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Continuous Reliability Enhancement for Wind (CREW) Database: Wind Plant Reliability Benchmark

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Valerie A. Hines, Alistair B. Ogilvie, Cody R. Bond
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Abstract

To benchmark the current U.S. wind turbine fleet reliability performance and identify the major contributors to component-level failures and other downtime events, the Department of Energy funded the development of the Continuous Reliability Enhancement for Wind (CREW) database by Sandia National Laboratories. This report is the third annual Wind Plant Reliability Benchmark, to publically report on CREW findings for the wind industry.

The CREW database uses both high resolution Supervisory Control and Data Acquisition (SCADA) data from operating plants and Strategic Power Systems' ORAPWind® (Operational Reliability Analysis Program for Wind) data, which consist of downtime and reserve event records and daily summaries of various time categories for each turbine. Together, these data are used as inputs into CREW's reliability modeling.

The results presented here include: the primary CREW Benchmark statistics (operational availability, utilization, capacity factor, mean time between events, and mean downtime); time accounting from an availability perspective; time accounting in terms of the combination of wind speed and generation levels; power curve analysis; and top system and component contributors to unavailability.

Acknowledgments

This public Benchmark report is the third industry report to be issued under the Continuous Reliability Enhancement for Wind (CREW) national database project, with the first being published in October 2011. The CREW project is guided and funded by the Department of Energy, Energy Efficiency and Renewable Energy program office. Sandia National Laboratories would like to acknowledge the contributions of both Strategic Power Systems and the wind plant owner/operators who participated in the development of the CREW database as pilot partners. These partners include enXco Service Corporation, Shell WindEnergy Inc., Xcel Energy, and Wind Capital Group. Data gathered from these and other individual partners is proprietary and is only used in an aggregated manner, in order to protect data privacy.

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Executive Summary

To benchmark the current U.S. wind turbine fleet reliability performance and identify the major contributors to component-level failures and other downtime events, the Department of Energy (DOE) funded the development of the Continuous Reliability Enhancement for Wind (CREW) database by Sandia National Laboratories (Sandia). This report is the third annual Wind Plant Reliability Benchmark, to publically report on CREW findings for the entire wind industry.

The five key CREW metrics are summarized in Table 1. The metrics show improvements in all categories compared to the 2012 and 2011 Benchmark reports.

Table 1. CREW Fleet Metrics.

	2013 Benchmark	2012 Benchmark	2011 Benchmark
Operational Availability	97.6%	97.0%	94.8%
Utilization	83.0%	82.7%	78.5%
Capacity Factor	36.1%	36.0%	33.4%
MTBE (Mean Time Between Events)	39 hrs	36 hrs	28 hrs
Mean Downtime	1.3 hrs	1.6 hrs	2.5 hrs

A graphic summary of how a typical CREW turbine spends its time is provided in Figure 1. For each primary system in a turbine, Figure 2 shows the Average Number of Events per Year per Turbine and the Mean Downtime per Event. Note that the generic system "Wind Turbine (Other)" dominates the frequency. This is due to a large number of SCADA events that do not have adequate detail to be assigned to a specific system.

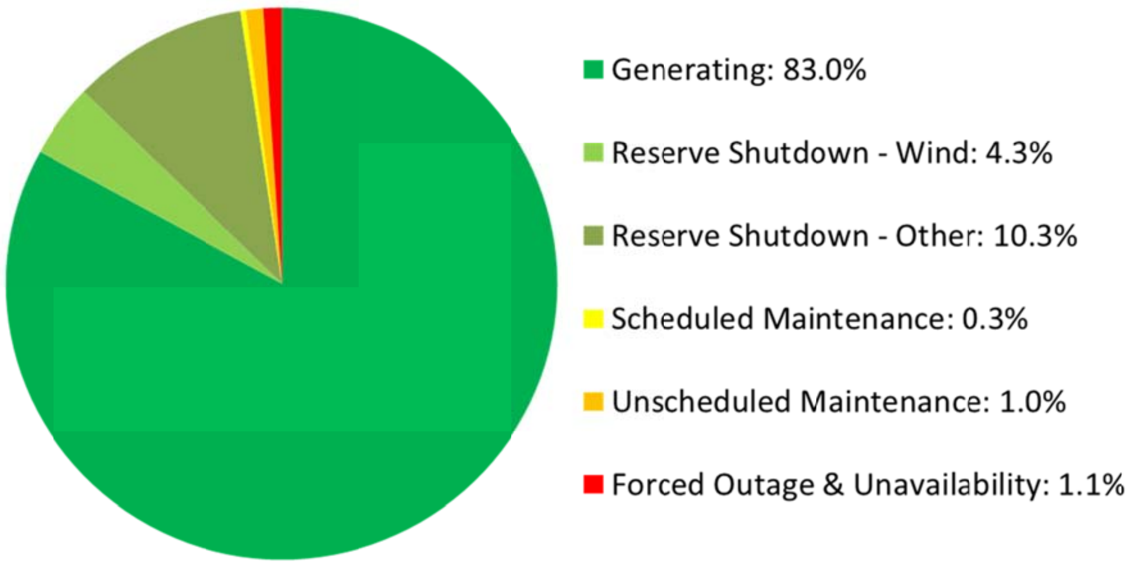


Figure 1. Availability Time Accounting.

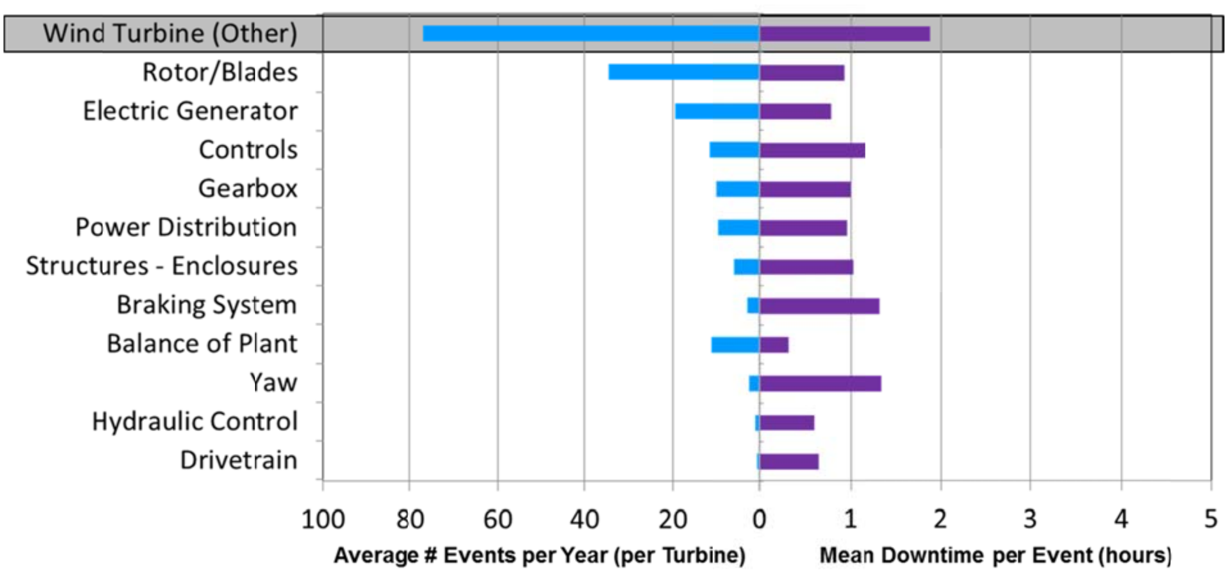


Figure 2. Event Frequency versus Downtime.

1.0 Introduction

The "20% Wind Energy by 2030" report[1], published in 2008 by a DOE collaborative, specifically discusses industry risk from lower-than-expected reliability and increasing operations and maintenance costs. To benchmark the current United Status (U.S.) wind turbine fleet reliability performance and identify the major contributors to component-level failures and other downtime events, DOE funded Sandia to develop the CREW database. This national reliability database of wind plant operating data enables reliability analysis, with the following six key objectives:

- Benchmark reliability performance
- Track operating performance at a system-to-component level
- Characterize issues and identify technology improvement opportunities
- Protect proprietary information
- Enable operations and maintenance cost reduction
- Increase confidence from the financial sector and policy makers

The goal of this Wind Plant Reliability Benchmark is to publically report on Sandia's reliability findings. Previous Benchmarks can be found at http://energy.sandia.gov/crewbenchmark.

