Continuous Reliability Enhancement for Wind (CREW) Database

Wind Turbine Reliability Benchmark

U.S. Fleet; Public Report

October 2011

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Acknowledgements

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•This public benchmark report is the first industry report to be issued under the Continuous Reliability Enhancement for Wind (CREW) national database project. 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 individual partners is proprietary and is only used in an aggregated manner in this report, in order to protect data privacy.

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NNSA National Nuclear Security Administration

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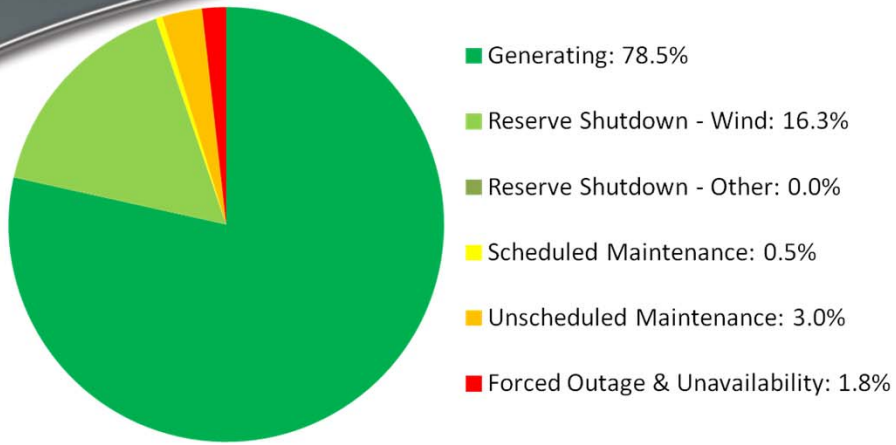
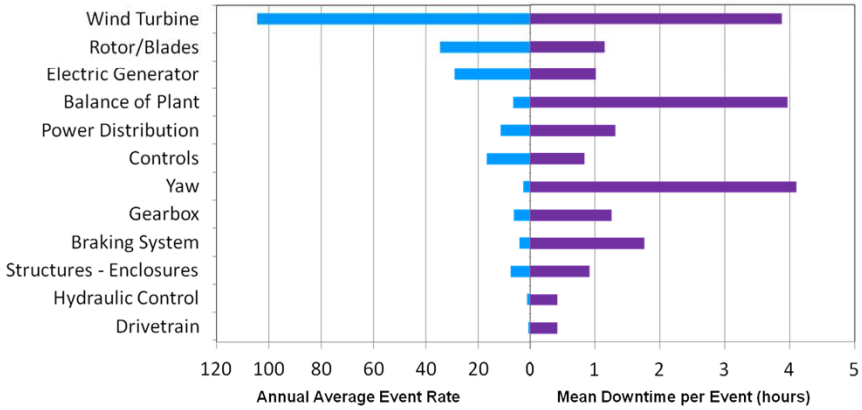
Results at a Glance



- Overall performance in line with expectations
- Data represents 39,000 turbine-days for analysis

- Gearbox not in top 5 systems
  - Have not collected data long enough to estimate impact of major repairs
  - Benchmarking day-to-day performance, at this point



Operational Availability	94.8%
Generating Factor (aka Utilization)	78.5%
Capacity Factor	33.4%
MTBE	28 hrs
Mean Downtime	2.5 hrs

- Approximately 1 day of generating (28 generating hours) between downtime events; events last 2.5 hours
  - Some events automatically reset, others need intervention

