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Continuous Reliability Enhancement for Wind (CREW)
Program Update

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Continuous Reliability Enhancement for Wind (CREW)

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Abstract

Sandia's Continuous Reliability Enhancement for Wind (CREW) Program is a follow on project to the Wind Plant Reliability Database and Analysis Program. The goal of CREW is to characterize the reliability performance of the US fleet to serve as a basis for improved reliability and increased availability of turbines. This document states the objectives of CREW and describes how data collected for CREW will be used in analysis.

A critical aspect to the success of the CREW project is data input from participating owner/operators. The level of detail and the quality of input data provided dictates the type of analysis that can be accomplished. Options for analysis range from high level availability summaries to detailed analysis of failure modes for individual equipment items. Specific types of input data are identified followed by samples of the type of output that can be expected along with a discussion of benefits to the user community.

Table of Contents

List of Figures

1 Introduction

The U.S. wind industry has experienced remarkable growth since the turn of the century. At the same time the physical size and electrical generation capabilities of wind turbines has also experienced remarkable growth. As the market continues to expand and as wind generation continues to gain a significant share of the generation portfolio, the reliability of wind turbine technology becomes increasingly important. Sandia's Continuous Reliability Enhancement for Wind (CREW) Program, funded by the U.S. Department of Energy's Wind and Water Power Technologies Office, was initiated to facilitate the collection, analysis, and dissemination of reliability and performance data essential for determining fleet reliability issues. The CREW Program is a follow on project to the Wind Plant Reliability Database and Analysis Program. As with its predecessor program, the goal of CREW is to characterize the reliability performance of the US fleet to serve as a basis for improved reliability and increased availability of turbines. CREW aims to extend the previous effort by including detailed analysis of maintenance records in order to provide more refined insight into reliability and sustainment of wind turbines. This document represents the long term vision for the CREW Program.

CREW is designed to fill a need identified by wind plant owners and operators to better understand wind turbine component failures so efforts can be focused to resolve these failures and /or mitigate the consequences, resulting in improved operations and reduced maintenance costs. With sufficient participation across the fleet, benchmarking of fleet-wide performance and reliability will characterize the industry as a whole. Characterization of reliability issues will help prioritize and facilitate R&D efforts to foster component and system design improvements. Together these actions are aimed at reducing financial and technical risks for a growing wind energy market.

A critical aspect to the success of the CREW project is data input from participating owner/operators. The level of detail and the quality of input data provided dictates the type of analysis that can be accomplished. Options for analysis range from high level availability summaries to detailed analysis of failure modes for individual equipment items. A goal of this document is to define various data input options with increasing level of details and discuss the benefits of the corresponding analysis. Specific types of input data are identified in this document followed by samples of the type of output that can be expected along with a discussion of benefits to the user community.

2 Background

A national vision of 20% of electrical demand supplied by wind energy by 2030 has been published by the Department of Energy (DOE). To accomplish a market penetration of this magnitude the following must occur:

- Wind turbines must be an economically competitive technology
- Risks to reliable plant performance must be known and manageable
- The technology must have strong public acceptance based on proven performance
- Policies that promote renewable energy must be put in place and maintained

Plant availability is a key metric of performance for wind plants as it is directly related to energy production and revenues. Energy is not generated while components are being repaired or replaced. Although a single failure of a critical component stops production from only one turbine, such losses can add up to significant sums of lost revenue. An availability increase will improve economics, reduce risks, and provide relevant contributions toward meeting 20% penetration goals.

Sandia has historically been engaged in system reliability research activities in safety, materials, and fatigue. The broad-based expertise and capabilities that evolved from this engineering of numerous critical systems is now being applied to wind energy systems. For example, wind turbines have mission requirements of high reliability to perform under specified conditions for established durations of time. Failures, events, repairs, and replacements will all have impacts on turbine and plant availability, and cost of operation.

The consequences of real or perceived reliability problems extend beyond the direct cost to the plant owners. Long-term loans are used to finance power plants that are heavy with upfront capital costs such as wind plants. Financial institutions assess the risk of investing in wind energy and set interest rates accordingly. Quantifying and reducing the risk of unpredictable or unreliable performance improves the ability to finance projects. As financial institutions gain confidence in wind power, insurance and financing costs could decrease, thus increasing the competitiveness and use of wind energy.

3 Objectives of the Continuous Reliability Enhancement for Wind Program

The goals of any wind plant reliability program are to improve availability, reduce costs of Operations and Maintenance (O&M), and maintain high levels of production.

To help wind plants reach these goals, the Continuous Reliability Enhancement for Wind Program has a mission to c*haracterize* reliability performance issues and *identify* opportunities for improving reliability and availability performance of the national wind energy infrastructure.

The following program objectives will help move the industry toward improved reliability:

- Guide DOE program Research and Development (R&D) investment through identification of critical issues, including determination of relative impact of component failures
- Provide data for root cause analyses of component failures
- Establish national benchmarks for performance and reliability
- Guide industry actions and standards for improved equipment performance and operating practices
- Provide data partners with benchmarking of their own equipment against national benchmarks
- Give specific feedback assessments to partners: operators, owners, asset managers, and equipment suppliers
- Identify components that result in highest cost, highest downtimes, and/or lowest availability, and which would be the best candidates for revised O&M practices, or other types of improvement
- Facilitate a culture change in wind plant operation to more effectively monitor and utilize reliability information

Part of the Program's goal is to help increase availability through well understood and numerically characterized reliability performance of component and systems. Reliability analysis is for the purposes of efficient planning. In this case, planning will include understanding failure rates, forestalling failures, managing efficient repairs and replacements, and having optimum spares inventory. Individualized reliability reports for each data partner will contribute to efficient planning. Published reports of aggregated reliability statistics of the US fleet, when sufficient numbers are included, will provide benchmarks of reliability performance and also trend reliability improvements over time. Aggregated reports will be developed in a manner that ensures safeguarding of participating partner's proprietary information.

4 Data Partnerships

The Continuous Reliability Enhancement for Wind Program is based on the acquisition of operational data to determine basic performance and reliability statistics of wind turbines deployed throughout the United States. It is in the operation of wind plants that reliability data of components are recorded. Outage events, faults, and failures contribute to the unreliability observed in the plant or individual turbines. Other types of reliability-related O&M data include the spare parts and human and equipment resources needed to perform preventative and corrective maintenance. Much of this data resides in plant SCADA systems and work orders.

The process to acquire data from partners requires some effort from the partners. Typically, data partners need to provide electronic or other forms of access to the SCADA and work order systems. Whether electronic or otherwise, SCADA codes, work orders, and operational practices will need to be understood for proper analysis. In exchange for the data, data partners are provided with individual reliability reports. Examples of such reports are provided in the section on “Reporting and Analysis Output” and a full sample report is provided in Appendix B.

Ensuring protection of information is critical for successful partnerships. Sandia and potential wind plant owners and operators prepare, review and sign non-disclosure agreements (NDAs) requiring that neither Sandia nor the data partner will share raw data or analysis results with parties outside the agreement. The process has become somewhat standardized as additional partnerships are formed. The NDA also makes clear that data provided will be used for purposes of aggregation into the US fleet National Reliability Database, but no individual contribution will ever be identified or attributed to a specific wind plant.

5 Data Sources

The transition of the CREW Program to target summarized SCADA data represents a shift in focus for source data that will be analyzed. Previous efforts relied primarily on raw Supervisory Control and Data Acquisition (SCADA) as the primary of source of data leading to the published metrics. Under CREW, SCADA data will still be used characterize availability and provide high level insight in to reliability drivers, but the data will come to Sandia in the form of summarized reports prepared by the participating partners, rather than as raw data.

Although an excellent source of data for availability, SCADA data can be limited in providing data to support reliability and sustainability assessments. Downtime is generally attributed to the primary element that caused the downtime. Other maintenance occurring at the same time is not captured. Additional failures can occur while a turbine is down that will not be recorded if the downtime is encompassed by the first event. Opportunistic maintenance can also occur. Opportunistic maintenance is accomplished while the turbine is already down in order to minimize overall downtime. This is typically scheduled preventive maintenance that is near its normal cyclic period.

Subject to data availability and quality, maintenance records will be analyzed to provide additional reliability and maintainability metrics. In addition to capturing all maintenance performed, details recorded in maintenance records will allow a much better assessment of each failure. In addition to just quantifying the duration of a downing event, detailed maintenance records will allow for analysis of failure modes, maintenance performed (repair or replace), logistics considerations, and many other aspects of sustainment.

6 Sample Data and Analysis Output

6.1 Turbine Group Data

Data describing the turbines included in the summarized reports and maintenance records is needed to facilitate various analyses. The extent of analysis to be performed is evolving, but metrics broken down by turbine MW and geography are anticipated. When performing analysis, in particular maintenance record analysis, it is important to know the entire set of turbines that generated the record set. Although it may be unlikely, if there are no maintenance records referring to a particular turbine, the positive operating time of that turbine needs to be accounted for.

The table below displays the desired meta data for a turbine group.

Turbine Group: Windy Gulch									
ID	**Plant Name**	**Turbine OEM & Model**	**Turbine MW**	**IEC Wind Class**	**Latitude**	**Longitude**	**Elevation (m)**	**Commission Date**	**Geography**
WG-1	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/1/2005	Ridgeline
WG-2	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/2/2005	Ridgeline
WG-3	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/3/2005	Ridgeline
WG-4	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/4/2005	Ridgeline
WG-5	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/5/2005	Ridgeline
WG-6	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/6/2005	Ridgeline
WG-7	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/7/2005	Ridgeline
WG-8	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/8/2005	Ridgeline
WG-9	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/9/2005	Ridgeline
WG-10	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/10/2005	Ridgeline
WG-11	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/11/2005	Ridgeline
WG-12	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/12/2005	Ridgeline
WG-13	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/13/2005	Ridgeline
WG-14	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/14/2005	Ridgeline
WG-15	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/15/2005	Ridgeline
WG-16	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/16/2005	Ridgeline
WG-17	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/17/2005	Ridgeline
WG-18	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/18/2005	Ridgeline
WG-19	Windy Gulch	XYZ - GustMaster 2000	1.5	Iia	37.68	-121.71	193	1/19/2005	Ridgeline

Figure 1 - Sample Turbine Group Data

6.2 Summarized SCADA Availability Data

Summarized reporting of availability will be based on the International Electrotechnical Commission (IEC) Standard 61400-26, *Time Based Availability for Wind Turbines*. Data will be submitted by participating partners that specifies for each turbine the time spent in each of the information categories indicated as Level 4 in Figure 2.