1.1. Wind Energy at Sandia National Laboratories

Sandia originated during the Manhattan Project of World War II as a single-purpose engineering organization for non-nuclear components of nuclear weapons. Today, it is a multiprogram lab engaged in creating solutions for a broad spectrum of national security issues. Our history reflects the evolving national security needs of postwar America. It was named Sandia Laboratory in 1948 and, a year later, Sandia Corporation was established to manage the lab. Congress made Sandia a Department of Energy national laboratory in 1979, and Sandia Corporation became a wholly owned subsidiary of Lockheed Martin Corporation in 1993. While we have a bold heritage, we focus on the future. We bring a tireless intellectual curiosity to our work and encourage openness to new ideas and perspectives that can help us address the nation's most daunting challenges.

Sandia National Laboratories, Perspectives, 2012[2]

CREW is managed by Sandia's Wind Energy Technologies department, which has roots in the energy crisis of the mid-1970s. The original focus was on vertical axis wind turbines, but shifted to wind turbine blades in the early 1990s. With the ever-present goal of increasing the viability

[1] U.S. DOE, Energy Efficiency and Renewable Energy. "20% Wind Energy by 2030. Increasing Wind Energy's Contribution to U.S. Electricity Supply." DOE/GO-102008-2567. Springfield, VA. Jul 2008. Accessed on Jul 8 2013 from http://www.eere.energy.gov/wind/pdfs/42864.pdf

[2] U.S. DOE, Sandia National Laboratories. "Perspectives" (2012 Annual Report). 2012. Accessed on Jul 3 2013 from http://www.sandia.gov/news/publications/annual_report/_assets/documents/perspectives.pdf

of wind technology, Sandia's current projects use applied research to improve wind plant performance, reliability, and cost of energy. Sandia's areas of wind expertise include blade design, manufacturing, and system reliability[3].

1.2. CREW Data

For the CREW project, Sandia partners with Strategic Power Systems (SPS) whose ORAPWind® system collects real-time data from partner plants. The majority of CREW data originates from ORAPWind® and its automated data collection, going through an SPS transformation process before being loaded into CREW, as illustrated in Figure 3.

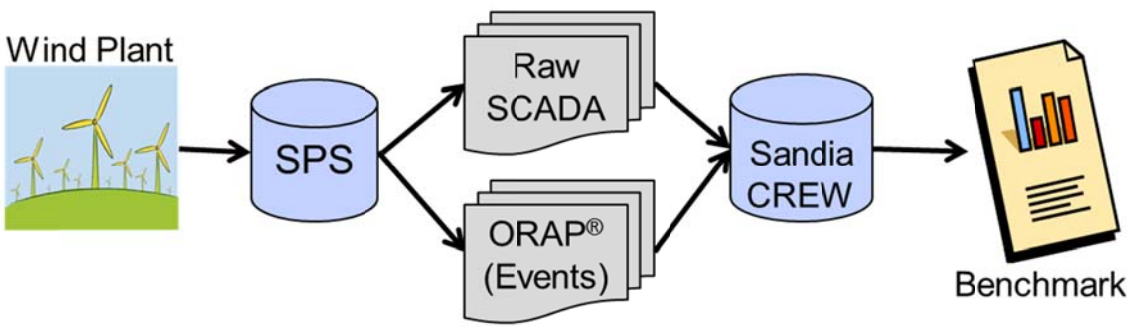


Figure 3. ORAPWind® Data Transfer Process to CREW.

The guiding principle for CREW data and reporting is that data gathered from individual partners is proprietary and will only be shared when it is sufficiently masked or aggregated, to protect data privacy. For more information about the data in the CREW database, please see the "Data Overview" in the Appendix.

Due to a large volume of requests and limited funding, Sandia cannot provide customized aggregated data outside the DOE's Energy Efficiency and Renewable Energy (EERE) program. For requests outside EERE, please see SPS' website at http://orapwind.spsinc.com. Past Sandia wind plant reliability publications are located at http://energy.sandia.gov/?page_id=3057#WPR.

[3] U.S. DOE, Sandia National Laboratories. "Wind Energy." Accessed on Jul 30 2012 from http://energy.sandia.gov/?page_id=344

2.0 Wind Plant Reliability Benchmark

2.1. Fleet Representation

CREW currently represents 2.7% of the large, modern turbines in the U.S. wind fleet. This equates to 2.4% of the megawatts (MW) and 1.9% of the plants. The scope of the CREW database includes wind turbines that are at or above 1 MW in size, from plants with at least 10 turbines. The operations breadth provided by the data partners has generated a dataset that provides a useful view of the U.S. fleet's operational and reliability performance, even though the current result may not be fully representative.

Since its inception, the CREW database has continued to grow, in terms of new plants, new technologies, and more information from existing partners. Table 2 summarizes the metadata for the CREW database, capturing the depth and breadth quantitatively. The current data cover 3 turbine manufacturers, 6 turbine models, and over 327,000 turbine-days.

Table 2. CREW Database Metadata.

Plants	10
Turbines	800-900
Megawatts	1300-1400
Manufacturers	3
Turbine Models	6
Turbine-Days[4]	327,000

CREW's ability to represent the U.S. wind fleet's performance is based on its volume and variety of operating data. All U.S. wind plant owners, operators, and original equipment manufacturers (OEMs) are invited to participate. For more information, please contact Jon White, Sandia CREW Project Lead at (505) 284-5400 or jonwhit@sandia.gov.

[4] This metric and all other analyses use only the Information Available time. The only exception is in the discussion of the Information Available metric.

2.2. Key Results

The five key CREW metrics are summarized in Table 3. Note that the benchmarks are currently cumulative, with each including all the valid information gathered as of its preparation for publication. As with last year's benchmark, all metrics have improved over the previous year. Actual performance improvement and improved data quality are the likely contributors to this improvement.

Table 3. CREW Fleet Metrics.

	2013 Benchmark	2012 Benchmark	2011 Benchmark
Operational Availability	97.6%	97.0%	94.8%
Utilization	83.0%	82.7%	78.5%
Capacity Factor	36.1%	36.0%	33.4%
MTBE (Mean Time Between Events)	39 hrs	36 hrs	28 hrs
Mean Downtime	1.3 hrs	1.6 hrs	2.5 hrs

2.3. Other Benchmarks

There is reasonably good alignment between other objective sources and the CREW metrics, though CREW's Availability and Capacity Factors are generally slightly larger than these other sources. In 2011, GL Garrad Hassan reported 94% mean Availability, with "newer projects" achieving 95.5%[5]. The DOE's Wind Technologies Market Report provides an average U.S Capacity Factor of 32.1% for 2006-12, up from 30.3% in 2000-05[6].

CREW's value of 97.6% availability is closer to what is reported or guaranteed by the OEMs, which is generally 97% and higher[7, 8, 9, 10]. In late 2012, Bloomberg's Wind Operations and Maintenance Price Index found average contract availability guarantees of 96.9%[11].

[5] GL Garrad Hassan. Syme, C. "O&M Trends in 2011." American Wind Energy Association 2012 Wind Project Operations, Maintenance, & Reliability Seminar. San Diego, CA. January 2012.
[6] US DOE, Lawrence Berkeley National Laboratory. Wiser, R. and Bolinger, M. "2012 Wind Technologies Market Report." August 2013. Accessed Aug 7 2013 from http://www1.eere.energy.gov/wind/resources.html
[7] GE Energy. "Wind Turbines." Accessed 7/3/2013 from http://www.ge-energy.com/wind
[8] Vestas. "Service." Accessed Jul 3 2013 from http://www.vestas.com/en/wind-power-plants/operation-and-service/service.aspx#/vestas-univers
[9] Suzlon. "Introducing the S9X." Accessed Jul 3 2013 from http://www.suzlon.com/products/l3.aspx?l1=2&l2=44&l3=128
[10] REpower Systems. "Complete Safety for Your Wind Power Plants." Accessed Jul 3 2013 from http://www.repower.de/wind-power-solutions/operation/service/onshore-maintenance/isp/isp/
[11] Bloomberg New Energy Finance, "Wind farm operation and maintenance costs plummet." November 1, 2012. Access Jun 6 2013 from https://www.bnef.com/PressReleases/view/252

Also, the 2013 Benchmark values are in alignment with informal feedback the CREW team has received from wind plant operators. By comparison, the 2011 Benchmark was in closer alignment with the third party estimates, but lower than the performance reported by operators and OEMs.