Event & SCADA Data Source: ORAP ® for Wind

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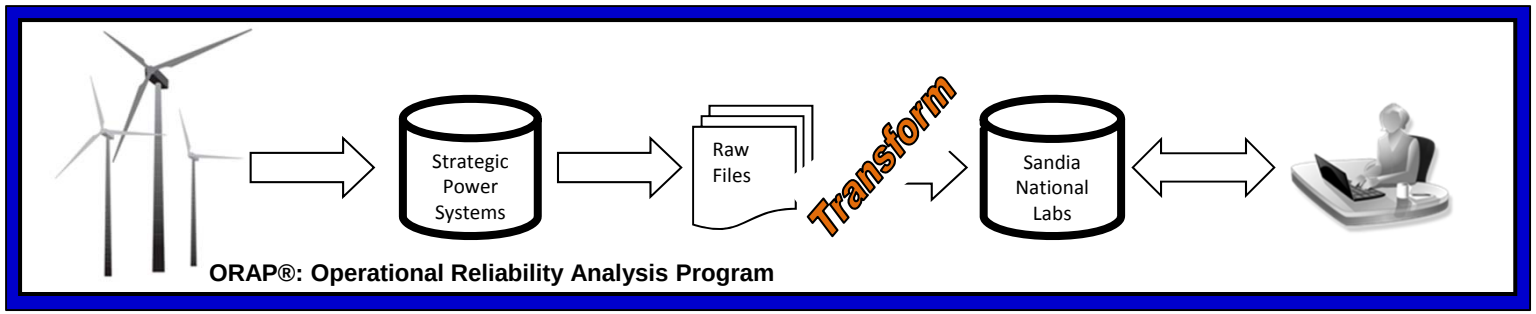
Outline

CREW: Continuous Reliability Enhancement database for Wind

Create a *national reliability database* of wind plant operating data to enable reliability analysis

Sandia partnered with Strategic Power Systems (SPS), whose ORAP® software collects real-time data from wind plant partners.



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

Fleet Representation

- The results presented here are considered "directional" by the authors. This is the first CREW public benchmark, and is based on data collected during the development phase of the project.
- Because the database does not yet represent a significant portion of the U.S. wind turbine fleet*, it would be premature to consider the results here fully "actionable."*
- However, the data quality and operations breadth provided by early data partners has generated a dataset that provides a useful initial view of the U.S. fleet's operational and reliability performance.

- The CREW database continues to grow, in terms of new plants, new technologies, and more information from existing partners.
  - Current data covers three seasons and 58,000 turbine-days of data.
    - 39,000 turbine-days of 'known' time
    - 19,000 turbine-days of unknown time
  - **Future reporting will be based on larger samples** and will fulfill the goal of representing the US fleet's performance.

- Scope includes wind turbines at or above 1 MW in size.

- **Work Order information** is critical to "filling in the blanks" about downtime event root cause. This valuable data will be aggressively pursued.