<table>
<tr><th colspan="5">Information Categories</th></tr>
<tr><th>Mandatory Level 1</th><th>Mandatory Level 2</th><th>Mandatory Level 3</th><th>Mandatory Level 4</th><th>Optional description see Annex A Level 5</th></tr>
<tr><td rowspan="13">INFORMATION AVAILABLE (IA)</td><td rowspan="8">OPERATIVE (IAO)</td><td rowspan="3">GENERATING (IAOG)</td><td>FULL PERFORMANCE (IAOGFP)</td><td></td></tr>
<tr><td rowspan="2">PARTIAL PERFORMANCE (IAOGPP)</td><td>Derated</td></tr>
<tr><td>Degraded</td></tr>
<tr><td rowspan="5">NON-GENERATING (IAONG)</td><td>TECHNICAL STANDBY (IAONGTS)</td><td></td></tr>
<tr><td rowspan="2">OUT OF ENVIRONMENTAL SPECIFICATION (IAONGEN)</td><td>Calm Winds</td></tr>
<tr><td>Other Environmental</td></tr>
<tr><td>REQUESTED SHUTDOWN (IAONGRS)</td><td></td></tr>
<tr><td>OUT OF ELECTRICAL SPECIFICATION (IAONGEL)</td><td></td></tr>
<tr><td rowspan="4">NON-OPERATIVE (IANO)</td><td colspan="2">SCHEDULED MAINTENANCE (IANOSM)</td><td rowspan="3">Response
Diagnostic
Logistic
Failure Repair</td></tr>
<tr><td colspan="2">PLANNED CORRECTIVE ACTIONS (IANOPCA)</td></tr>
<tr><td colspan="2">FORCED OUTAGE (IANOFO)</td></tr>
<tr><td colspan="2">SUSPENDED (IANOS)</td><td>Scheduled Maintenance
Planned Corrective Actions
Forced Outage</td></tr>
<tr><td colspan="3">FORCE MAJEURE (AIFM)</td><td></td></tr>
<tr><td colspan="4">INFORMATION UNAVAILABLE (IU)</td><td></td></tr>
</table>

Figure 2 - IEC Availability Categories

6.2.1 Sample SCADA Availability Data Input

The figure below is sample summarized availability input.

Summarized SCADA Availability Data		Total Energy Production	Potential Energy Production	FULL PERFORMANCE (IAOGFP)	PARTIAL PERFORMANCE (IAOGPP)	TECHNICAL STANDBY (IAONGTS)	OUT OF ENVIRONMENTAL SPECIFICATION (IAONGEN)	REQUESTED SHUTDOWN (IAONGRS)	OUT OF ELECTRICAL SPECIFICATION (IAONGEL)	SCHEDULED MAINTENANCE (IANOSM)	PLANNED CORRECTIVE ACTION (IANOPCA)	FORCED OUTAGE (IANOFO)	FORCE MAJEURE (IAFM)	SUSPENDED (IANOS)	INFORMATION UNAVAILABLE (IU)
Turbine Group															
Windy Gulch_All															
Data Start	1/1/2016														
Data End	12/31/2016														
Turbine XXX		8415	10638	6920	138	303	161	363	6	82	19	72	169	240	38
Turbine XXX		7806	10638	6307	296	371	326	17	3	56	278	477	231	221	35
Turbine XXX		4499	10638	3538	316	91	95	56	0	66	72	33	41	13	9
Turbine XXX		9817	10638	7688	740	130	18	33	13	33	19	26	6	22	116
Turbine XXX		5386	10638	4304	276	183	185	215	127	51	31	4	7	10	94
Turbine XXX		7382	10638	5470	1022	156	216	97	7	22	28	25	22	18	8
Turbine XXX		9777	10638	7534	921	111	59	6	26	11	16	6	23	24	49
Turbine XXX		8444	10638	6833	306	189	665	205	20	124	81	110	11	120	38
Turbine XXX		9609	10638	7796	317	233	137	96	73	30	26	12	2	20	27
Turbine XXX		9632	10638	7709	476	276	53	31	103	8	3	34	22	32	52
Turbine XXX		8416	10638	6920	139	185	691	342	55	5	7	124	103	148	17
Turbine XXX		8419	10638	6745	406	25	162	546	86	166	119	75	172	50	69
Turbine XXX		9268	10638	7183	810	350	171	66	13	22	47	3	48	28	3
Turbine XXX		8944	10638	7008	668	101	119	101	129	29	170	22	27	220	77

Figure 3 - Sample SCADA Availability Data

All numbers shown are notional and were created using a random number generator.

For each turbine the total energy produced during the reporting period is listed along with the number of hours each turbine was in each of the categories.

6.2.2 Sample SCADA Availability Data Output

The primary display method for availability data is pie charts. Charts will be created for the entire population of turbines as well as for various subsets of turbines

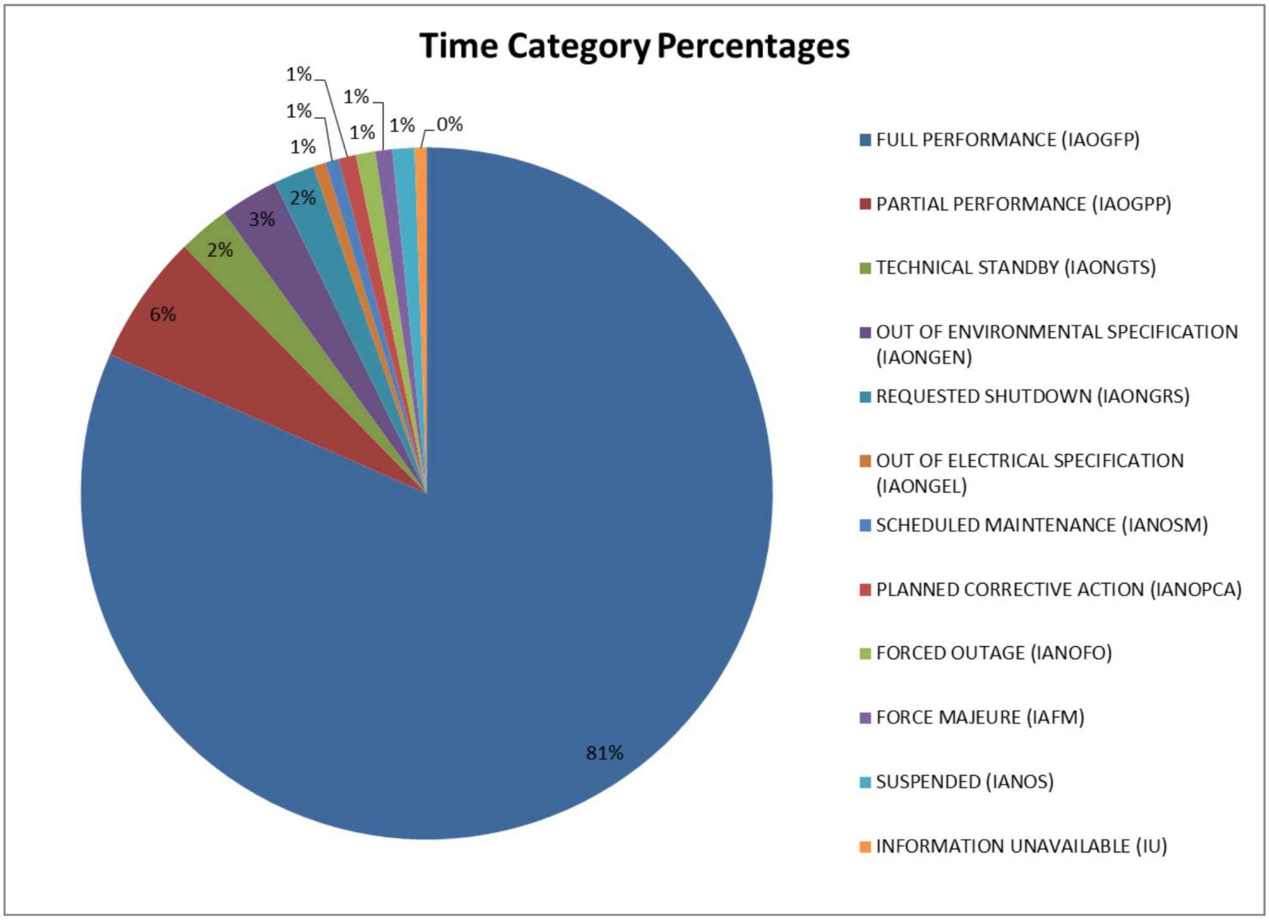


Figure 4 -Sample Availability Pie Chart

Additional possible analysis

- Assessment of the variation in availability across turbines. (for example, 5th, 50th, and 95th percentiles for full performance)
- Availability by turbine age
- Availability by turbine MW

6.2.3 Benchmarking Reporting

The metrics below will be calculated based on the summarized SCADA availability data.

Operational Availability – Operation Availability (A_O) is the fraction of a given period of time in which a turbine is actually generating. Lost operating hours due to any reason are included as unavailability.

In this definition, time considered as available includes:

Generating – full performance

Generating – partial performance

Time considered unavailable include

Technical Standby

Out of Environmental Specification
Requested Shutdown
Out of Electrical Specification
Scheduled Maintenance
Planned Corrective Action
Forced Outage
Suspended
Force Majeure

Time not included in the calculation include:
Information not available

This definition is consistent with IEC TS 61400-26-1 (Section B.2.2) and is considered a "User's View" of availability. An equation for A_O is shown below.

$$A_O = \frac{IAOGFP + IAOGPP}{IAOGFP + IAOGPP + IAONGTS + IAONGEN + IAONGRS + IAONGEL + IANOSM + IANOPCA + IANOFO + IANOS + IAFM}$$

<u>Technical Availability</u> – Technical Availability (A_T) is the fraction of a given period of time in which a turbine is operating according to its design specifications.

In this definition, time considered as available includes:
Generating – full performance
Generating – partial performance
Technical Standby
Out of Environmental Specification
Requested Shutdown
Out of Electrical Specification

Time considered as unavailable include
Planned Corrective Action
Forced Outage

Time not included in the calculation include:
Scheduled Maintenance
Suspended
Force Majeure
Information not available

This definition is consistent with IEC TS 61400-26-1 (Section B.3.2) and is considered a "Manufacturer's View" of availability. An equation for A_T is shown below.

$$A_T = \frac{IAOGFP + IAOGPP + IAONGTS + IAONGEN + IAONGRS + IAONGEL}{IAOGFP + IAOGPP + IAONGTS + IAONGEN + IAONGRS + IAONGEL + IANOPCA + IANOFO}$$

Utilization – Utilization is the percentage of the total turbine capacity that is realized. Non-utilization of turbine capacity is a combination of downing events, lack of wind, and any other shutdown or non-use events. It is calculated using the equation below.

$$Utilization = \frac{\sum_{All\ Turbines} Total\ Energy\ Production}{\sum_{All\ Turbines} Turbine\ MW * Time\ Period}$$

Production Based Availability (PBA) – PBA is a measure of the portion of energy that could have been produced that was produced.

$$PBA = \frac{Actual\ Energy\ Production}{Potential\ Energy\ Production}$$

Or equivalently,

$$PBA = 1 - \frac{Lost\ Production}{Actual\ Energy\ Production - Lost\ Production}$$

where lost production = (potential energy production) – (actual energy production).

Potential energy production is an estimate of the energy that could have been produced based on the cumulative total energy produced over a given time period calculated by analyzing 10 minute intervals and averaging the power output SCADA signals for turbines operating at full performance for that period.

6.3 Summarized SCADA Maintenance Data

Downtime periods recorded with SCADA attribute the down time to primary system and component that is causing the down time. The purpose of the summarized SCADA maintenance data is to record the frequency and duration of downing events attributed to each component.

6.3.1 Sample SCADA Maintenance Data Input

The figure below is sample summarized SCADA component maintenance data. The example below shows failures per turbine, but the form could show total number of failures, as long as the number of turbines is specified.