2.4. Availability Time Accounting

An availability summary is provided below, in Figure 4. This represents the various states for a turbine and how a typical turbine's time is allocated across those states. Compared to the 2012 Benchmark, the time spent in each downtime category (Scheduled Maintenance, Unscheduled Maintenance and Forced events) decreased or stayed the same, while the time for Reserve events stayed the same.

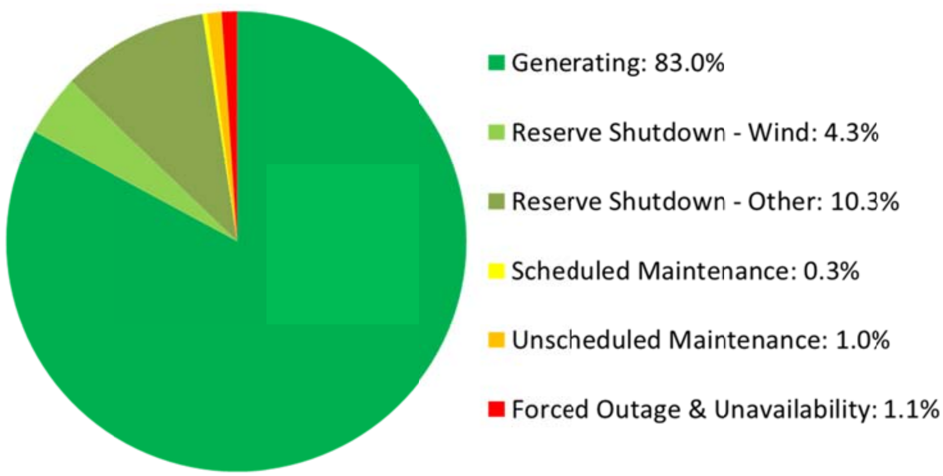


Figure 4. Availability Time Accounting.

2.4.1. Information Available

Any analysis of SCADA data needs to highlight the common communication and information technology issues that can result in missing data. The current value of 71.9% Information Available time represents a cumulative value since CREW's inception. The monthly history of the Information Available metric is illustrated in Figure 5.

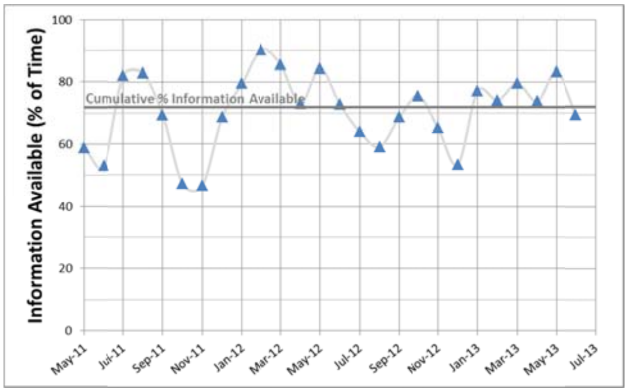


Figure 5. Information Available History.

The Information Available history reflects a varied path toward improved data quality and improved ability to *assess* data quality[12]. The CREW and SPS teams continue to work with the partner plants and industry to illustrate the impact and address the problem where possible. Figure 6 illustrates the Availability Time Accounting graph with the Information Unavailable category in gray.

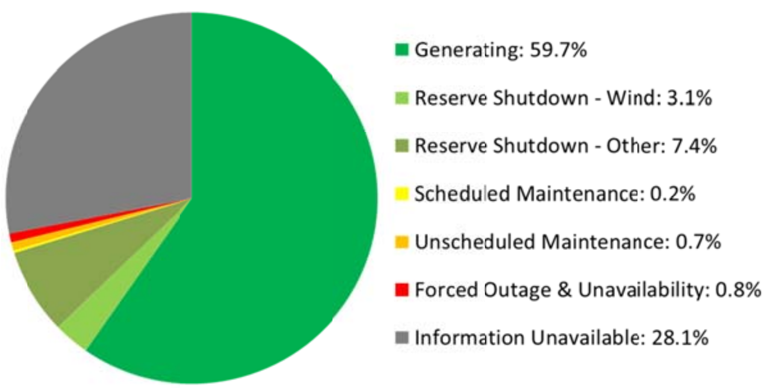


Figure 6. Availability Time Accounting – All Time Accounted.

[12] The method for calculating Information Available for a plant's first month of CREW data was changed slightly, to only capture the part of the month the plant was actually contributing data. This lead to some changes in the Information Available metric for certain months, as compared to the 2012 Benchmark.

2.5. Wind Speed and Generation Time Accounting

The wind speed and generation categories combine to show the turbine state and part of the environmental state – the wind speed. Table 4 lists the time spent in each category and Figure 7 illustrates the resulting Time Accounting. The colors represent levels of generation (green = Rated, yellow = Moderate, orange = Low, red and blue = None) and the color intensity represents wind speed (darker = higher winds). "Up/Idle/RunUp" indicates turbines not generating, but not clearly experiencing a downtime event; they are in reserve or preparing to generate. (Note that ten minute SCADA summaries are used here, while basic time accounting comes from both events and ten minute SCADA summaries. Thus, the two will not perfectly match, due to the discrete nature of the ten minute summaries.)

Table 4: Time Accounting, Wind Speed and Generation.

Percent of Time		Wind				
		Above Cut Out	Rated	Moderate	Below Cut In	Sum
Generation	Rated, Over-Rated	0.0%	12.0%	4.0%	0.0%	15.9%
	Moderate	0.0%	2.1%	51.1%	0.0%	53.2%
	Low	0.0%	0.1%	10.4%	3.5%	14.0%
	None (Up/Idle/RunUp)	0.0%	0.3%	1.6%	11.8%	13.8%
	None (Down)	0.0%	0.2%	1.1%	1.7%	3.0%
	Sum	0.0%	14.8%	68.2%	17.0%	100.0%

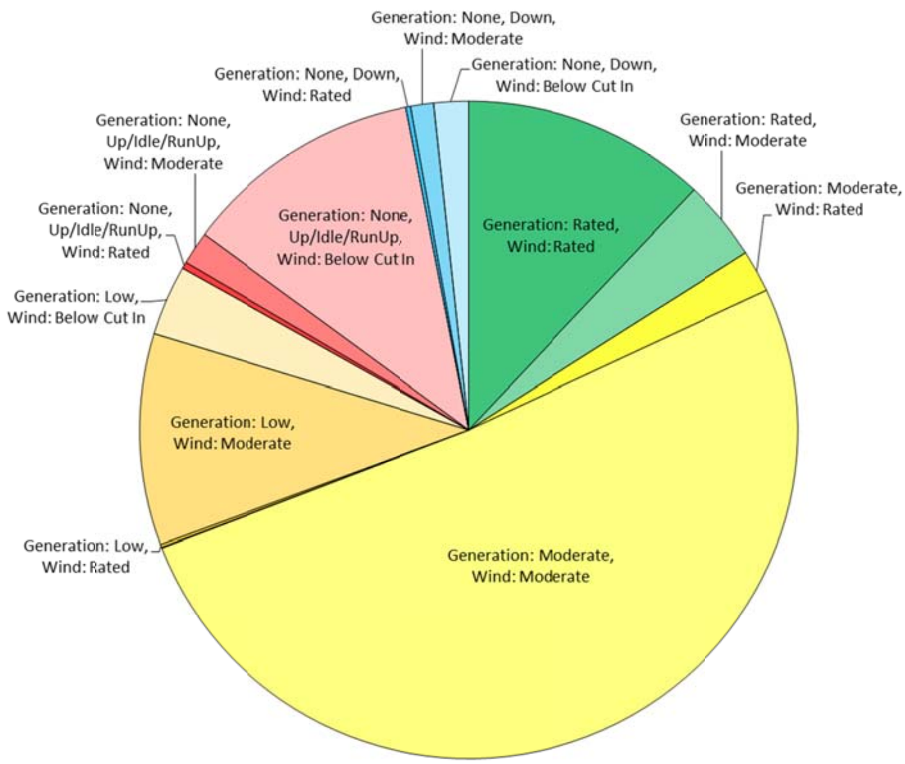


Figure 7. Wind Speed and Generation Time Accounting.

2.6. Power Curve

Exploring the relationship between wind speed and generation in more detail, the CREW data was used to create an air-density-adjusted power curve. Figure 8 shows the power curve, based on adjusted ten minute average wind speed and ten minute average power, with the dot size proportional to the amount of time in each combination. To compare across multiple technologies, the power is normalized to represent the fraction of nameplate capacity produced.

As expected, the power curve shows the real-world variability that is usually absent from theoretical power curves. Note that the differences across technologies are minimal in comparison to the variability between actual performance and each technology's OEM curve.