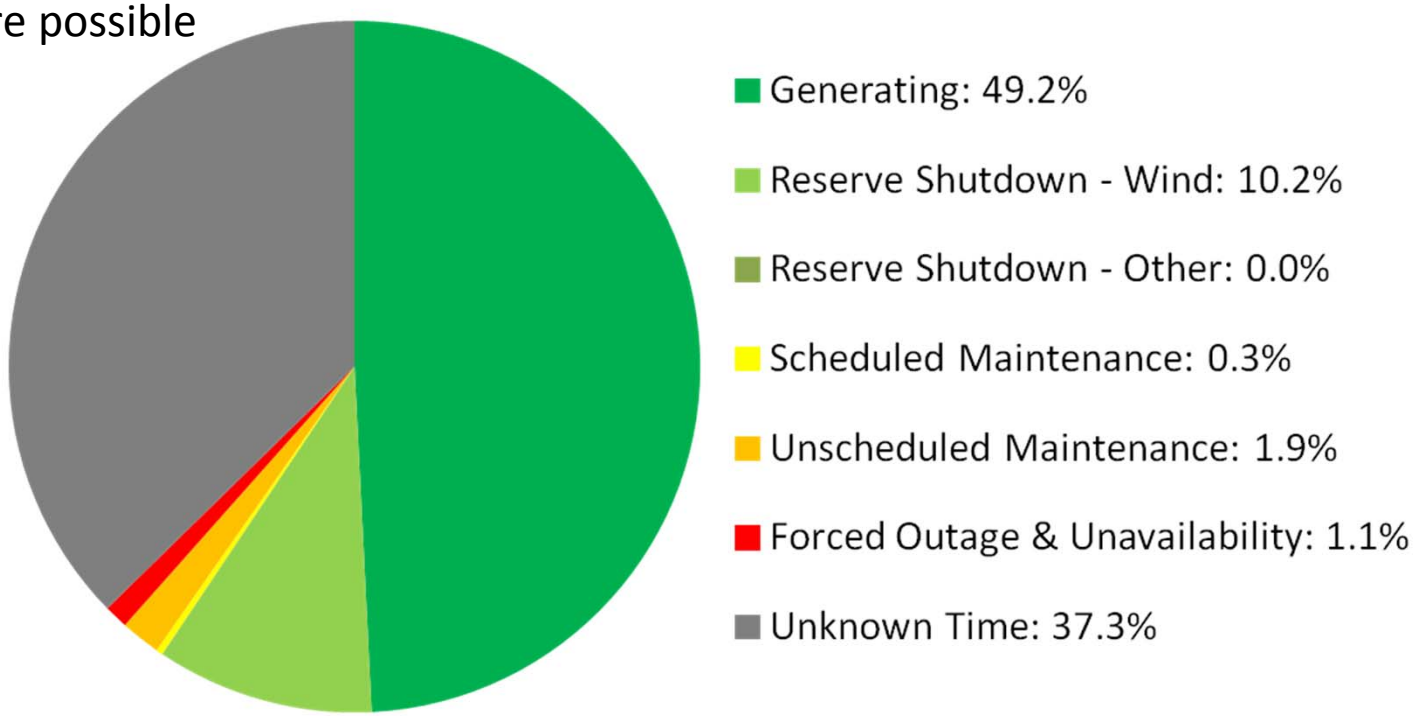
- A non-trivial amount of **variability** exists in the data, with best-in-class performance sometimes varying by as much as an order of magnitude over typical performance.

Results & Discussion

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Availability Time Accounting

- **SCADA and data transfer challenges lead to "Unknown Time"**
  - Availability analysis needs to highlight the common communication and IT issues resulting in missing data*
  - CREW team is actively identifying these industry-wide issues & addressing them where possible