Summarized SCADA Component Maintenance Data					
Turbine Group				**Data Start**	1/1/2015
Windy Gulch_All				**Data End**	12/31/2015
Subsystem	Component	Corr Maint Events	Corr Maint DT	Sched Maint Events	Sched Maint DT
-	-	-	-	-	-
Balance of Plant::Substation	Switches	38	463.97	77	231
Balance of Plant::Substation	VAR Control System	24	82.53	43	86
Control System	Ambient temperature	13	122.66	81	243
Control System	Cabinet, power supply or UPS	21	202.64	31	31
Control System	Central Processor, CPU or I/O board	18	309.87	2	6
Control System	Control Pad	8	189.88	31	62
Control System	Software fault, version history issue, interface	39	48.99	89	89
Control System::SCADA Interface	Cables and Connections	1	7.04	95	380
Control System::SCADA Interface	External Communications	23	249.22	8	32
Control System::SCADA Interface	Internal Communications	36	439.79	34	136
Control System::SCADA Interface	Power Metering	7	16.77	40	120
Drivetrain	Actuator	11	179.99	76	304
Drivetrain	Brake Calipers	6	17.04	50	150
Drivetrain	Brake Disc	10	51.70	14	42
Drivetrain	Brake Pads	33	737.73	62	124
Drivetrain	Compression Coupling (Low Speed Side)	24	82.07	85	85
Drivetrain	Connector Plate (Low Speed Side)	37	519.67	17	34
Drivetrain	High Speed Coupling	23	98.05	93	372
Drivetrain	High Speed Shaft	15	21.54	72	72
Drivetrain	Main Bearing (Low Speed Side)	32	590.51	60	180
Drivetrain	Main Bearing Seal (Low Speed Side)	22	39.96	34	68
Drivetrain	Main Shaft (Low Speed Side)	24	358.47	57	114
Drivetrain	Rotor Lock (High Speed Side)	32	168.10	22	88
Drivetrain	Rotor Lock (Low Speed Side)	39	482.69	41	82
Drivetrain	Slip Ring Assembly (Low Speed Side)	12	257.05	8	24
Drivetrain	Transmission Lock	6	86.54	23	92
Drivetrain::Gearbox	Carrier Bearing	35	633.58	70	280
Drivetrain::Gearbox	Cooling System::Hoses	33	313.31	55	55
-	-	-	-	-	-

Figure 5 - Sample SCADA Maintenance Data

All numbers shown are notional and were created using a random number generator.

6.3.2 Sample SCADA Maintenance Data Output

The figure below is sample output based on SCADA summarized input data.

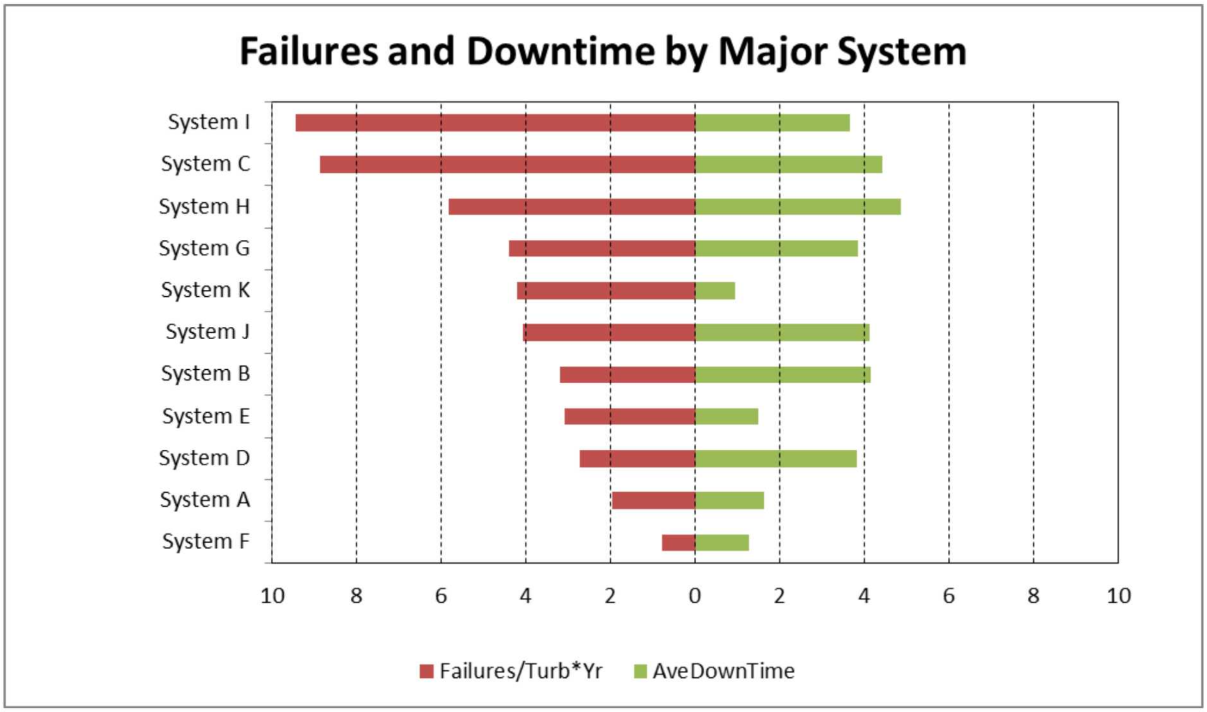


Figure 6 - Tornado Chart of SCADA Data

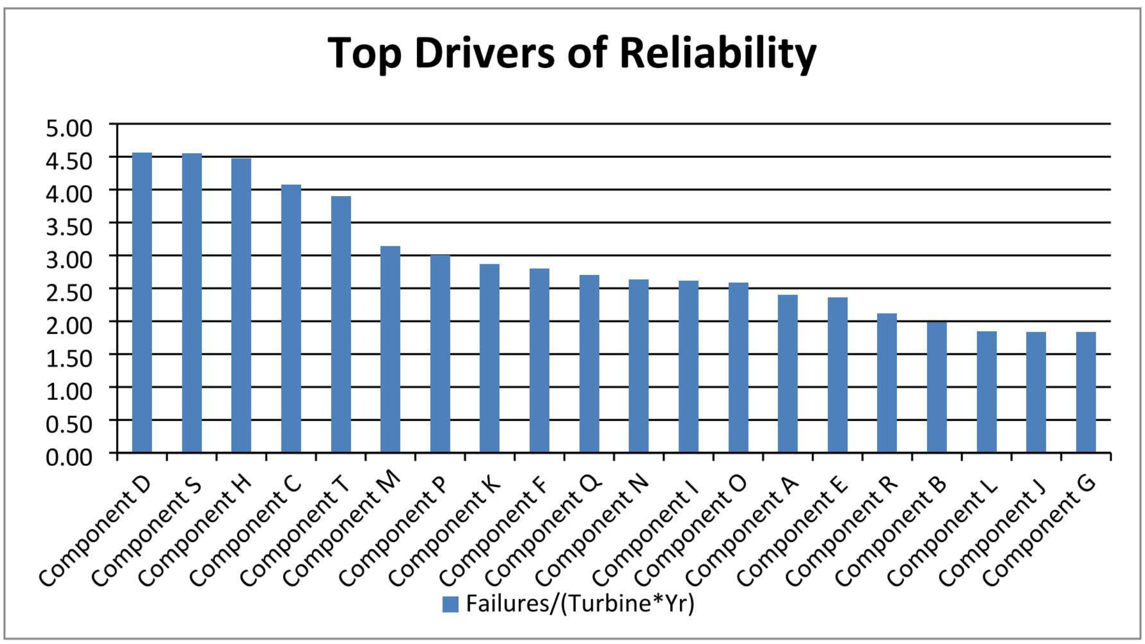


Figure 7 - Top Reliability Drivers

6.3.3 Benchmark Reporting

The following metrics will be calculated using SCADA availability data to determine operating hours and event counts.

Mean Time Between Maintenance - Corrective: This is the average amount of "Uptime" or operating hours between corrective maintenance events.

$$MTBM_C = \frac{\text{Uptime}}{\text{Number of Corrective Maintenance Events}}$$

Calculation of $MTBM_C$ uses data from the availability data table and maintenance table.

$$MTBM_C = \frac{\sum_{All\ Turbines}(\text{IAOGFP} + \text{IAOGPP+IAONGTS+IAONGEN+IAONGRS+IAONGEL})}{\sum_{All\ Components} CorrMaintEvents}$$

Mean Down Time - Corrective Maintenance: This is the average down time per corrective maintenance event.

$$MDT_{CM} = \frac{\text{Corrective Maintenance Downtime}}{\text{Number of Corrective Maintenance Events}}$$

$$MDT_{CM} = \frac{\sum_{All\ Components} CorrMaintDowntime}{\sum_{All\ Components} CorrMaintEvents}$$

Mean Time Between Maintenance - Scheduled: This is the average amount of "Uptime" or operating hours between scheduled maintenance events.

$$MTBM_S = \frac{\text{Uptime}}{\text{Number of Scheduled Maintenance Events}}$$

Calculation of $MTBM_S$ uses data from the availability data table and maintenance table.

$$MTBM_S = \frac{\sum_{All\ Turbines}(\text{IAOGFP} + \text{IAOGPP+IAONGTS+IAONGEN+IAONGRS+IAONGEL})}{\sum_{All\ Components} SchedMaintEvents}$$

Mean Down Time - Scheduled Maintenance: This is the average down time per corrective maintenance event.

$$MDT_{SM} = \frac{\text{Scheduled Maintenance Downtime}}{\text{Number of Scheduled Maintenance Events}}$$

$$MDT_{SM} = \frac{\sum_{All\ Components} SchedMaintDowntime}{\sum_{All\ Components} SchedMaintEvents}$$

Mean Time Between Maintenance: This is the average amount of "Uptime" or operating hours between maintenance events.

$$\text{MTBM} = \frac{\text{Uptime}}{\text{Number of Maintenance Events}}$$

$$\text{MTBM} = \frac{\sum_{All\ Turbines}(\text{IAOGFP}+\text{IAOGPP}+\text{IAONGTS}+\text{IAONGEN}+\text{IAONGRS}+\text{IAONGEL})}{\sum_{All\ Components} MaintEvents}$$

Mean Down Time - Maintenance: This is the average down time per corrective maintenance event.

$$\text{MDT} = \frac{\text{Maintenance Downtime}}{\text{Number of Maintenance Events}}$$

$$\text{MDT} = \frac{\sum_{All\ Components} MaintDowntime}{\sum_{All\ Components} MaintEvents}$$

6.4 Maintenance Record Data

The need to include maintenance records as a source of data for reliability and maintainability metrics is driven by the need for additional information to better characterize the nature of failures and maintenance actions. The goal is to assess all records including both scheduled (preventive) and unscheduled (corrective) maintenance. Sandia will receive maintenance records in raw data form without summarization. Transferring raw data ensures that Sandia is responsible for the assumptions used to summarize the data – leading to a standardized and uniform approach in creating a baseline and benchmarking the industry.

The ultimate goal of CREW is provide deeper insight into reliability of wind turbines and the total sustainment effort required. Accomplishing this goal requires collecting data that currently may not be collected by participating partners. This could require an additional effort on the part of maintainers to record additional fields and possibly additional cost to the owner operators to modify maintenance recording procedures.

For these reasons CREW is proceeding with a stepped approach in which different level of data collection are requested. The paragraphs below describe the fields included in each step and provide sample of the type of analysis that can be performed.

6.4.1 Sample Maintenance Record Data Input – Initial Level

The figure below shows a data form that includes the fields required for the initial venture into maintenance record analysis. Most of the fields are basic information that likely would be included on any maintenance record such as the date and time of discovery. Also included are the date and time the work started and the maintenance time. The “Time Discovered” and “Time Work Started” fields can be used to determine the logistics delays associated with various failures. The last three fields on the form were added to quantify the impacts of the maintenance event in terms of energy lost and cost.