This power curve shows under- and over-performance. The under-performance is visible as data below and to the right of the main curve ("paint drips"). Under-performance may be caused by a variety of factors, including ramp up, ramp down, true turbine performance issues, and intentional turbine setting changes (for example, to decrease noise or extend the life of a failing part). The over-performance is visible in the section of the graph above the thick gray line. This represents time when the turbine's ten-minute average power is exceeding nameplate capacity. Some small over-performance power values of 1.00-1.02 are expected. The power is above nameplate capacity 8% of the time, but it is only above 1.02 times nameplate capacity 0.54% of the time (47.4 hours per turbine per year).

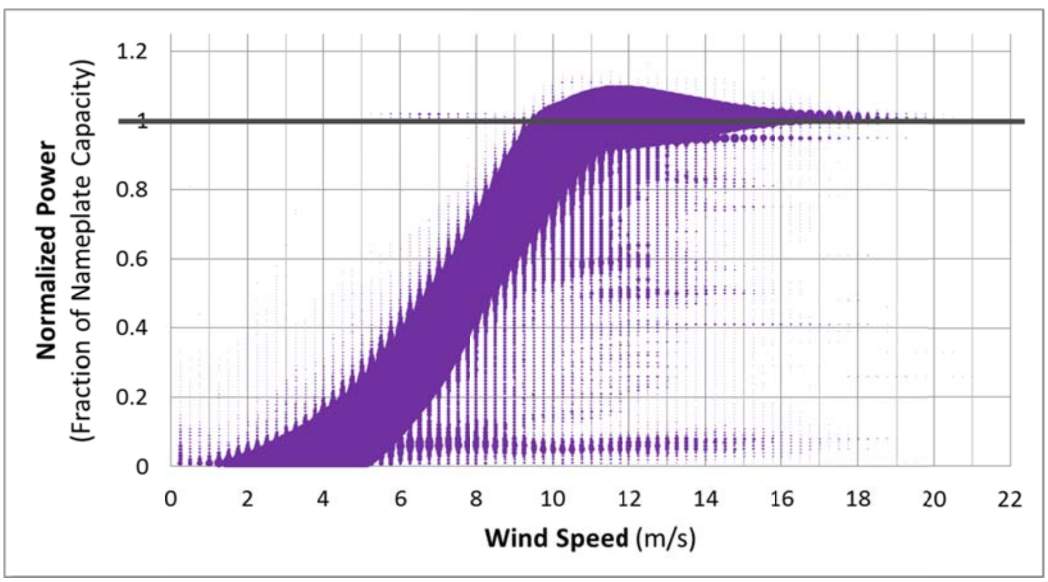


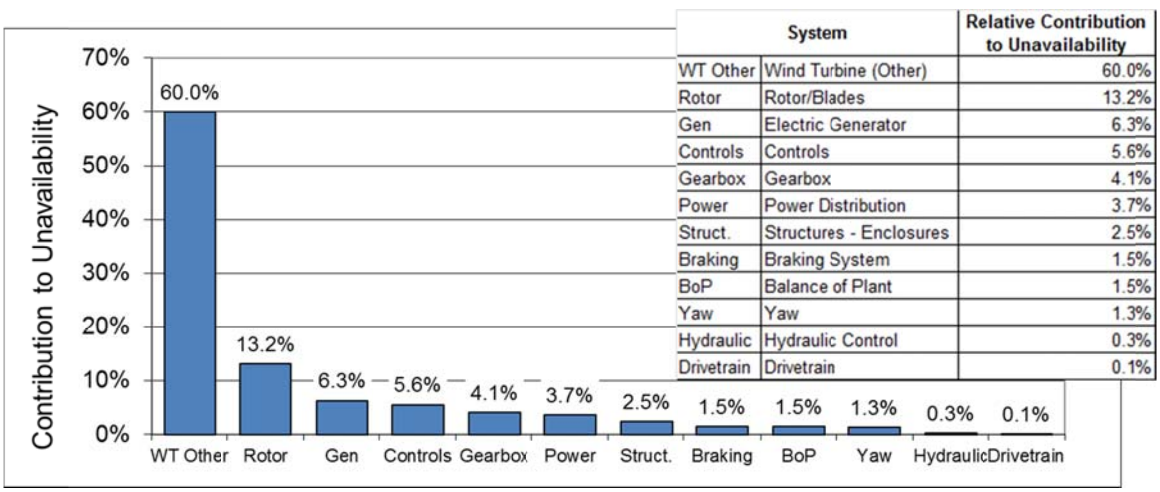
Figure 8. Power Curve.

2.7. Wind Turbine Unavailability Contributors

Recall that events currently come only from SCADA, and not yet from work orders or technician's logs. Thus, the associated system and component are based on the indicated symptom, not necessarily the root cause. For example, a blade replacement is not captured by SCADA as a blade replacement; instead, it is captured as general Unscheduled Maintenance and thus would be assigned to the "Wind Turbine (Other)" system.

2.7.1. Systems

The system-level contributors to unavailability are illustrated in Figure 9, ordered from greatest impact on unavailability to least. The "Wind Turbine (Other)" category currently accounts for only 60% of the downtime, down from 72% in the 2011 Benchmark. Just as in the 2012 Benchmark, the top three system-level contributors to unavailability are Rotor/Blades, Electric Generator, and Controls. Additionally, Rotor/Blades and Electric Generator have been the top two system-level contributors for all three years of this Benchmark.



System		Relative Contribution to Unavailability
WT Other	Wind Turbine (Other)	60.0%
Rotor	Rotor/Blades	13.2%
Gen	Electric Generator	6.3%
Controls	Controls	5.6%
Gearbox	Gearbox	4.1%
Power	Power Distribution	3.7%
Struct.	Structures - Enclosures	2.5%
Braking	Braking System	1.5%
BoP	Balance of Plant	1.5%
Yaw	Yaw	1.3%
Hydraulic	Hydraulic Control	0.3%
Drivetrain	Drivetrain	0.1%

Figure 9. Unavailability Contributors, Systems.

Unavailability is driven by two basic aspects of reliability – the downtime event frequency (how often) and duration (how long). The systems in Figure 10 are ordered by their overall contribution to unavailability, but have their event frequency and duration broken out. Event frequency is measured by the average number of events per year per turbine, while event duration is measured by the Mean (average) Downtime per Event. Aside from the generic system "Wind Turbine (Other)," the Rotor/Blades, Generator, and Controls systems have the most frequent downtime events, matching the order from the 2012 Benchmark. There is low variability in mean downtime across the systems, with 10 of the 12 systems having a mean downtime between 0.5 and 1.5 hours, compared to 8 of the systems in the 2012 Benchmark.

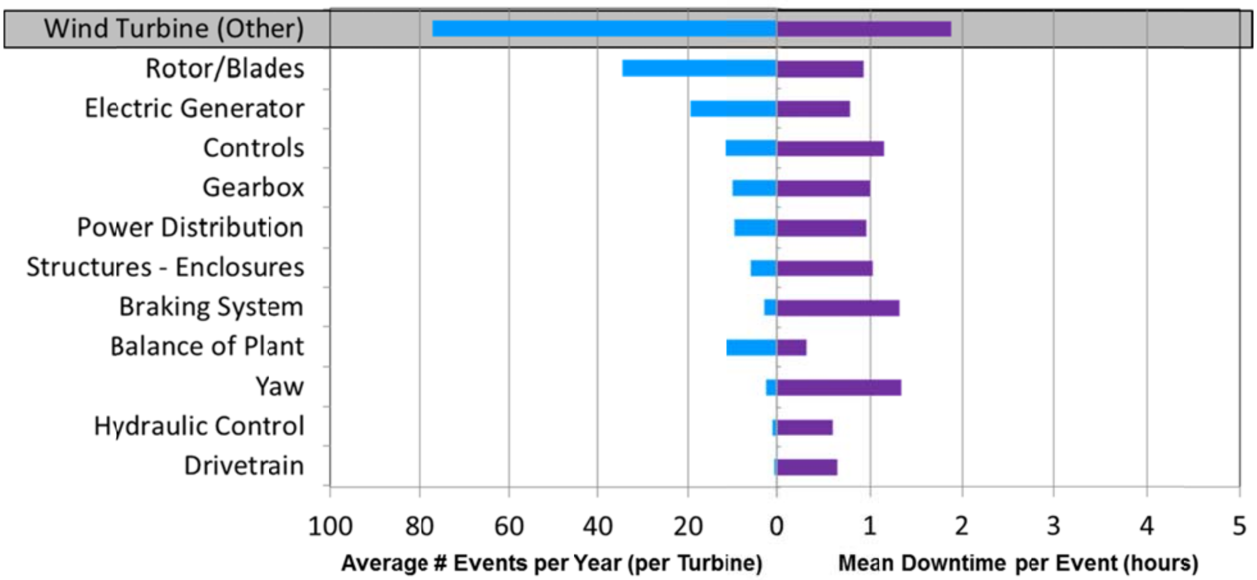


Figure 10. Unavailability Contributors, System Event Frequency and Downtime.