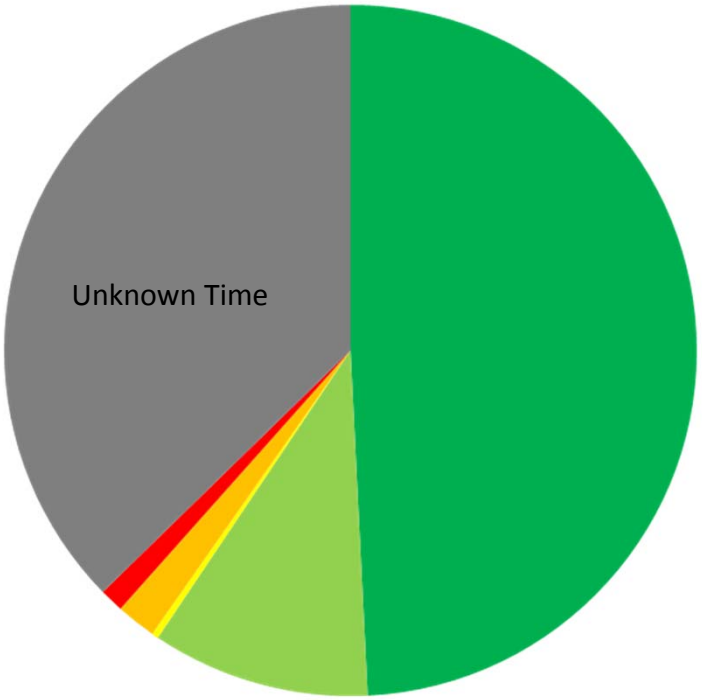


**Substantial portion of Unknown Time is attributable to pilot program & associated beta testing*

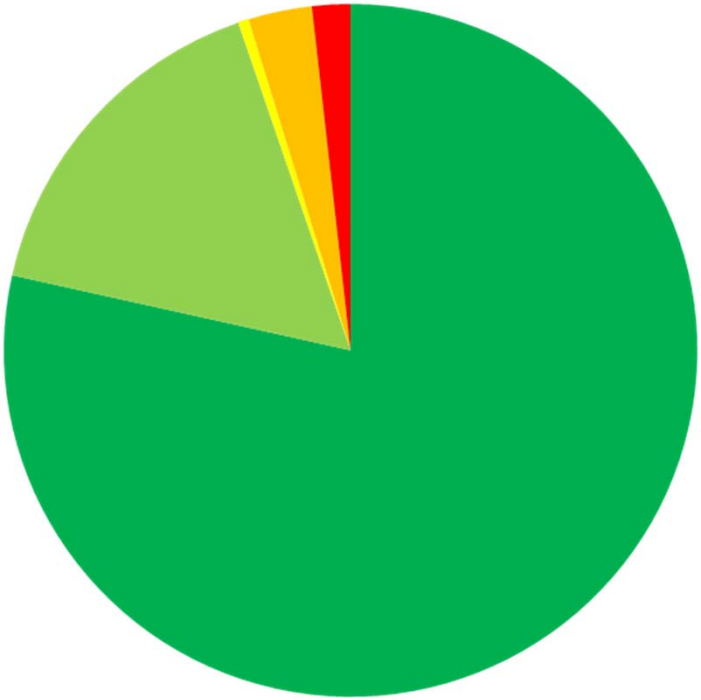
Focusing on What is Known

- **In addition to understanding Unknown Time impact, also explore results after this time is removed**
  - Essentially treated as if it never existed; did not assume turbine's status

