic brakes, pitch mechanisms, etc. Some of these have shown high failure rates or “hard” failures, for instance, a flexible hub WT, or even two-bladed machines. It is also true that some of these concepts were not tested enough or were not tested by different manufacturers, lacking the opportunity to mature the technology. This can
be seen from the evaluation of different models of mega-watt machines. However, it is shown that WTs of all power classes suffer from several unforeseen downtimes due to failures of one or few subcomponents.

Other than innovating in components or technology, what can be seen in this extensive database is that topologies of WTs are in many cases a combination of standard components. For instance, WTs can use a pitch, stall, or active-stall control, with synchronous or induction generators, or they could use direct-drive train or the gearbox, aerodynamic brakes, etc. There is still a lack of understanding on what the best configuration is. Nevertheless, some conclusions can be made by looking at failures in the WMEP database from the main component point of view. These reports show significantly higher total failure rates for pitch-controlled WT than for stall-controlled ones. However, for pitch-controlled WTs, failure rates in the hydraulic systems and mechanical brakes are lower than for stall-controlled WTs. On the other hand, rotor failure rates (without the blades) are much higher. In the case of generator types, WTs with synchronous generators show higher failure rates than those using induction generators. Looking at component failures, electrical components also showed higher failure rates in WTs with synchronous generators. This is mainly due to the use of a full electronic converter. Accordingly, synchronous generators show higher failure rates than induction generators. The use of direct drive shows higher failure rates compared with WTs using gearboxes. However, the synchronous generators of these direct-drive machines show a constant failure rate after the first operational year. This brings into consideration that other components are responsible for these high failure rates, such as the case of power electronics. The latter follow a similar failure behavior throughout the ten years of the WMEP program.

In general, these maintenance reports show that half of the WTs failures are due to the electric components and to the control system. These failures represent in most cases low downtime compared with failures in other components such as generator or gearbox [3,10].

Another aspect that influences reliability in this study is the fact that WTs have escalated in size, keeping the basic concepts. Failure rates have also escalated with them as shown at the beginning of this analysis. On the other hand, WTs with low failure rates are mostly low rated power machines. They do not show a specific type of topology but usually they have a simple configuration. Their highest failure rates are due to the control system and to electrical components, which are the most common failures [10].

Entering in more detail, results show that early failures, especially when introducing a new model of WTs, are high but they decrease with years of operation.

To conclude, it is important to mention that even though there are not enough data collected for the lifetime of WTs, failure rates in general decrease with time. In addition, based on these data, it can be expected that the WTs under 1 MW to the stage of wear-out failures do not begin before the 11th year of operation.

5 Conclusions

Reliability of WTs has improved with time and has achieved an availability of 98% [10]. However, WTs fail at least once a year or even more often for larger turbines. As future plans look for offshore use of wind energy, reliability of WT components has to improve. Otherwise, a significantly reduced availability is to be expected [17] partly by the increase in downtimes due to failures combined with low site accessibility.

However, gathering and analyzing operational data give reliable hints on potential for improving component reliability. It is shown that mechanical brakes of stall-controlled turbines suffer from higher failure rates, which might be due to the necessity to dissipate all the energy of the drive train by the disk brake on the high speed shaft. Since modern megawatt turbines usually apply aerodynamic brakes, this kind of failures might get diminished. Furthermore, the reliability of components is affected by the introduction of a new concept or technology. Not always the new component should be the focus of the reliability analysis. While the new component may seem to be highly reliable, it may affect the behavior or reliability of other components due to changes in operational conditions. For instance, in the analysis of WTs with direct drive, the actual failures of the generator follow a “constant or random” rate, while the total failure rate of these turbines shows a different pattern. This pattern is similar to the failure rates of electrical components, which are expected to be affected by the operation of the generator.

Even with reduced failure rates, the reliability of modern WT still seems quite high compared to the more matured technologies. Especially, for offshore application, this will cause low availabilities due to the difficult access. Thus, for future wind energy use, it will be of great advantage not only to reduce failure rates of these components but also to develop a new maintenance strategy such as using condition monitoring of critical components. In that way, the number of failures and unplanned repairs gets reduced, maintenance activities get planned, total downtimes will be reduced, and maintenance can be done during periods of low wind.

It is evident that there exists a lack of reliable operational data. Ten to fifteen years of failure events collected represent now one of the few if not the only source (in terms of year data) of information. The wind energy community should go on gathering information, which is needed for improving reliability, and present it to the public.

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References