Table 5 provides the Mean Time Between Events (MTBE) and Average Downtime (DT) for each combination of wind turbine system and downtime event type (Forced, Scheduled Maintenance, and Unscheduled Maintenance). If no events are attributed to a given combination, the information is left blank.

Table 5. Wind Plant Reliability Model, System Detail.

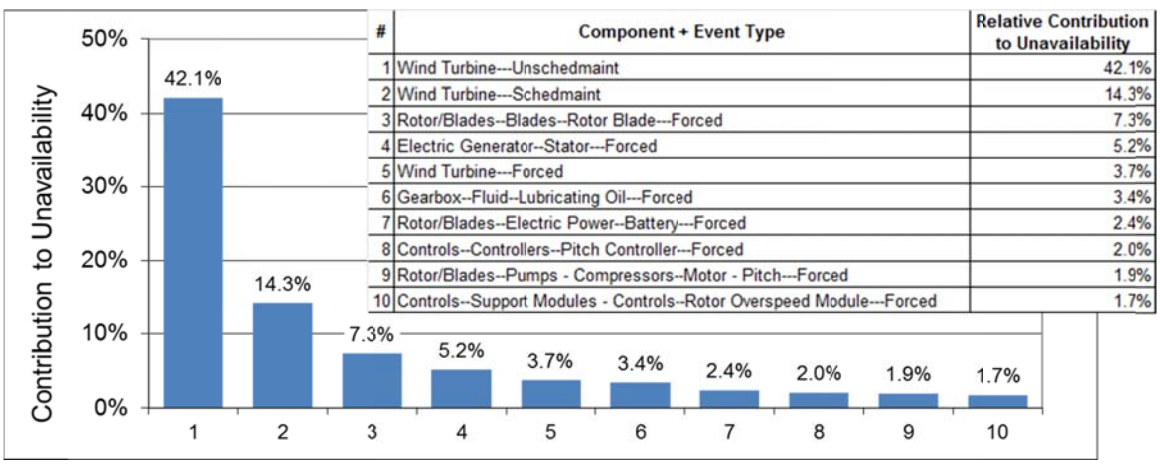
	All Downtime Events		Forced		Scheduled Maintenance		Unscheduled Maintenance	
Representative	MTBE	DT	MTBE	DT	MTBE	DT	MTBE	DT
Turbine	39	1.3	46	0.7	506	2.4	558	7.8
System	**MTBE**	**DT**	**MTBE**	**DT**	**MTBE**	**DT**	**MTBE**	**DT**
Balance of Plant	644	0.3	644	0.3				
Braking System	2,681	1.3	2,681	1.3				
Controls	631	1.2	631	1.2				
Drivetrain	15,921	0.7	15,921	0.7				
Electric Generator	373	0.8	373	0.8				
Gearbox	736	1.0	736	1.0				
Hydraulic Control	7,087	0.6	7,087	0.6				
Power Distribution	781	1.0	781	1.0				
Rotor/Blades	211	0.9	212	0.9	26,746	2.4		
Structures - Enclosures	1,259	1.0	1,259	1.0				
Yaw	3,108	1.4	3,108	1.4				
Wind Turbine (Other)	*95*	*1.9*	*146*	*0.2*	*516*	*2.4*	*558*	*7.8*

MTBE: Mean Time Between Events (hrs)
DT: Mean Downtime (hrs)

As an example of how to use Table 5, one can calculate the frequency for Wind Turbine (Other) Maintenance, both Scheduled and Unscheduled. The combined event rate is 0.00373 events per operating hour (= 1/516 + 1/558), or 268 operating hours per event, on average. In other words, a typical turbine generates for 11.2 days between Maintenance events. Using a Utilization of 83%, this corresponds to every 13.4 days (1.9 weeks).

2.7.2. Components

The top ten component contributors to unavailability are illustrated in Figure 11. Recall that these are component + downtime event types that are attributable to a SCADA event. Note that "Wind Turbine---Unscheduled Maintenance" and "Wind Turbine---Scheduled Maintenance" are the two most common types listed, making up 56.4% of unavailability. This means that the majority of downtime occurs when the turbine itself is the most specific component that can be identified as the symptom or cause based on SCADA data. This list is very consistent with the 2012 Benchmark, with 8 of the top 10 items on both lists. The two new items are "Controls--Controllers--Pitch Controller---Forced" and "Rotor/Blades--Pumps--Compressors--Motor - Pitch---Forced" which moved from 12th and 11th place, respectively. The two items that dropped out of the top ten were "Balance Of Plant--Non-Component Chargeable Event--External Circumstances--Grid Instability---Forced" and "Braking System---Forced" which moved into 12th and 13th place, respectively.



#	Component + Event Type	Relative Contribution to Unavailability
1	Wind Turbine---Unschedmaint	42.1%
2	Wind Turbine---Schedmaint	14.3%
3	Rotor/Blades--Blades--Rotor Blade---Forced	7.3%
4	Electric Generator--Stator---Forced	5.2%
5	Wind Turbine---Forced	3.7%
6	Gearbox--Fluid--Lubricating Oil---Forced	3.4%
7	Rotor/Blades--Electric Power--Battery---Forced	2.4%
8	Controls--Controllers--Pitch Controller---Forced	2.0%
9	Rotor/Blades--Pumps - Compressors--Motor - Pitch---Forced	1.9%
10	Controls--Support Modules - Controls--Rotor Overspeed Module---Forced	1.7%

Figure 11. Unavailability Contributors, Top 10 Component + Downtime Event Types.

3.0 Observations

Analysis Results Are Stabilizing

While the amount of data included in the 2013 Benchmark is approximately double that of the 2012 Benchmark, the overall results are very similar. This implies that the results may be stabilizing around the true fleet values. Comparing 2012 and 2013, the Operational Availability, Utilization, and Capacity Factor each increased, but by less than 1%. The MTBE and Mean Downtime changed by 8.3% and 18.8%, respectively, implying that these metrics may still be in flux.

In addition to similarities in overall metrics, the 2013 top contributors for both systems and components are almost identical from the 2012 lists. Besides "Wind Turbine (Other)," the top three system-level contributors to unavailability were Rotor/Blades, Electric Generator, and Controls for both the 2012 and 2013 benchmarks. For components, 8 of the top 10 were identical, and the two that moved out of the top 10 are still in the top 13.

The stabilization of results, combined with continued alignment with industry sources, demonstrates CREW's ability to describe the industry's overall performance and provides a foundation for showing representation.

Electronic Work Orders

The gearbox is notably absent from the top three system-level contributors to unavailability. This may be due to a lack of insight into major maintenance, as SCADA data alone makes it very difficult to obtain detail about such repairs. To understand a complete reliability picture, it is critical to capture data from high quality electronic work orders and computerized maintenance management systems, to enable root cause insight at the component level. Sandia's reliability efforts continue to include providing the wind industry with information and tools to increase and improve the use of electronic work orders.

Event Frequency

From the CREW reliability data, an average turbine will actively generate power for 1.6 days between downtime events, with additional breaks for reserve events. The average downtime event lasts 1.3 hours. Focusing on only Scheduled and Unscheduled Maintenance events, these occur every 1.9 weeks. Because the events are based on SCADA data, there are many short duration and nearly back-to-back events. Counting only Maintenance events that last at least 1.5 hours and are at least 4 hours apart, these events occur an average of every 3.8 weeks.

Appendix A: Methodology and Calculations

Data and Analysis Changes

Since the first Wind Plant Reliability Benchmark report was published in the fall of 2011, there have been some small and some more significant changes to the input data and analysis processes used. Those more significant changes are summarized here. The year listed is for the first Benchmark with the given change.