All Data



Unknown Time Removed

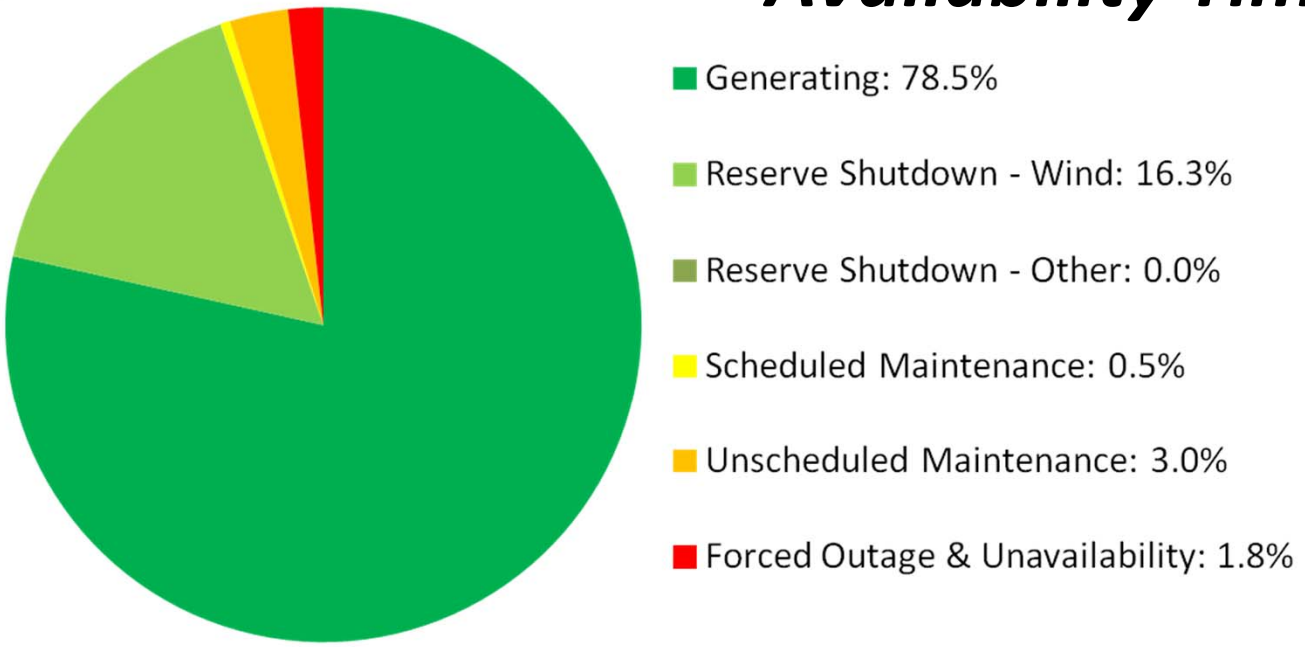


**Substantial portion of Unknown Time is attributable to pilot program & associated beta testing*

Event & SCADA Data Source: ORAP ® for Wind

Without Unknown Time

Availability Time Accounting



Generating Factor (aka Utilization)	78.5%
Operational Availability	94.8%

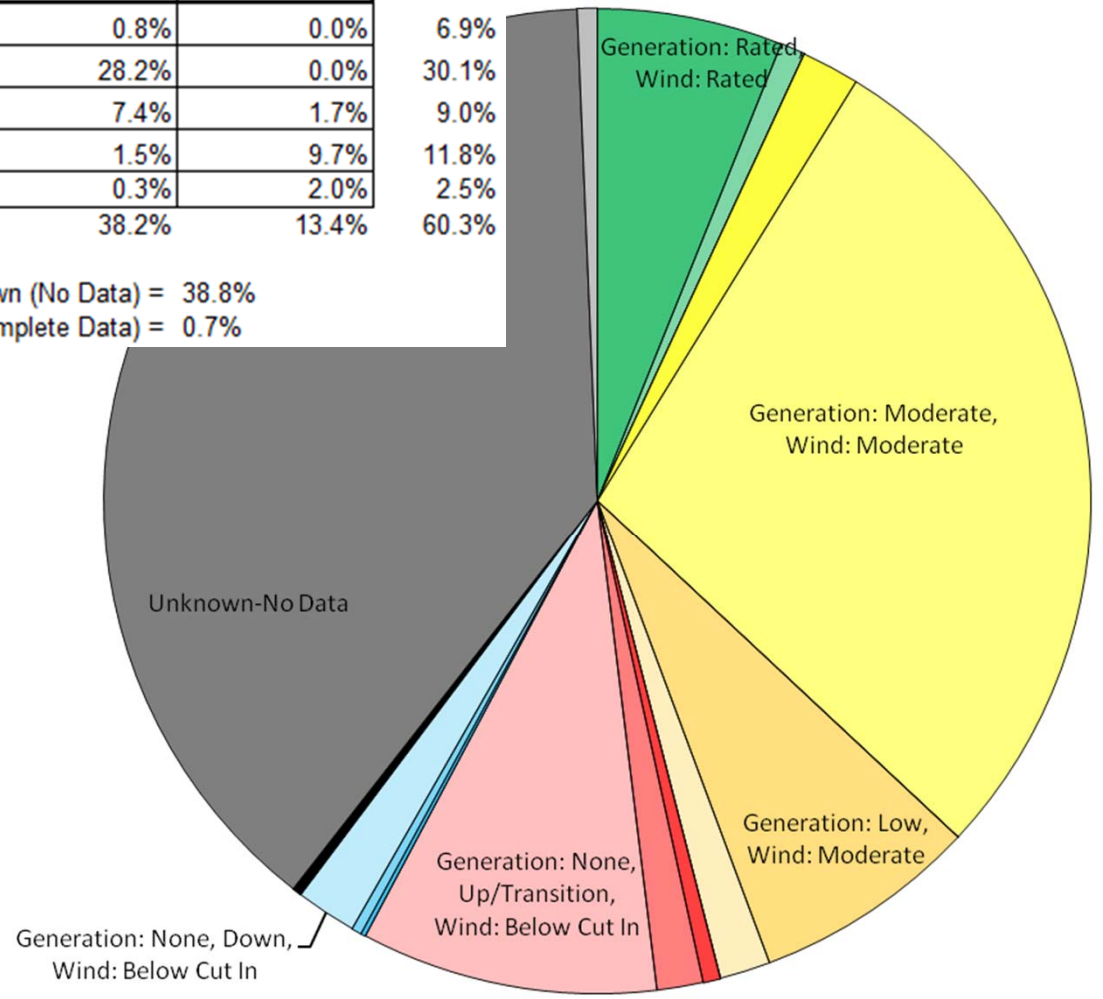
- **Generating Factor** = Generating
- **Operational Availability** = Generating + Reserve Shutdown Wind
- Can calculate other metrics of interest from these categories
  - Example: Technical Availability
    - Up Time: (Generating + Reserve Shutdown Wind + Reserve Shutdown Other)
    - Down Time: (Unscheduled Maintenance + Forced Outage & Unavailability)