This form is a tabular summary form that displays data from all maintenance records. The individual maintenance records are completed at the time the maintenance occurs. It is envisioned that the individual maintenance records will utilize drop down boxes for some of the fields, such as Maintenance Type and Component, to ensure consistency across records. The aggregated summary form is compressed horizontally for display purposes so all field are visible.

The intent of this effort is to capture all maintenance performed including preventive maintenance and inspections.

Turbine Maintenance Records												
Turbine Group												
Windy Gulch_All												
Data Start	1/1/2015											
Data End	12/31/2015											
Record ID		**Maintenace Type**	**Date Discovered**	**Time Discovered**	**Turbine ID Number**	**Component**	**Date Work Started**	**Time Work Started**	**Repair Time**	**Energy Lost (MWhr)**	**Labor Cost**	**Material Cost**
100001												
100002												
100003												
100004												
100005												
100006												
100007												
100008												
100009												
100010												
100011												
100012												
100013												
100014												

Figure 8 - Sample Maintenance Record Data

The table below provides a brief description of each field.

Field	Description:
Record ID	This is the operator's job number.
Maintenance Type	Indicates if maintenance is unscheduled (corrective), scheduled (preventive), or inspection
Date Discovered	Date failure was discovered or PM was initiated
Time Discovered	Time failure was discovered or PM was initiated
Turbine ID Number	Identifier for turbine (Unique across all operators and sites)
Component	Item undergoing maintenance (selected from taxonomy list)
Date Work Started	Date work started.
Time Work Started	Time work started.
Maintenance Time	Total duration of the repair or maintenance action in clock hours
Energy Lost (MWhr)	Energy lost due to turbine being inoperable
Labor Cost	Labor cost of repair action
Material Cost	Cost of materials/replacement parts

Figure 9 - Data Field Descriptions

6.4.2 Sample Maintenance Record Data Output – Initial Level

The figure below is sample summarized maintenance record output.

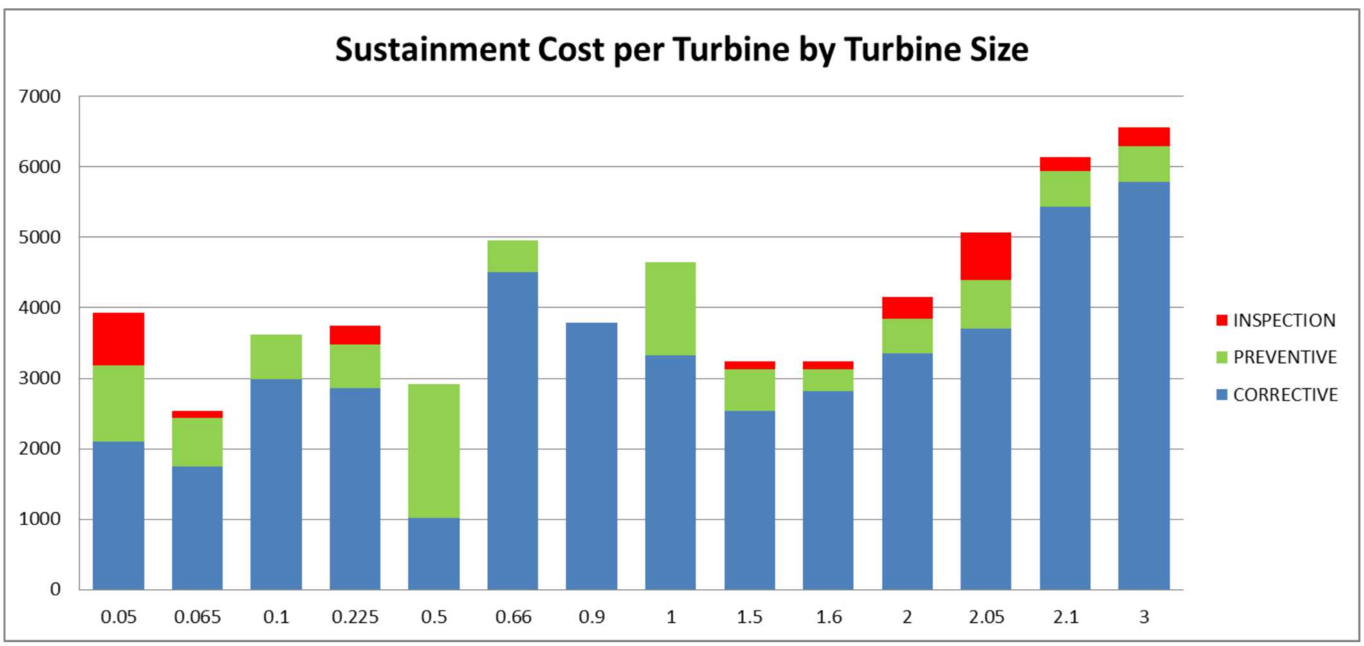


Figure 10 - Sample Maintenance Record Analysis Output

All numbers shown are notional and were created using a random number generator.

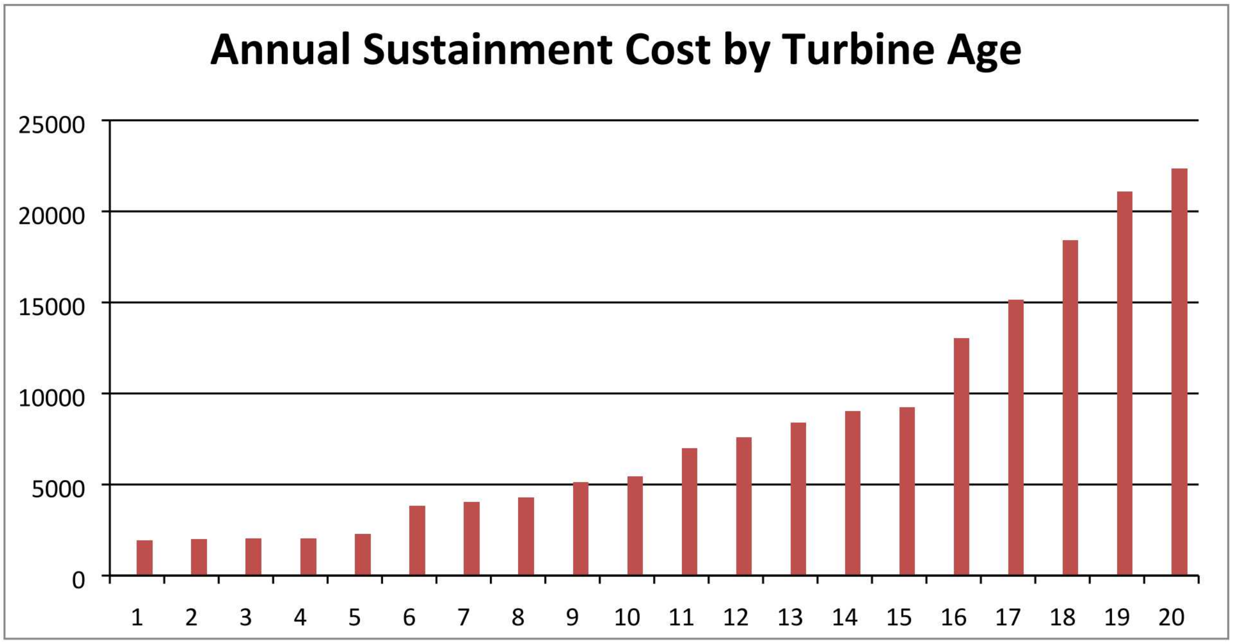


Figure 11 - Sample Output - Cost by Age

All numbers shown are notional and were created using a random number generator.

Additional possible analysis:

- Sorted list of items with the longest logistic delays.
- Sorted list of items requiring the most preventive maintenance.

6.4.3 Sample Maintenance Record Data Input – Enhanced Level

The table shown below is a sample maintenance record table containing additional fields that will greatly enhance analysis capability and opportunity.

Turbine Maintenance Records	
Turbine Group	
Windy Gulch_All	
Data Start	1/1/2015
Data End	12/31/2015

Record ID	**Maintenace Type**	**Date Discovered**	**Time Discovered**	**Turbine ID Number**	**Component**	**Date Work Started**	**Time Work Started**	**Repair Time**	**Energy Lost (MWhr)**	**Labor Cost**	**Material Cost**	**Maintenance Man-Hours**	**Failure Type**	**Failure Mode**	**Action Taken**	**Failed Item Age**
100001																
100002																
100003																
100004																
100005																
100006																
100007																
100008																
100009																
100010																
100011																
100012																
100013																
100014																

Figure 12 - Enhanced Maintenance Record Data

A brief description of each field is provided below.

Field	**Description:**
Maintenance Man-Hours	Total maintenance man-hours of repair action
Failure Type	Indicates if failure was inherent or induced. "No failure" can be indicated for other maintenance actions.
Failure Mode	Indication of the cause of failure/failure mode. This is selected from a pre-populated drop down list of failure modes.
Action Taken	Indicates if items was repaired, removed and reinstalled, replaced, other. This is selected from a pre-populated drop down list of possible actions.
Failed Item Age	Age of the failed item in hours or cycles. This data will facilitated development of failure distributions for time to failure of key equipment items

Figure 13 - Enhanced Data Field Descriptions

To facilitate analysis, it is desirable to standardize the terminology and taxonomies of certain data fields. Using pre-populated drop-down lists for the “Failure Type”, “Failure Mode”, and “Action Taken” fields will allow better automation of record analysis. A failure mode list is provided in Appendix B, and lists for failure type and action taken are provided in Appendix C. Often for database compactness and sizing it is advantageous to use codes for these selected options. The suggested code may be used or another code as long the code system is provided to Sandia for use in data analysis.

The “Maintenance Type” will provide a simple filter for distinguishing corrective maintenance from scheduled maintenance.

The failure type indication goes further in characterizing the maintenance. If a record is created to record the removal of an burned out electrical component, the failure type field will allow the maintainer to indicate whether the component failed itself (inherent failure) or burned out because of failure of another part (an induced failure). Induced failures would typically not be included when attempting to characterize the MTBF of a part.

A key goal of the expanded CREW program is to identify common failure modes for equipment. The "Failure Mode" field allows the maintainer to select from a list of common failure modes. Although the description field contains a narrative description of the failure, this field does not work well with database filtering. The failure mode field list generally includes short descriptions such as bent, corroded, cracked, etc.

The "Action Taken" field is a short description of the maintenance action that is suitable for filtering. Actions include adjustment, clean, repair, remove and replace, and a few others. Filters focusing on this field can distinguish between actions that required a replacement versus other actions which is useful for sparing analysis.

6.4.4 Sample Maintenance Record Data Output – Enhanced Level

The table below shows a sample summary of the action taken after component failure.