- **Reclassified Reserve Events (2012)**: Upon learning more about the turbine manufacturers' fault codes and braking procedures, many of the reserve events previously categorized as "Reserve Shutdown – Wind" were re-categorized as "Reserve Shutdown – Other."
- **Modified Definition of Operational Availability (2012)**: Due to the re-classification of reserve events, a huge number of very short "Reserve Shutdown – Other" events were created. To ensure the impact of downtime events was appropriately modeled and illustrated, the definition of Operational Availability was updated. Now, Operational Availability considers all reserve events as "Available." (Before only "Reserve Shutdown – Wind" events were considered "Available.")

Planned Changes

- **Alignment with IEC 61400-26-1 (2014 – expected)**: Currently, the CREW Benchmark uses SPS' implementation of the Institute of Electrical and Electronics Engineers (IEEE) 762 standard for categorizing event types. Now that the International Electrotechnical Commission (IEC) 61400-26-1 standard, "Time-based availability for wind turbine generating systems," has been published, SPS and CREW are implementing it for categorizing event types. When complete, this implementation will result in new Availability time categories and results.
- **Grouping Back-to-Back Events (2014 – expected)**: Currently, back-to-back events are counted separately. This contributes to smaller mean time between events (larger event frequencies) and smaller event durations. As part of a transformation logic upgrade, SPS will group back-to-back events with the same event type.

Data Overview

For the CREW project, Sandia partners with SPS whose ORAPWind® system collects real-time data from partner plants. Currently, the vast majority of CREW data originates from ORAPWind® and its automated data collection, going through an SPS transformation process before being loaded into CREW. SPS algorithms both gather the raw plant SCADA data and also transform it into ORAPWind® "time, capacity, and events." As **Error! Reference source not found.** illustrates, Sandia uses both the raw SCADA data and transformed events data from ORAPWind®.

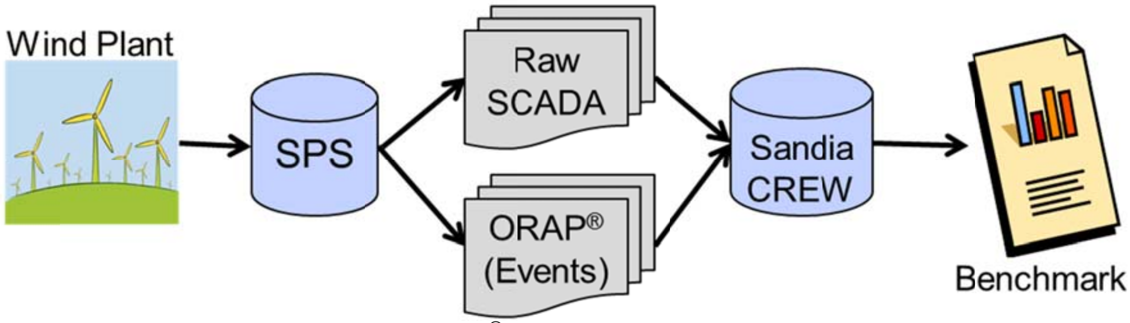


Figure 12. ORAPWind® Data Transfer Process to CREW.

In addition to the data from ORAPWind®, a smaller portion of the CREW data comes directly from wind plant owner/operators, usually in the form of ten minute SCADA summaries. All relevant data is used in each piece of the analysis, though a given graph or metric may not include every plant in the dataset. The guiding principle of data and reporting from the CREW database is that data gathered from individual partners is proprietary and will only be shared when it can be sufficiently masked or aggregated, in order to protect data privacy.

SCADA Data

High Resolution SCADA Data: SPS' automated data collection process gathers observations recorded by the SCADA systems at their partners' wind plants. These data are collected by the ORAPWind® tool every time a data point changes, which is approximately every two to ten seconds for quick-changing values such as wind speed. The data are then transferred to SPS and then to Sandia. Data points cover the "heartbeat" of the turbine (e.g., operating state, rotor speed) and environmental conditions measured by the turbines and the meteorological towers (e.g., wind speed, air pressure, ambient air temperature, etc.).

Ten Minute SCADA Summaries: In addition to storing the high resolution SCADA data, CREW also uses this data to create ten minute summaries. These summaries consist of a ten minute minimum, maximum, mean (average), and standard deviation for each numeric data stream in the high resolution data (e.g., wind speed). Values that are not truly numeric (e.g. an integer representing turbine state) are summarized by taking the most common observation across the ten minute period (statistical mode).

ORAPWind® Data

ORAPWind® Events: The ORAPWind® tool summarizes the SCADA data into downtime and reserve events, covering all time when any turbine is not generating. Reserve events capture when the turbine is available to generate, but not generating due to external circumstances; these are NOT counted by the CREW team as "downtime events." Each event consists of a start and end date/time, affected turbine, and description of the problem. This description includes a general event type (e.g., Reserve Shutdown or Unscheduled Maintenance) and affected component from SPS' Equipment Breakdown Structure (EBS) (e.g., Rotor Blade or Stator - Electric Generator). Table 6 shows some key data fields for two hypothetical ORAPWind® events.

Table 6. Example of ORAPWind® Events.

Turbine ID	Event ID	Event Type	Begin Date	End Date	EBS Component
123	5688	Forced Outage Automatic Trip	1/3/13 15:16	1/4/13 11:34	Pitch Controller
123	5678	Reserve Shutdown	1/1/13 01:23	1/1/13 04:56	Yaw Cable Twist Counter

ORAPWind® Operational Records: ORAPWind® also summarizes the SCADA data by reporting the amount of time each turbine spends in various states. For each 24 hour day, the total time in each state is calculated, including the time with Information Unavailable.

Data Quality and Completeness

Information Unavailable time is treated as neither up-time nor downtime. The CREW team feels strongly that making assumptions about this time can produce misleading results. The amount of Information Unavailable time is reported, and then treated as if it never existed. As a simple example, if 20 hours of data were missing in a 168 hour week, then the analysis is performed as if the turbines were monitored for 148 hours.

There are two situations that result in Information Unavailable time for CREW calculations. The first is time when the data are simply missing. The second is time when the data are recorded, but are known to be bad. The most common cause of known bad data is an overloaded server at the wind plant, which slows down or stops data updates to accommodate its load. When no new wind speed information is reported for an entire 10 minute period, CREW considers the data to be "static" and that time is categorized as Information Unavailable.

CREW Reliability Model

The CREW team creates individual plant reliability models, by summarizing the ORAPWind® downtime events using the EBS components and general event types. The event duration and frequency are modeled for each component + event type. For downtime events, Sandia's Pro-Opta reliability analysis tool suite is used to create a fault-tree-based reliability model from the ORAPWind® downtime events. Pro-Opta summarizes the individual downtime events into a fault tree model of a single, representative turbine. Then, a combination of its calculation algorithms and a simulation are used to create a downtime distribution and frequency distribution for each component + downtime event type. The means (averages) of these distributions are used in the Benchmark and associated reporting.

Due to their substantially larger volume of events, reserve events are processed separately from downtime events. A deterministic equation, based on the total operating time and the total number of events for each component + event type, is used to calculate the mean event frequency for reserve events. As shown in Equation 1, this value can be calculated for each component + reserve event type, for a single, representative turbine at the plant. Similarly, Equation 2 shows how the mean downtime is calculated from the event durations and total number of events.

Equation 1. Event Frequency, Plant Model, Reserve Events.

$$Event\ Frequency_{Plant,component+event\ type} = \frac{\sum_{Turbines} Event\ Count_{component+event\ type}}{\sum_{Turbines} Operating\ Hours}$$

Equation 2. Mean Downtime, Plant Model, Reserve Events.

$$Mean\ Downtime_{Plant,comp.+event\ type} = \frac{\sum_{Turbines} Event\ Duration_{comp.+event\ type}}{\sum_{Turbines} Event\ Count_{comp.+event\ type}}$$

Based upon preliminary data analysis, it is assumed that the failure rates (event frequencies) are constant values that need to be estimated. Thus, exponential time-to-failure distributions are used. During a component's useful life (after any initial burn-in and before wear out), these assumptions have been proven to be realistic for many components, and they greatly simplify calculations[13].

Individual plant models, consisting of an event frequency and mean downtime for each component + event type, are aggregated into the CREW Reliability Model. It is important that there is sufficient data, both breadth and duration, to aggregate without violating anonymity. At this point, downtime events and reserve events are both included and treated the same. The aggregation takes a weighted average, across plants, of the event frequency and downtime values for each component + event type. The weight used is the number of turbine-days of Information Available time for that plant. Compared to a simple average, this weighting scheme places more importance on plants with a larger number of turbines, a longer data history, or both. Equation 3 shows how the weighting creates the CREW model's event frequency for each component + event type. Because mean downtimes cannot be considered additive, the downtimes must be weighted by both their event frequency and the turbine-days, before a weighted average can be found[14]. The CREW mean downtime calculation is shown in Equation 4.