Wind Speed & Generation Time Accounting

Percent of Time		Wind				
		Above Cut Out	Rated	Moderate	Below Cut In	
Generation	Rated, Over-Rated	0.0%	6.1%	0.8%	0.0%	6.9%
	Moderate	0.0%	1.9%	28.2%	0.0%	30.1%
	Low	0.0%	0.0%	7.4%	1.7%	9.0%
	None (Up, Transition)	0.0%	0.6%	1.5%	9.7%	11.8%
	None (Down)	0.0%	0.2%	0.3%	2.0%	2.5%
		0.0%	8.7%	38.2%	13.4%	60.3%

Transition = 0.3%
Down with Generation = 0.0%

Unknown (No Data) = 38.8%
Unknown (Incomplete Data) = 0.7%



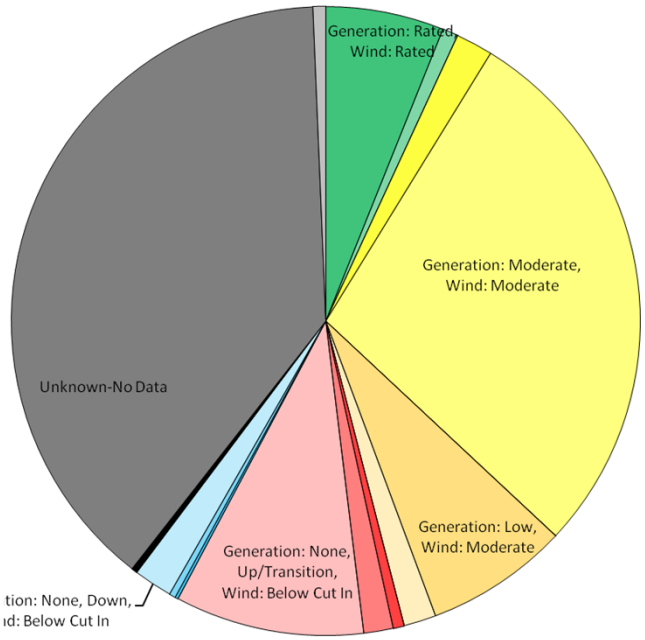
- Categories show combination of what the turbine is doing & what the wind is doing
  - Adds Environmental Impact (Wind Speed) on Turbine (Power Generation)