Component	Adj	Calib	Clean	CorrCon	CND	Install	Reboot	Replace	Cannib	Repair
Accumulator or Battery	33.3%	0.0%	0.0%	0.0%	0.0%	33.3%	0.0%	0.0%	33.3%	0.0%
Actuator	16.7%	0.0%	16.7%	0.0%	16.7%	0.0%	16.7%	0.0%	0.0%	33.3%
motor	0.0%	25.0%	0.0%	0.0%	0.0%	25.0%	0.0%	0.0%	0.0%	50.0%
Aerodynamic devices	0.0%	11.1%	11.1%	11.1%	0.0%	22.2%	0.0%	0.0%	11.1%	11.1%
Ambient temperature	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%
Anemometer	0.0%	7.7%	15.4%	0.0%	0.0%	7.7%	7.7%	7.7%	53.8%	0.0%
Auto Lube System	11.1%	5.6%	0.0%	5.6%	11.1%	0.0%	5.6%	0.0%	5.6%	33.3%
Aux equipment (crane, fork lift etc)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%
Barometer/Temperature	0.0%	0.0%	0.0%	0.0%	33.3%	16.7%	33.3%	16.7%	0.0%	0.0%
Bearings	0.0%	0.0%	0.0%	40.0%	0.0%	0.0%	0.0%	0.0%	40.0%	20.0%
Brake	25.0%	0.0%	0.0%	0.0%	12.5%	12.5%	0.0%	12.5%	25.0%	12.5%
Brake Calipers	0.0%	0.0%	16.7%	16.7%	0.0%	0.0%	16.7%	0.0%	0.0%	50.0%
Brake Disc	0.0%	0.0%	0.0%	25.0%	25.0%	0.0%	0.0%	0.0%	25.0%	0.0%
Brake Pads	20.0%	0.0%	0.0%	0.0%	20.0%	0.0%	0.0%	40.0%	0.0%	20.0%
Bushing	16.7%	0.0%	0.0%	0.0%	0.0%	0.0%	16.7%	16.7%	16.7%	0.0%
Cabinet Heater	60.0%	0.0%	0.0%	0.0%	20.0%	0.0%	0.0%	0.0%	0.0%	20.0%
Cabinet, power supply or UPS	0.0%	0.0%	0.0%	0.0%	0.0%	50.0%	0.0%	0.0%	0.0%	50.0%
Cable Twist/Untwist	0.0%	28.6%	0.0%	0.0%	0.0%	0.0%	14.3%	0.0%	28.6%	0.0%
Cable Twist/Untwist::Position Sensor	0.0%	0.0%	50.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	50.0%
Cables and Connections	7.7%	15.4%	15.4%	0.0%	15.4%	7.7%	0.0%	0.0%	0.0%	30.8%
Cabling	0.0%	25.0%	0.0%	0.0%	25.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Carrier Bearing	0.0%	33.3%	0.0%	33.3%	0.0%	33.3%	0.0%	0.0%	0.0%	0.0%
Cat Walks	0.0%	16.7%	0.0%	0.0%	16.7%	16.7%	16.7%	0.0%	33.3%	0.0%
Central Processor, CPU or I/O board	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	40.0%	0.0%	0.0%	40.0%
Circuit Breakers	0.0%	0.0%	20.0%	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	60.0%
Climb Assist	0.0%	10.0%	20.0%	0.0%	10.0%	20.0%	10.0%	0.0%	20.0%	0.0%
Collector System	0.0%	33.3%	0.0%	0.0%	0.0%	33.3%	0.0%	0.0%	0.0%	33.3%
Communications	20.0%	40.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	20.0%	20.0%
Commutator and Brushes	0.0%	25.0%	25.0%	0.0%	0.0%	25.0%	0.0%	0.0%	25.0%	0.0%

Figure 14 - Sample Enhanced Data Analysis Output

All numbers shown are notional and were created using a random number generator.

This data provides a wealth of information that can direct efforts to improve system performance. Example of information that can be extracted include

- Identification of components requiring frequent corrosion control
- Identification of components that require frequent rebooting
- Calculating the percentage of failures that require replacement, enabling more accurate sparing projections

Several industries have databases of common parts and their historical life expectancy. The table below is a sample of a larger table created by Barringer & Associates, Inc. of Humble, Texas that provides expected values for a range of commonly used components in the petrochemical industry.

Components	Beta Values (Weibull Shape Factor)			Eta Values (Weibull Characteristic Life--hours)		
	Low	Typical	High	Low	Typical	High
Ball bearing	0.7	**1.3**	3.5	14,000	**40,000**	250,000
Roller bearings	0.7	**1.3**	3.5	9,000	**50,000**	125,000
Sleeve bearing	0.7	**1**	3	10,000	**50,000**	143,000
Belts, drive	0.5	**1.2**	2.8	9,000	**30,000**	91,000
Bellows, hydraulic	0.5	**1.3**	3	14,000	**50,000**	100,000
Bolts	0.5	**3**	10	125,000	**300,000**	100,000,000
Clutches, friction	0.5	**1.4**	3	67,000	**100,000**	500,000
Clutches, magnetic	0.8	**1**	1.6	100,000	**150,000**	333,000
Couplings	0.8	**2**	6	25,000	**75,000**	333,000
Couplings, gear	0.8	**2.5**	4	25,000	**75,000**	1,250,000
Cylinders, hydraulic	1	**2**	3.8	9,000,000	**900,000**	200,000,000
Diaphragm, metal	0.5	**3**	6	50,000	**65,000**	500,000
Diaphragm, rubber	0.5	**1.1**	1.4	50,000	**60,000**	300,000
Gaskets, hydraulics	0.5	**1.1**	1.4	700,000	**75,000**	3,300,000
Filter, oil	0.5	**1.1**	1.4	20,000	**25,000**	125,000
Gears	0.5	**2**	6	33,000	**75,000**	500,000
Impellers, pumps	0.5	**2.5**	6	125,000	**150,000**	1,400,000
Joints, mechanical	0.5	**1.2**	6	1,400,000	**150,000**	10,000,000
Knife edges, fulcrum	0.5	**1**	6	1,700,000	**2,000,000**	16,700,000
Liner, recip. comp. cyl.	0.5	**1.8**	3	20,000	**50,000**	300,000
Nuts	0.5	**1.1**	1.4	14,000	**50,000**	500,000
"O"-rings, elastomeric	0.5	**1.1**	1.4	5,000	**20,000**	33,000
Packings, recip. comp. rod	0.5	**1.1**	1.4	5,000	**20,000**	33,000
Pins	0.5	**1.4**	5	17,000	**50,000**	170,000
Pivots	0.5	**1.4**	5	300,000	**400,000**	1,400,000
Pistons, engines	0.5	**1.4**	3	20,000	**75,000**	170,000
Pumps, lubricators	0.5	**1.1**	1.4	13,000	**50,000**	125,000
Seals, mechanical	0.8	**1.4**	4	3,000	**25,000**	50,000
Shafts, cent. pumps	0.8	**1.2**	3	50,000	**50,000**	300,000
Springs	0.5	**1.1**	3	14,000	**25,000**	5,000,000
Vibration mounts	0.5	**1.1**	2.2	17,000	**50,000**	200,000
Wear rings, cent. pumps	0.5	**1.1**	4	10,000	**50,000**	90,000
Valves, recip comp.	0.5	**1.4**	4	3,000	**40,000**	80,000
Machinery Equipment						
Circuit breakers	0.5	**1.5**	3	67,000	**100,000**	1,400,000
Compressors, centrifugal	0.5	**1.9**	3	20,000	**60,000**	120,000
Compressor blades	0.5	**2.5**	3	400,000	**800,000**	1,500,000
Compressor vanes	0.5	**3**	4	500,000	**1,000,000**	2,000,000
Diaphgram couplings	0.5	**2**	4	125,000	**300,000**	600,000
Gas turb. comp. blades/vanes	1.2	**2.5**	6.6	10,000	**250,000**	300,000
Gas turb. blades/vanes	0.9	**1.6**	2.7	10,000	**125,000**	160,000
Motors, AC	0.5	**1.2**	3	1,000	**100,000**	200,000
Motors, DC	0.5	**1.2**	3	100	**50,000**	100,000
Pumps, centrifugal	0.5	**1.2**	3	1,000	**35,000**	125,000
Steam turbines	0.5	**1.7**	3	11,000	**65,000**	170,000
Steam turbine blades	0.5	**2.5**	3	400,000	**800,000**	1,500,000
Steam turbine vanes	0.5	**3**	3	500,000	**900,000**	1,800,000
Transformers	0.5	**1.1**	3	14,000	**200,000**	14,200,000

Figure 15 - Detailed Failure Analysis

The table provides typical, low, and high values for the shape and scale parameters of the Weibull distribution for each component. The Weibull distribution is commonly used in reliability analysis. As a two parameter distribution, it has the flexibility to model components such as electronics that are often modeled with an exponential distribution, and mechanical systems with wear-out such as gearboxes. A Weibull distribution with a shape parameter of 1 is mathematically the same as an exponential distribution. The “failed item age” field in the enhanced data set will allow development of this type of data. This information can be useful for reliability predictions and cost projections.

Additional possible analysis:

- Maintenance Man Hours by turbine size
- Maintenance Man Hours by turbine type
- Maintenance Man Hours by component
- Failure Mode Breakdown by Component

7 Data Challenges

The largest single challenge in collecting reliability data from wind farms is the proprietary nature of the data. To address concerns of the protection of proprietary information from release, Sandia implemented the following expectations for information sharing:

- Each data partner will be asked to sign a Non-Disclosure Agreement which will protect that member's data along with other commercially sensitive information.
- Information to be presented at any advisory or internal meetings will be specifically marked as proprietary and will be shared only with any attendees covered by an NDA.
- Publically available reporting will only contain data aggregated sufficiently that the original data sources cannot be identified.

Other challenges exist because of large individual variability from turbine to turbine and because the individual event data sets may be extremely sparse. Further, the descriptive characteristics from event to event can be quite inconsistent.

It is expected that data provided initially will not contain data for many of the desired fields. Failure data for plant equipment and processes likely contains issues with the definition of "failure," data accuracy, data recording ambiguities, data accessibility, and incomplete cost information. In some cases terminology differences can be resolved and data can be converted in a format that will facilitate aggregating the data with data from other sources.

Over time, the steering committee consisting of Sandia and the participating partners will work toward standardization where possible.

7.1 Data Formatting and Normalization

Wind plants have many different methods for gathering and processing their data. Although turbine manufacturers collect similar data values, the data points are structured, stored, named, and aggregated in a variety of ways. An understanding of these differences and a standardized approach for inputs into the database are necessary. To get data into the National Reliability Database, the proper structure must be in place to import the data.

A wind turbine taxonomy has been developed (see Appendix A for the taxonomy breakdown) that lists the components and subcomponents of most modern wind turbines. SCADA codes from the data partners' plant SCADA systems are each matched to a single component in this taxonomy. For example, a SCADA code by the name of "Generator Overspeed Sensor" would be matched to the "Generator::Shaft::Encoder" component in the taxonomy. Once the data has been entered and matched to the appropriate component, analysis can begin.

Work order data is also entered into the National Reliability Database. The process entails preparing electronic work order data into the proper format so that the information matches the fields in the database tables. This is a time consuming process, but the information in the work orders is valuable as a useful work order will contain information regarding symptom, cause and corrective action.

8 Reporting and Analysis Output

Reporting and analysis is performed on two levels – national baseline reports and partner reports. National Baseline Reports illustrate the national performance of the wind energy industry as a whole. These reports document performance, highlight unexpected (both positive and negative) findings, and make TIO (Technology Improvement Opportunity) recommendations. Partner Reports are provided to each of the data partners illustrating their wind plant(s) performance and comparing this to the national baseline. In addition to the partner report, custom analysis may be performed for partners with specific questions, as time and resources permit.