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[13] Rausand, M. and Høyland, A. "System Reliability Theory. Models, Statistical Methods, and Applications." 2nd Ed. John Wiley & Sons. Hoboken, New Jersey. 2004.

[14] As an example, consider a plant with 1 event lasting 99 hours and 99 events of a different event type that last 1 hour each. The simple average of downtimes by event type would lead to a mean downtime of 50 hours, but this is not how long a "typical" event lasts, because almost all the events are only 1 hour. Weighting by event frequency gives a mean downtime of approximately 2 hours, which is more representative.

Equation 3. Event Frequency, CREW Model.

$$Event\ Frequency_{comp.+event\ type} = \frac{\sum_{Plants}(Event\ Frequency_{Plant,comp.+event\ type} * Turbine\ Days_{Plant})}{\sum_{Plants} Turbine\ Days_{Plant}}$$

Equation 4. Mean Downtime, CREW Model.

$$Mean\ Downtime_{comp.+event\ type} = \frac{\sum_{Plants}(Mean\ Downtime_{Plant,comp.+event\ type} * Event\ Frequency_{Plant,comp.+event\ type} * Turbine\ Days_{Plant})}{\sum_{Plants}(Event\ Frequency_{Plant,comp.+event\ type} * Turbine\ Days_{Plant})}$$

Once the plant models are aggregated, the CREW Reliability Model consists of a mean downtime and event frequency for each component + event type. Because the turbine is viewed as a series system and the constant failure rate assumption is applied, the turbine's overall event frequency can be treated as additive (the event frequencies can simply be summed to calculate the overall turbine event frequency). Equation 5 illustrates how the individual event frequencies for the component + event types are added together to create the CREW turbine-level event frequency. Taking the downtimes for the individual component + event type, and then weighting them by their event frequency, allows for a mean downtime to be calculated for a single, representative turbine, as shown in Equation 6. (Recall that mean downtimes are not additive and cannot simply be summed or averaged, but instead have to be weighted by their event frequencies.) Additionally, the Mean Time Between Events is calculated as the inverse of event frequency, as shown in Equation 7. Similar methods can be followed to summarize component + event type values to other rollup levels, such as system or event type.

Equation 5. Single Turbine, Overall Event Frequency.

$$Event\ Frequency = \sum_{comp.+event\ type}(Event\ Frequency_{comp.+event\ type})$$

Equation 6. Single Turbine, Overall Mean Downtime.

$$Mean\ Downtime = \frac{\sum_{comp.+event\ type}(Event\ Frequency_{comp.+event\ type} * Downtime_{comp.+event\ type})}{\sum_{comp.+event\ type}(Event\ Frequency_{comp.+event\ type})}$$

Equation 7. Single Turbine, Overall Mean Time Between Events.

$$Mean\ Time\ Between\ Events = \frac{1}{Event\ Frequency}$$

Basic Time Accounting

In addition to the reliability models, time accounting results are also calculated. The time accounting categories are:

- Generating: time when turbine is creating power and not experiencing an event
- Reserve Shutdown – Wind: time when the turbine is NOT experiencing another event and the wind conditions are not appropriate for generation
- Reserve Shutdown – Other: time when the turbine is experiencing a reserve event other than "Reserve Shutdown – Wind" (e.g., run-up before generation; cable unwind; curtailment)
- Scheduled Maintenance: time during a planned maintenance downtime event, scheduled well in advance, which puts the turbine in a down state (ex: annual maintenance)
- Unscheduled Maintenance: time during a repair downtime event which cannot be deferred for any significant length of time (e.g., troubleshooting; major repair)
- Forced (Outage or Unavailability): time during an unplanned downtime event indicating a fault or failure (e.g., automatic trip; manual stop by operator)
- Information Unavailable: time when the SCADA data is missing or unusable

The total time in each category is found by summing the durations for the appropriate type of downtime or reserve events. The Generating time is calculated by summing all of the ten minute periods where the mode of the turbine state indicates it is connected to the grid and making power. This simple method naturally provides greater impact from plants that have a larger number of turbines, a longer data history, or both. Lastly, the Information Unavailable time can be calculated by finding the total number of hours in the data timeframe (time period over which data was collected and analyzed), and subtracting all the time in the other categories. If all data was fully and correctly captured, there would be no Information Unavailable time.

Operational Availability is defined as the percent of Information Available time that the turbines are not experiencing any downtime events. This is equivalent to calculating the percent of Information Available time that the turbines are either generating or in reserve, as shown in Equation 8. Similarly, Utilization is defined as the percent of Information Available time that the turbines are generating, as shown in Equation 9. The various time categories can be used to calculate other availability metrics for comparison to one's own key performance indicators.

Equation 8. Operational Availability.

$$Operational\ Availability = \frac{Generating\ Hours + Reserve\ Shutdown\ Wind\ Hours + Reserve\ Shutdown\ Other\ Hours}{Information\ Available\ Hours}$$

Equation 9. Utilization.

$$Utilization = \frac{Generating\ Hours}{Information\ Available\ Hours}$$

Wind Speed and Generation Time Accounting

The CREW Benchmark also includes time accounting focused on Wind Speed and Generation, as defined by the categories in Table 7 and Table 8. Cut In and Cut Out wind speeds are the minimum and maximum wind speeds at which a turbine can generate power and the Rated wind speed is the speed at which nameplate capacity is first generated. The Cut In wind speed is somewhat theoretical, as the turbines sometimes generate power at lower speeds and sometimes do not generate power above the Cut In speed. Likewise, the Rated and Cut Out wind speed may be somewhat flexible, depending on the turbine controller and ambient conditions.

Table 7. Wind Speed Categories.

Wind Speed Category	Definition
None or Below Cut In	≤ Cut In m/s
Moderate	Cut In – 11 m/s
Rated	11 – Cut Out m/s
Above Cut Out	> Cut Out m/s
Unknown	Missing, Blank, or > 100 m/s

Table 8. Power Generation Categories.

Generation Category	Definition
None	≤ 0% of Nameplate Capacity
Low	0 – 10% of Nameplate Capacity
Moderate	10 – 90% of Nameplate Capacity
Rated	90 – 100% of Nameplate Capacity
Over-Rated	100 – 200% of Nameplate Capacity
Unknown	Missing, Blank, or > 200% Nameplate

When Generation is None, a distinction is drawn between turbines in a “Down” state versus turbines in an “Up/Idle/RunUp” state. A Down state applies to turbines that are experiencing a downtime event. An Up/Idle/RunUp state applies to turbines that are not generating and not experiencing a downtime event (they are presumably in a state of reserve). The metrics for Wind Speed and Generation Time Accounting are created by first taking each combination of wind speed category, generation category, and (if applicable) Down or Up status. This categorization is done for each ten minute period, for each turbine. The ten minute average power, average wind speed, and most common operating state (statistical mode) are used for the assignment. Then, the total amount of time (in ten minute increments) the turbines spend in each combination category is summed to create the values that are reported.

Power Curve

To create power curves, the CREW team follows the guidance of the International Electrotechnical Commission (IEC) standard 61400-12, "Wind turbine generator systems – Part 12: Wind turbine power performance testing".[15] To calculate the air-density-adjusted wind speed for a given ten minute period, the CREW team uses the following steps.

For each plant, for each ten minute period:

1. Calculate the average air temperature [K], by averaging all high resolution SCADA air temperature observations from each met tower. (If a site utilizes multiple met towers, then the met tower with the best overall data is chosen.)
2. Calculate the average air pressure [Pa] by averaging all the high resolution SCADA air pressure observations from the met tower.
3. Use Equation 10 to calculate the derived air density [kg/m^3] using the average air temperature, average air pressure, and the gas constant R [measured in J/(kg*K)].

Equation 10. Derived Air Density.

$$Air\ Density = (Air\ Pressure)/(R * Temperature)$$

For each turbine, for each ten minute period:

4. Calculate the average wind speed [m/s] by averaging the high resolution SCADA wind speed observations from the turbine.[16]
5. Use Equation 11 to calculate the adjusted average wind speed, using a reference air density [1.225 kg/m^3], the derived air density based on the met tower data, and the turbine's average wind speed.