Event & SCADA Data Source: ORAP ® for Wind

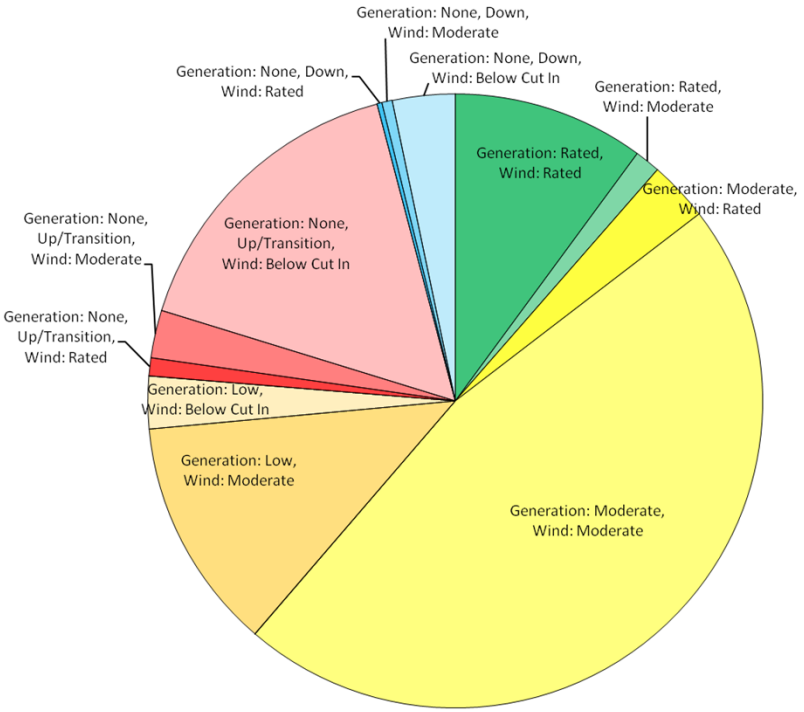
Focusing on What is Known

- **In addition to understanding impact from unknowns, also explore results after Unknown Time is removed**