8.1 National Baseline Report

Data from each of the participating partners will be combined and five key metrics will be computed as shown in the table below. Additionally, a graphic summary of how a typical turbine spends its time will be provided. For each main turbine system, the annual number of events per year per turbine, and the mean downtime per event will be reported as well. Examples of these figures are shown below. Note that the benchmarks are currently cumulative, with each including all the valid information gathered as of its preparation for publication.

		Last 6 Months	*All Available Data*
Events Included	**Metric**	**National Mean Value**	**National Mean Value**
All Events	Operational Availability	X%	X%
	Technical Availability	X%	X%
	Utilization	X%	X%
	Production Based Availability	X%	X%
Corrective Maintenance Events	Mean Time Between Maintenance - Corrective ($MTBM_C$)	X	X
	Mean Down Time - Corrective Maintenance (MDT_{CM})	X	X
Scheduled Maintenance Events	Mean Time Between Maintenance - Scheduled ($MTBM_S$)	X	X
	Mean Down Time - Scheduled Maintenance (MDT_{SM})	X	X
All Maintenance Events	Mean Time Between Maintneance (MTBM)	X	X
	Mean Down Time - Maintenance (MDT_M)	X	X

Figure 16 - National Summary Statistics

Where appropriate various charts and graphs providing additional information related to these metrics will be provided. Examples are provided below.

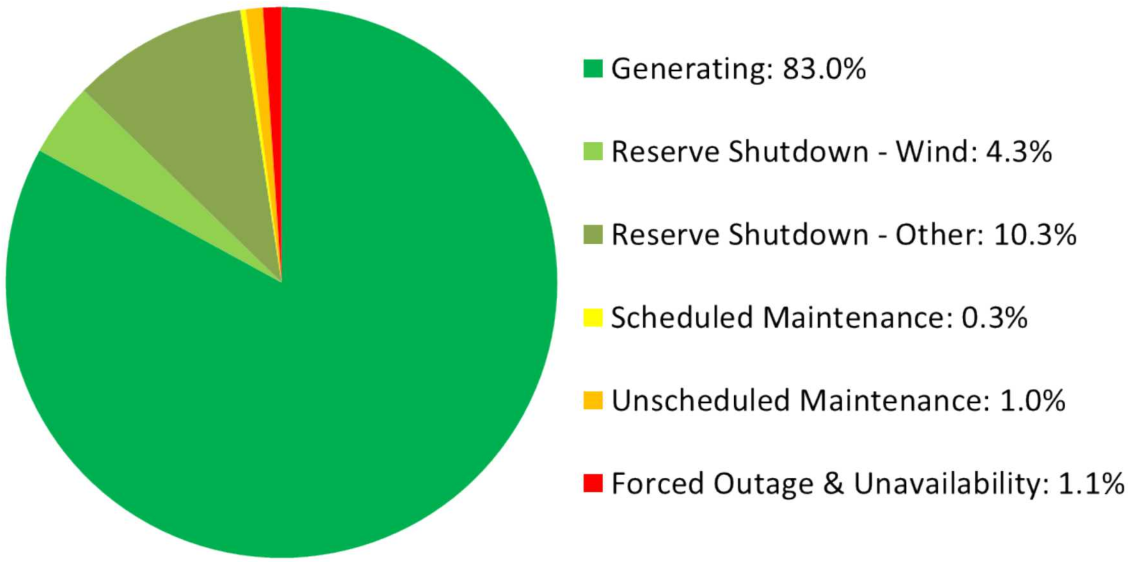


Figure 17 - Availability Time Accounting

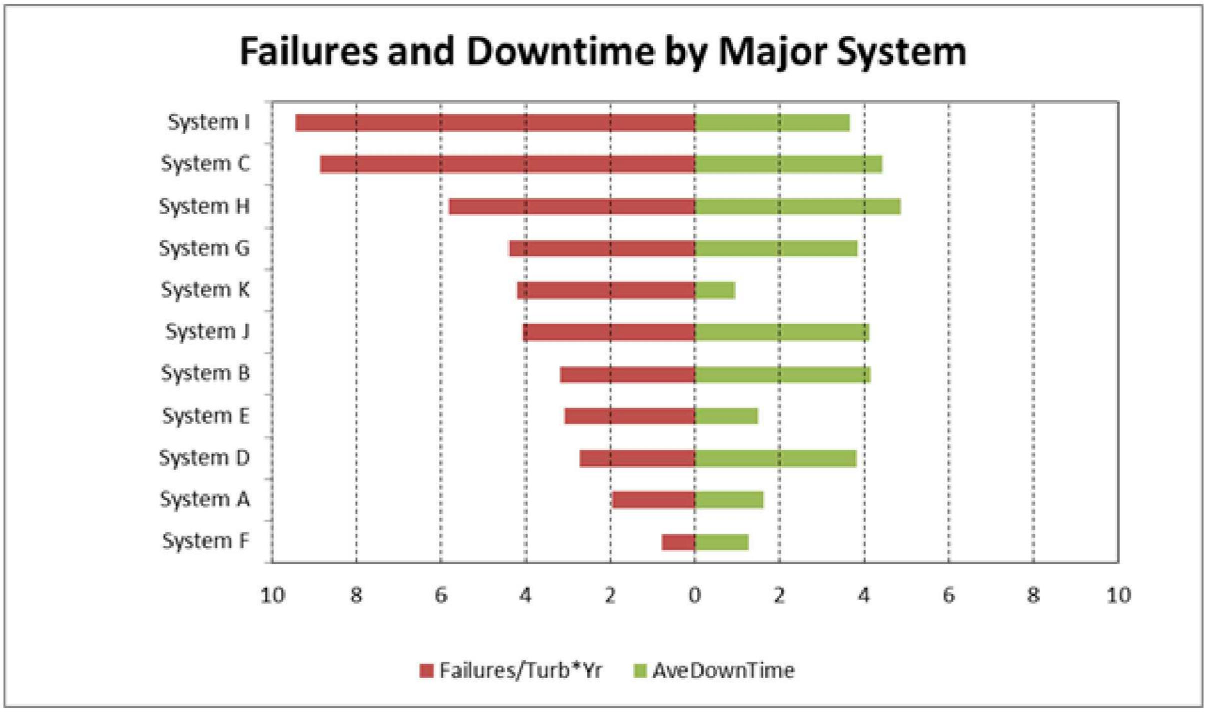


Figure 18 - Event Frequency versus Downtime

8.2 Partner Report

Partner reports contain graphs, charts, and analysis results intended to address two distinct needs: understanding of the partner's wind power plants' performance, and comparing the partner's fleet against the national baseline. Depending on the structure of the NDA with the partner, this may also include comparing a single plant against other plants owned by the same entity.

The report begins with high-level "Summary Statistics" of the partner's fleet performance, which is contrasted with National performance, as shown in Figure 19 below. This information creates a one-page "Executive" summary of the partner's fleet performance. The chart provides high level metrics which include the effects of all down time events, and provided additional metrics related to corrected (unscheduled) and scheduled maintenance.

		Last 6 Months		*All Available Data*	
Events Included	Metric	Plant Mean Value	National Mean Value	Plant Mean Value	National Mean Value
All Events	Operational Availability	X%	X%	X%	X%
	Technical Availability	X%	X%	X%	X%
	Utilization	X%	X%	X%	X%

	Production Based Availability	X%	X%	X%	X%
Corrective Maintenance Events	Mean Time Between Maintenance - Corrective ($MTBM_C$)	X	X	X	X
	Mean Down Time - Corrective Maintenance (MDT_{CM})	X	X	X	X
Scheduled Maintenance Events	Mean Time Between Maintenance - Scheduled ($MTBM_S$)	X	X	X	X
	Mean Down Time - Scheduled Maintenance (MDT_{SM})	X	X	X	X
All Maintenance Events	Mean Time Between Maintenance (MTBM)	X	X	X	X
	Mean Down Time - Maintenance (MDT_M)	X	X	X	X

Figure 19 - Partner Summary Statistics Compared with National Baseline

Charts containing more detail on the frequency and duration of failures will be provided with both partner fleet and national results where possible as shown in Figure 20.