Equation 11. Adjusted Wind Speed.

$$Adjusted\ Wind\ Speed = Wind\ Speed * \left(\frac{Derived\ Air\ Density}{Reference\ Air\ Density}\right)^{1/3}$$

6. Round the adjusted wind speed down to the nearest 0.25 m/s.
7. Calculate the average power [kW] by averaging all the high resolution SCADA power observations from the turbine.
8. Use Equation 12 to calculate the normalized power, using the average power and the nameplate capacity. Then, round this value down to the nearest 0.01 (1%).

[15] International Electrotechnical Commission. "Wind turbine generator systems – Part 12: Wind turbine power performance testing." IEC 61400-12. Geneva, Switzerland. 1998.

[16] The wind speeds recorded at the turbine and at the met tower frequently differ by a few meters per second. Having explored power curves based on the met tower wind speed and the turbine's wind speed, the CREW team has found the wind turbine's recorded speed better aligns with power output, and therefore is a better signal to use.

Equation 12. Adjusted Wind Speed.

$$Normalized\ Power = \frac{Power}{Nameplate\ Capacity}$$

Lastly:

9. For each unique combination of rounded adjusted wind speed and rounded normalized power, count the number of ten minute periods observed with these values.

In the power curve graph, the point size plotted is proportional to the count of rounded observations. Only positive values for rounded adjusted wind speed and rounded normalized power are used in the graph.

Other Calculations

Many other calculations are possible from the information calculated above and from other data in the CREW database. For example, Annual Average Event Rate can be calculated, which is simply another way of looking at event frequency. The Average Number of Events per Year is the expected number of downtime events per turbine per calendar year, and it can be calculated using Equation 13. There are approximately 8760 hours per calendar year, thus multiplying Utilization by 8760 results in the number of generating hours per year. Multiplying the number of generating hours per year by the number of events per generating hour (also known as the Event Frequency) results in the number of events per year.

Equation 13. Average Number of Events per Year, per Turbine.

$$Average\ Number\ of\ Events\ per\ Year, per\ Turbine = Utilization * 8760 * Event\ Frequency_{downtime\ events\ only}$$

The Capacity Factor calculation is different from many of the others defined so far, as it is not based upon categorizing time. The Capacity Factor is defined as the percent of nameplate capacity that the turbines generated, over some data timeframe of interest. Another way of calculating Capacity Factor is averaging the instantaneous power, over some data timeframe of interest, and then dividing this by the nameplate instantaneous power. Equation 14 uses this second approach. Note that it only covers Information Available time (i.e., time when the power output is actually known and not pre-determined to be bad data).

Equation 14. Capacity Factor.

$$Capacity\ Factor = \frac{Average\ (Ten\ Minute\ Average\ Power)}{Nameplate\ Capacity}$$

Equipment Breakdown Structure

CREW uses the SPS EBS and its four-level hierarchy, with levels for major system, system, component group, and component. The full EBS is proprietary to SPS, though Figure 13 shows an excerpt. For example, the component "Up-Wind Carrier Bearing," has "Wind Turbine" as its major system, "Gearbox" as its system, and "Bearings" as its component group.

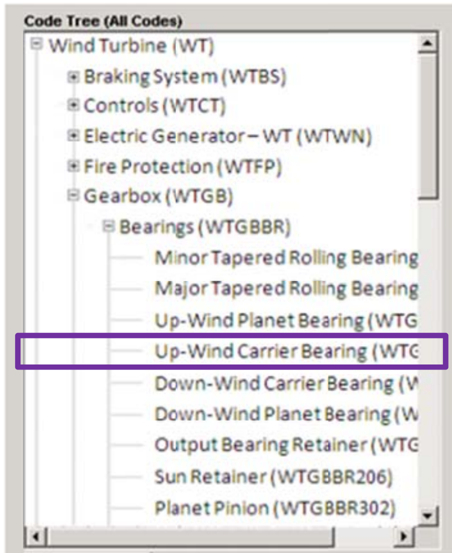

Figure 13. Equipment Breakdown Structure Excerpt.

Other Assumptions

A variety of assumptions are made during data preparation, analysis, and reporting. Assumptions not already captured elsewhere in this report are:

- If a plant does not experience any instances of an event with a given component + event type, then that plant is not included in the calculations for that component + event type.
  - This may slightly increase the reported frequency for events that could occur at a plant, but have not yet. However, it ensures that the event rate is not falsely decreased for events that could never occur at a given plant.
- Back-to-back events are counted separately.
- Events with no duration are given 0.0001 hours (0.36 seconds) of downtime.
  - These events contribute to increased event frequency and decreased mean downtimes. These events can occur because SCADA processes data on the order of milliseconds, and thus, an event that lasts for milliseconds can *appear* as if it began and ended at exactly the same time when recorded in seconds.

Appendix B: Terminology and Definitions

- **Availability**: see “Operational Availability”
- **Capacity Factor**: the percent of total nameplate capacity that was actually generated, factoring in only time when the generation is known
- **Component**: lowest level of the Equipment Breakdown Structure
- **CREW**: Continuous Reliability Enhancement for Wind
- **Cut In (wind speed)**: theoretically, the minimum wind speed at which a turbine can generate power
- **Cut Out (wind speed)**: theoretically, the maximum wind speed at which a turbine can generate power
- **Data Timeframe**: time period over which data was collected and analyzed
- **DOE:** Department of Energy
- **Downtime Event**: SCADA fault state that stops the turbine and takes it out of service (both automatic & manual stops), including technician work when the turbine is stopped
- **DT:** Average Downtime
- **EBS**: (Equipment Breakdown Structure); logical hierarchy of components for a wind turbine
- **EERE:** Energy Efficiency and Renewable Energy
- **Event**: SCADA state that either stops the turbine, takes it out of service, or indicates that it is not generating; an event is either a downtime event or a reserve event
- **Event Frequency**: the expected number of events per generating hour; unless otherwise specified, the CREW values only include downtime events
- **Forced (Outage or Unavailability)**: time during an unplanned downtime event indicating a fault or failure (e.g., automatic trip; manual stop by operator)
- **Generating**: turbine is creating power and is not experiencing a downtime or reserve event
- **IEEE**: Institute of Electrical and Electronics Engineers
- **IEC**: International Electrotechnical Commission
- **Information Available**: time when the SCADA data has been fully transferred into CREW and is also usable for analysis
- **Information Unavailable**: time when the SCADA data is missing or unusable
- **Mean Downtime**: the average duration of an event, in hours; unless otherwise specified, the CREW values only include downtime events
- **MTBE**: (Mean Time Between Events); average number of generating hours between events; unless otherwise specified, the CREW values only include downtime events
- **MW**: Megawatt
- **Nameplate Capacity**: nominal full-load rating of a wind turbine (e.g., a “1.0” turbine should generate 1.0 MW of power during rated wind)
- **OEM**: Original Equipment Manufacturer

- **Operational Availability**: the percent of known time that turbines are NOT down for downtime events (i.e., turbines are either generating or in a state of reserve)
- **ORAPWind®:** Operational Reliability Analysis Program for Wind
- **Rated Wind Speed**: theoretically, the wind speed at which nameplate capacity is first generated
- **Reserve Event**: SCADA turbine state that indicates the turbine is not generating, though it is available and does not have any equipment problems.
- **Reserve Shutdown – Other**: time when the turbine is experiencing a reserve event other than "Reserve Shutdown – Wind" events (e.g., run-up before generation; cable unwind; curtailment).
- **Reserve Shutdown – Wind**: time when the turbine is NOT experiencing another event and the wind conditions are not appropriate for generation
- **Sandia**: Sandia National Laboratories
- **SCADA**: Supervisory Control and Data Acquisition
- **Scheduled Maintenance**: time during a planned maintenance downtime event, scheduled well in advance, which puts the turbine in a down state (ex: annual maintenance)
- **SPS**: Strategic Power Systems, Inc.
- **System**: top-level component grouping in the Equipment Breakdown Structure (e.g., Rotor/Blades)
- **Turbine-Days**: a unit of data volume found by multiplying the number of turbines represented by the number of days in the data timeframe
    - For example, consider a database with a 50-turbine plant and a 100-turbine plant, each which has a data timeframe of 30 days:
      This database would have (50*30) + (100*30) = 4,500 turbine-days of data
- **Unavailability**: 1 – Availability; the percent of known time that turbines are experiencing downtime events
- **Unscheduled Maintenance**: time during a repair downtime event which cannot be deferred for any significant length of time (e.g., troubleshooting, major repair)
- **U.S.**: United States
- **Utilization**: the percent of known time that turbines are generating; sometimes referred to as "Generating Factor"

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