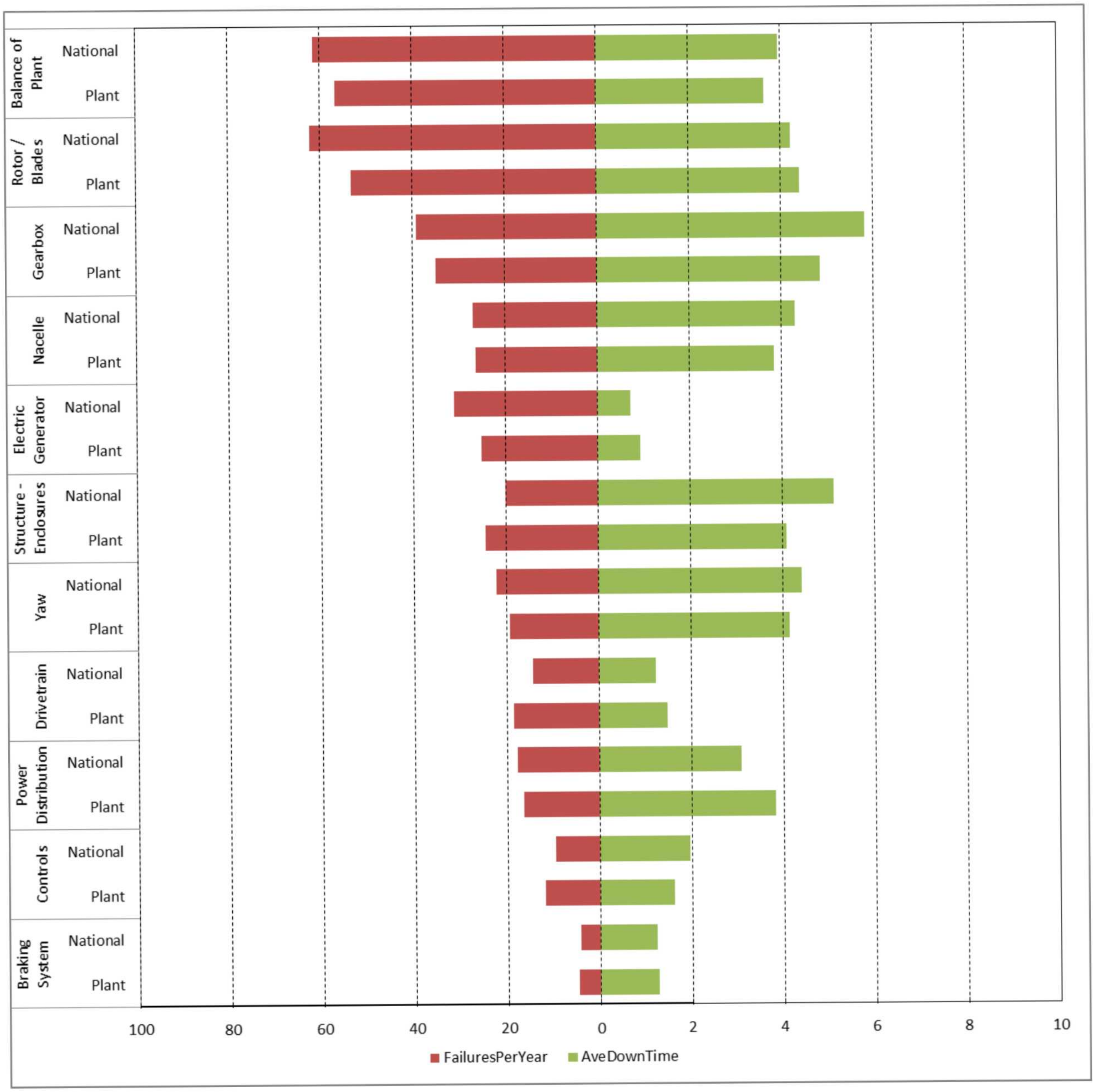


Figure 20 - Partner Failure Summary Compared with National Baseline

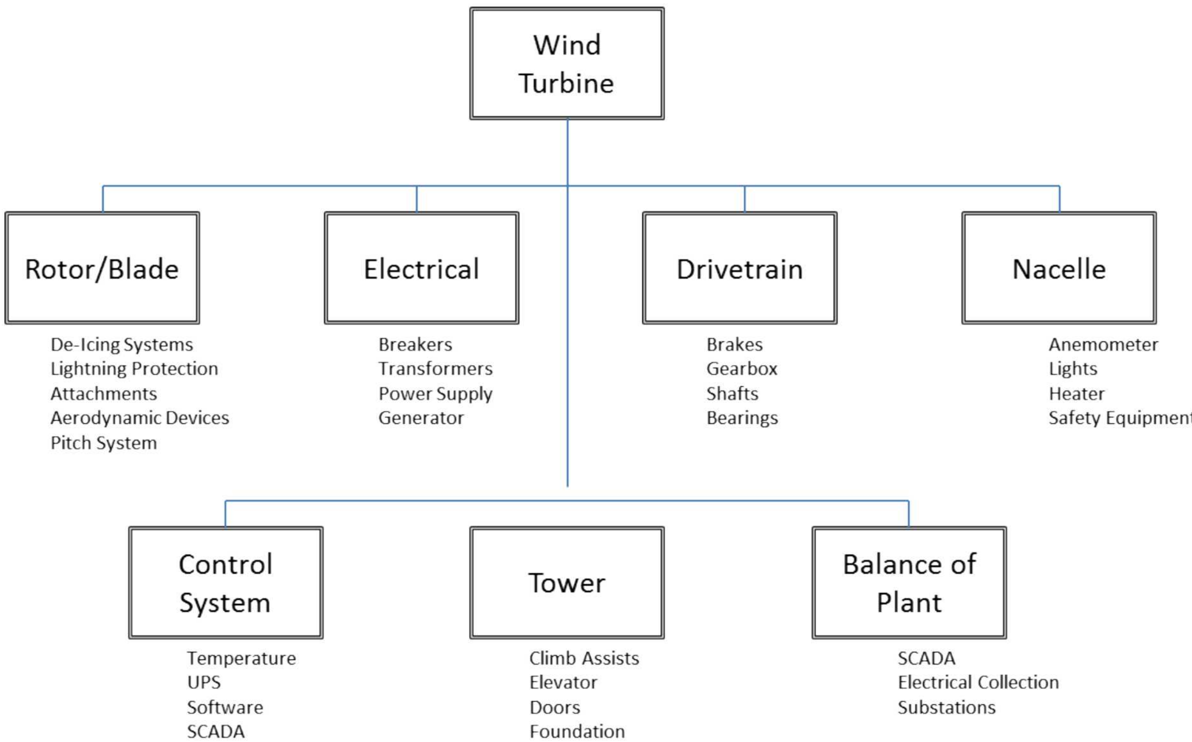
9 Summary

Sandia's Continuous Reliability Enhancement for Wind (CREW) Program, funded by the U.S. Department of Energy's Wind and Water Power Technologies Office, was initiated to facilitate the collection, analysis, and dissemination of reliability and performance data essential for determining fleet reliability issues. The CREW Program is a follow on project to the Wind Plant Reliability Database and Analysis Program. As with its predecessor program, the goal of CREW is to characterize the reliability performance of the US fleet to serve as a basis for improved reliability and increased availability of turbines. CREW extends the previous effort by including detailed analysis of maintenance records in order to provide more refined insight into reliability and sustainment of wind turbines.

Reporting and analysis is performed on two levels –partner reports and national baseline reports. Partner Reports are provided to each of our data partners illustrating their wind plant(s) performance and comparing this to the national baseline. National Baseline Reports illustrate the national performance of the wind energy industry as a whole. These reports document performance, highlight unexpected (both positive and negative) findings, and make TIO (Technology Improvement Opportunity) recommendations.

Appendix A: Full Taxonomy

The following taxonomy has been developed for the Continuous Reliability Enhancement for Wind Program. All data will be associated with one of the components listed.



Subsystem	Component
Balance of Plant	SCADA
Balance of Plant	Aux equipment (crane, fork lift etc)
Balance of Plant	Infrastructure (roads, buildings, etc)
Balance of Plant::Electrical Collection	Collector System
Balance of Plant::Electrical Collection	Grounding Transformer
Balance of Plant::Electrical Collection	Metering and Relays
Balance of Plant::Electrical Collection	Transmission Lines
Balance of Plant::Meteorological Tower	Anemometer
Balance of Plant::Meteorological Tower	Barometer/Temperature
Balance of Plant::Meteorological Tower	Communications
Balance of Plant::Meteorological Tower	Foundation
Balance of Plant::Meteorological Tower	Guidewires

Subsystem	Component
Balance of Plant::Meteorological Tower	Wind Vane
Balance of Plant::Substation	Circuit Breakers
Balance of Plant::Substation	Current Transformers
Balance of Plant::Substation	Fault Recorder
Balance of Plant::Substation	Grid Connection
Balance of Plant::Substation	Ground Conductors
Balance of Plant::Substation	Ground Rods
Balance of Plant::Substation	Grounding Fault Relay
Balance of Plant::Substation	Grounding system
Balance of Plant::Substation	Lightning Arrestors
Balance of Plant::Substation	Over Current Relay
Balance of Plant::Substation	Over or Under Frequency Relay
Balance of Plant::Substation	Phase Imbalance Relay
Balance of Plant::Substation	Phaser Measurement Units
Balance of Plant::Substation	Potential Transformers
Balance of Plant::Substation	Remote Telecon Unit (RTU)
Balance of Plant::Substation	Sequence of Events Recorder
Balance of Plant::Substation	Step Up Transformer
Balance of Plant::Substation	Substation
Balance of Plant::Substation	Switches
Balance of Plant::Substation	VAR Control System
Control System	Ambient temperature
Control System	Cabinet, power supply or UPS
Control System	Central Processor, CPU or I/O board
Control System	Control Pad
Control System	Software fault, version history issue, interface
Control System::SCADA Interface	Cables and Connections
Control System::SCADA Interface	External Communications
Control System::SCADA Interface	Internal Communications
Control System::SCADA Interface	Power Metering
Drivetrain	Brake Calipers
Drivetrain	Brake Disc
Drivetrain	Brake Pads
Drivetrain	Actuator
Drivetrain	Transmission Lock
Drivetrain::Gearbox	Carrier Bearing
Drivetrain::Gearbox	Cooling System::Hoses
Drivetrain::Gearbox	Cooling System::Pump
Drivetrain::Gearbox	Cooling System::Radiator
Drivetrain::Gearbox	Hollow Shaft
Drivetrain::Gearbox	Housing
Drivetrain::Gearbox	Lube System Sensor

Subsystem	Component
Drivetrain::Gearbox	Lube System::Hose/Fitting/Resovoir
Drivetrain::Gearbox	Lube System::Filtration
Drivetrain::Gearbox	Lube System::Pump & pump motor
Drivetrain::Gearbox	Particulate Sensor
Drivetrain::Gearbox	Planet Bearing
Drivetrain::Gearbox	Planet Gear
Drivetrain::Gearbox	Ring Gear
Drivetrain::Gearbox	Seals
Drivetrain::Gearbox	Shaft Bearing
Drivetrain::Gearbox	Spur Gear
Drivetrain::Gearbox	Sun Gear
Drivetrain::Gearbox	Temperature Sensor
Drivetrain::Gearbox	Torque Arm System
Drivetrain	High Speed Coupling
Drivetrain	High Speed Shaft
Drivetrain	Rotor Lock (High Speed Side)
Drivetrain	Compression Coupling (Low Speed Side)
Drivetrain	Connector Plate (Low Speed Side)
Drivetrain	Main Bearing (Low Speed Side)
Drivetrain	Main Bearing Seal (Low Speed Side)
Drivetrain	Main Shaft (Low Speed Side)
Drivetrain	Rotor Lock (Low Speed Side)
Drivetrain	Slip Ring Assembly (Low Speed Side)
Electrical	Cabinet Heater
Electrical	Crowbar System
Electrical	Harmonics Filter
Electrical	IGBT Module
Electrical	Main Circuit Breaker
Electrical	Main Contactor
Electrical	Main Disconnect
Electrical	Motor Contactor
Electrical	Transformer (Nacelle-Mounted)
Electrical	Transformer (Pad-Mounted)
Electrical	Power Supply
Electrical	Rectifier Bridge
Electrical	Soft Starter
Electrical::Generator	Auto Lube System
Electrical::Generator	Commutator and Brushes
Electrical::Generator	Cooling Fan
Electrical::Generator	Encoder
Electrical::Generator	Exciter
Electrical::Generator	Generator Temperature Sensor

Subsystem	Component
Electrical::Generator	Housing
Electrical::Generator	Radiator
Electrical::Generator	Resistance Controller
Electrical::Generator	Rotor Front Bearing
Electrical::Generator	Rotor Lamination
Electrical::Generator	Rotor Magnets
Electrical::Generator	Rotor Rear Bearing
Electrical::Generator	Rotor Winding
Electrical::Generator	Shaft
Electrical::Generator	Slip Ring
Electrical::Generator	Stator Lamination
Electrical::Generator	Stator Winding
Nacelle	Anemometer
Nacelle	Cat Walks
Nacelle	Crane
Nacelle	Hatches
Nacelle	De-icing Heater
Nacelle	Exit Latches
Nacelle	FAA Lights
Nacelle	Ladders, landings and landing pads
Nacelle	Nacelle Heater
Nacelle	Nacelle Lighting
Nacelle	Nacelle Vent
Nacelle	Fire suppression system
Nacelle	Safety Equipment
Nacelle	Support Frame
Nacelle	Temperature Sensor
Nacelle	Wind Vane
Nacelle::Yaw	Brake
Nacelle::Yaw	Cable Twist/Untwist
Nacelle::Yaw	Cable Twist/Untwist::Position Sensor
Nacelle::Yaw	Damper
Nacelle::Yaw	Gear
Nacelle::Yaw	Hydraulic Hoses, Valves, Accumulator
Nacelle::Yaw	Hydraulic Pump and motor
Nacelle::Yaw	Motor
Nacelle::Yaw	Pinion
Nacelle::Yaw	Slew Ring
Rotor/Blade	De-icing System
Rotor/Blade	Hub Nose Cone and hatch
Rotor/Blade	Internal Structure (Laminates)
Rotor/Blade	Lightning Protection, receptor(s) (or conductive skin)

Subsystem	Component
Rotor/Blade	Lightning Protection, down conductors
Rotor/Blade	Lightning Protection, connectors to hub
Rotor/Blade	Paint and Coatings damage
Rotor/Blade	Rotor Attachment Nuts, Bolts, T bolts, flanges
Rotor/Blade	Skins (Laminates)
Rotor/Blade	Sandwich failure
Rotor/Blade	Leading edge gluebond
Rotor/Blade	Trailing edge gluebond
Rotor/Blade	Spar and other gluebonds
Rotor/Blade	Aerodynamic devices (vortex generators, stall strips, gurney flaps etc)
Rotor/Blade	Leading edge protection (heli tape, coating etc.)
Rotor/Blade::Pitch System	Accumulator or Battery
Rotor/Blade::Pitch System	Auto Lube System
Rotor/Blade::Pitch System	Bearings
Rotor/Blade::Pitch System	Bushing
Rotor/Blade::Pitch System	Cabling
Rotor/Blade::Pitch System	Contactor/Circuit Breaker Fuse
Rotor/Blade::Pitch System	Actuator: Pitch Cylinder or Electrical motor, pinion and gear
Rotor/Blade::Pitch System	Encoder
Rotor/Blade::Pitch System	Heater
Rotor/Blade::Pitch System	Hydraulic components Hose/Fitting/drive
Rotor/Blade::Pitch System	Limit Switch
Rotor/Blade::Pitch System	Linkage
Rotor/Blade::Pitch System	Pitch Cylinder Linkage
Rotor/Blade::Pitch System	Pitch Gear
Rotor/Blade::Pitch System	Position Controller
Rotor/Blade::Pitch System	Position Sensor
Rotor/Blade::Pitch System	Power Electronics/Drive
Rotor/Blade::Pitch System	Power Supply or battery charger
Rotor/Blade::Pitch System	Proportional Valve
Rotor/Blade::Pitch System	Pitch actuator, Pump and motor
Rotor/Blade::Pitch System	Rotary Electric Drive
Rotor/Blade::Pitch System	Seals
Rotor/Blade::Pitch System	Spherical Bushing
Tower	Climb Assist
Tower	Elevator
Tower	Doors and hatches
Tower	Foundation
Tower	Foundation::Bolts
Tower	Foundation::Rebar
Tower	Damper system

Subsystem	Component
Tower	Ladders, stairs, landings and landing pads
Tower	Lighting and working power
Tower	Maintenance Crane
Tower	Section Nuts and Bolts
Tower	Flanges and weldings
Tower	Paint and Coatings

Appendix B: Failure Modes

Performance drivers are events which affect reliability metrics. The following figures illustrate the performance drivers (using the full level of detail in the taxonomy) with the most significant negative effect on the metric listed.

Failure Modes
ABRASIONS, EROSION, PIT (COMPOSITES)
ADJUSTMENT OR ALIGNMENT IMPROPER
ADVERSE OIL CONSUMPTION TREND
ADVERSE RPM TREND
ATTENUATION INCORRECT
BACKUP/EMERGENCY CONTROL SYSTEM FAILURE
BEARING AND/OR SUPPORT FAILURE
BEARING FAILURE (CAUSING ROTOR SHIFT SEIZURE)
BEARING FAILURE OR FAULTY
BEARING/HEADING ERROR
BENT, BUCKLED, COLLAPSED, DENTED, DISTORTED OR TWISTED
BINDING, STUCK OR JAMMED
BROKEN
BUILT IN TEST (BIT) FAILED TO INDICATE A FAULT WHEN ONE EXISTS
BUILT IN TEST (BIT) FALSE ALARM
BUILT IN TEST (BIT) INDICATED WRONG UNIT FAILED
BURNED OR OVERHEATED
BURNED OUT OR DEFECTIVE LAMP, METER OR INDICATING DEVICE
BURST OR RUPTURED
CAPACITANCE INCORRECT
CHEMICAL IMBALANCE (COMPOSITES)
COMPUTER EQUIPMENT MALFUNCTION
COMPUTER MEMORY ERROR/DEFECT
CONDUCTANCE INCORRECT
CONTACTS/CONNECTION DEFECTIVE
CONTAMINATED OIL
CONTAMINATION
CONTROL SYSTEM COMPONENT MALFUNCTION
CORRODED EXTERNAL SURFACES
CORRODED INTERNAL SURFACES
CORRODED MILD/MODERATE
CORRODED SEVERE
COULD NOT DUPLICATE
CRACKED
CURRENT INCORRECT
CUT
DAMAGE BY ACCIDENT OR INCIDENT
DAMAGE BY SEMI-SOLID FOREIGN OBJECT (BIRDS)

Failure Modes
DAMAGE BY SEMI-SOLID FOREIGN OBJECTS (ICE)
DAMAGE BY SOLID FOREIGN OBJECTS (METAL, STONE)
DAMAGED OR DEFECTIVE COMPONENT
DAMAGED PROBE
DAMAGED/CRACKED
DATA ERROR
DELAMINATED
DETERIORATED
DIRTY
DOES NOT ENGAGE, LOCK OR UNLOCK CORRECTLY
DOES NOT MEET SPECIFICATIONS
DOES NOT TRACK TUNING CURVE
EXCESSIVE VIBRATION OR ROUGH OPERATION
EXPIRATION OF MAXIMUM CYCLES
FAILED OR DAMAGED DUE TO MALFUNCTION OF ASSOCIATED EQUIPMENT
FAILED TO OPERATE- SPECIFIC REASON UNKNOWN
FAILS DIAGNOSTIC/AUTOMATIC TEST
FAILS TO TRANSFER TO REDUNDANT EQUIPMENT
FAILS TO TUNE OR DRIFTS
FAULTY CARD, TAPE, PROGRAM OR DISK
FAULTY TUBE, TRANSISTOR OR INTEGRATED CIRCUIT
FLUCTUATES, UNSTABLE OR ERRATIC
FREQUENCY OUT OF BAND, UNSTABLE OR INCORRECT
FROZEN
FROZEN TUNING MECHANISM
HIGH FREQUENCY VIBRATIONS
HIGH OIL PRESSURE
HIGH OR LOW OIL CONSUMPTION
HIGH VOLTAGE OR STANDING WAVE RATIO
HOLE WEAR, OUT OF ROUND (COMPOSITE STRUCTURE)
ILLEGAL OPERATION OR ADDRESS
IMPENDING FAILURE OR LATENT DEFECT
IMPENDING OR INCIPIENT FAILURE
IMPROPER HANDLING, SHIPPING OR MAINTENANCE DAMAGE
INCORRECT GAIN
INCORRECT MODULATION
INCORRECT OUTPUT
INDUCTANCE INCORRECT
INPROPER RESPONSE TO ELECTRICAL INPUT
INPROPER RESPONSE TO MECHANICAL INPUT
INPUT/OUTPUT PULSE DISTORTION
INSULATION BREAKDOWN
INTEGRAL REDUCTION GEAR FAILURE
INTERMITTENT

Failure Modes
INTERNAL NOISE
LACK OF/OR IMPROPER LUBRICATION
LEAD BROKEN
LEAKING
LIGHTNING STRIKE
LOOSE
LOOSE, DAMAGED OR MISSING HARDWARE
LOSS OF VACUUM
LOW COOLANT FLOW RATE
LOW FREQUENCY VIBRATIONS
LOW OIL PRESSURE
LOW POWER (ELECTRICAL)
METAL ON MAGNETIC PLUG/FILTER/SCREEN
MISSING
MISSING AND LOOSE FIBERS (COMPOSITES)
NO DEFECT
NO DISPLAY
NO OUTPUT
NOISY/CHATTERING
NONPROGRAMMED HALT
OPEN
OPERATOR ERROR
OPPORTUNISTIC MAINTENANCE REMOVAL
OSCILLATING
OUT OF BALANCE
OUT OF TRACK
OVERSPEED
OVERTEMPERATURE
PITTED, NICKED, CHIPPED, SCORED SCRATCHED OR CRAZED
POOR SPECTRUM
POTTING MATERIAL MELTING (REVERSION PROCESS)
REMOVAL FOR RESEARCH, TEST OR DIAGNOSTIC EVENT
REMOVAL FOR REUSE (CANNIBALIZATION)
REMOVAL TO PERFORM SCHEDULED/SPECIAL INSPECTION
RESISTANCE INCORRECT
SCOPE PRESENTATION INCORRECT OF FAULTY
SEIZED
SHEARED
SHORTED
SURFACE-PLY RIPS, PEELED (COMPOSITE STRUCTURE)
SYNC ABSENT OR INCORRECT
TEMPERATURE LIMITS EXCEEDED
TEMPERATURE SENSITIVE
TENSION OR TORQUE INCORRECT
TRAVEL OR EXTENSION INCORRECT

Failure Modes
UNABLE TO ADJUST TO LIMITS
UNABLE TO LOAD PROGRAM
UNBONDED DEFECTS IN BONDED JOINT (ALL STRUCTURES)
UPDATE/VERIFICATION OF PROGRAM/SOFTWARE LOAD
VIBRATION TREND CHANCE OCCURRENCES
VOIDS (COMPOSITE STRUCTURE)
VOLTAGE INCORRECT
WARPED
WET/CONDENSATION
WORN, CHAFFED, FRAYED OR TORN
OTHER
UNKNOWN

Appendix C: Maintenance Type, Failure Type, and Action Taken

Performance drivers are events which affect reliability metrics. The following figures illustrate the performance drivers (using the full level of detail in the taxonomy) with the most significant negative effect on the metric listed.

Maintenance Type
UNSCHEDULED (CORRECTIVE)
SCHEDULED (PREVENTIVE)
INSPECTION

Failure Type
INHERENT
INDUCED
NO FAILURE

Code	Action Taken
1	ADJUSTMENT
2	CALIBRATE
3	CLEAN
4	CORROSION TREATMENT
5	EQUIPMENT CHECKED - NO REPAIR REQUIRED
6	INSTALL
7	REBOOT OR MINOR ADJUSTMENT CLEARED FAULT
8	REMOVE AND REPLACE
9	REMOVE FOR CANNIBALIZATION
10	REPAIR
11	REPLACE FOR CANNIBALIZATION
12	TEST, INSPECT, SERVICE
13	OTHER

Appendix D: Acronyms

Acronym	Definition
A_O	Operational Availability
A_T	Technical Availability
CREW	Continuous Reliability Enhancement for Wind
DOE	Department of Energy
DT	Down Time
GE	General Electric
IAFM	Information Available, Force Majeure
IANOFO	Information Available, Non-Operative, Forced Outage
IANOPCA	Information Available, Non-Operative, Planned Corrective Action
IANOS	Information Available, Non-Operative, Suspended
IANOSM	Information Available, Non-Operative, Scheduled Maintenance
IAOGFP	Information Available, Operative, Generating, Full Performance
IAOGPP	Information Available, Operative, Generating, Partial Performance
IAONGEL	Information Available, Operative, Non-Generating, Out of Electrical Specification
IAONGEN	Information Available, Operative, Non-Generating, Out of Environmental Specification
IAONGRS	Information Available, Operative, Non-Generating, Requested Shutdown
IAONGTS	Information Available, Operative, Non-Generating, Technical Standby
IEC	International Electrotechnical Commission
IU	Information Unavailable
MDT	Mean Down Time
MHI	Mitsubishi Heavy Industries
MTBCF	Mean Time Between Critical Failures
MTBDE	Mean Time Between Downing Events
MTBM	Mean Time Between Maintenance
$MTBM_{CM}$	Mean Time Between Maintenance - Corrective Maintenance
$MTBMS_{M}$	Mean Time Between Maintenance - Scheduled Maintenance
MW	Megawatts
PBA	Production Based Availability
SCADA	Supervisory Control and Data Acquisition
SNL	Sandia National Laboratories
UPS	Uninterruptible Power Supply

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