All Data



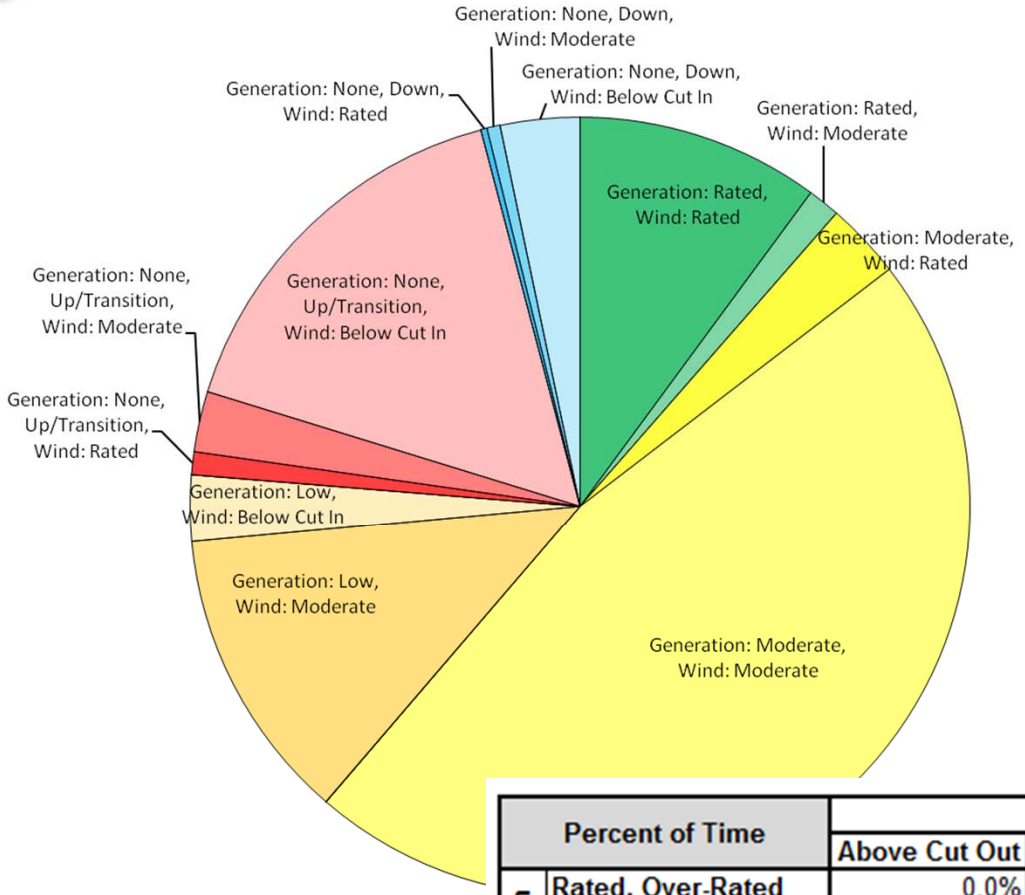
Unknown Time Removed



**Substantial portion of Unknown Time is attributable to pilot program & associated beta testing*

Without Unknown Time

Wind Speed & Generation Time Accounting



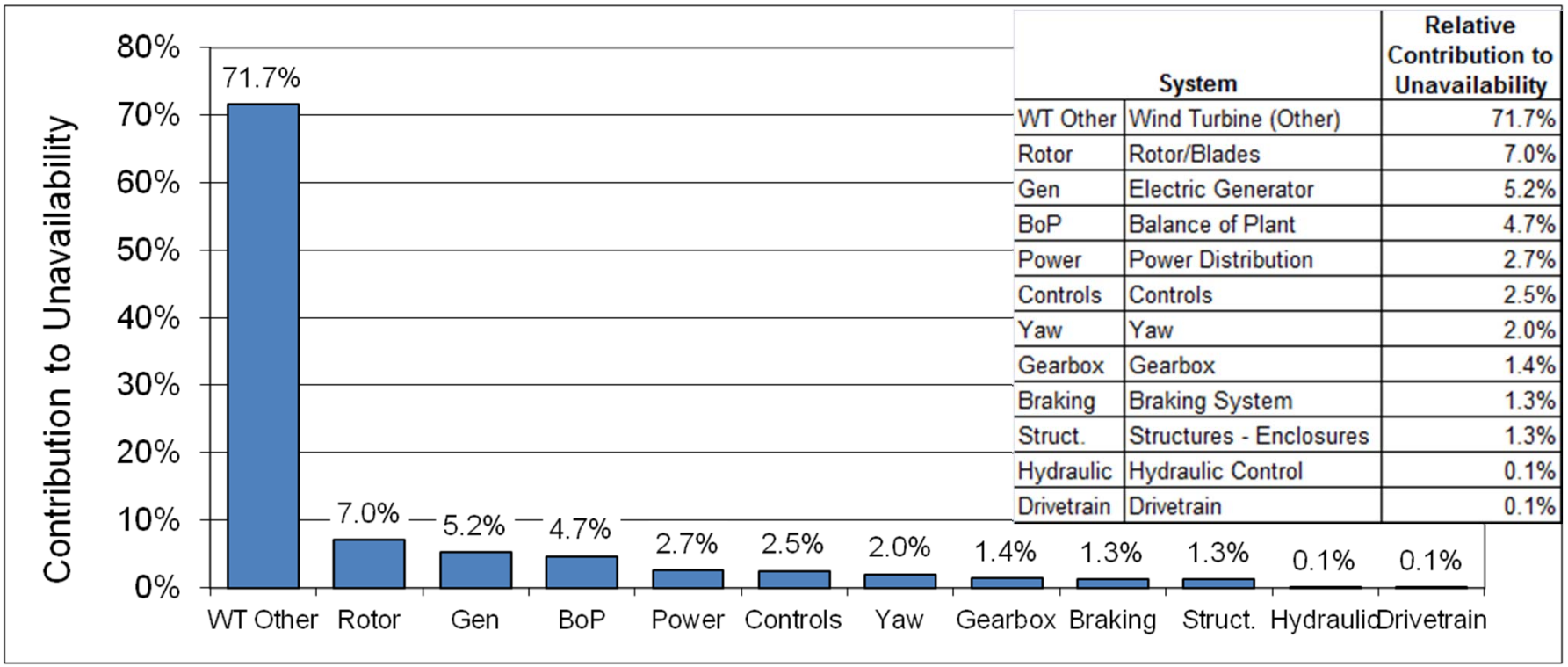
- Generation: Rated, Wind: Above Cut Out
- Generation: Rated, Wind: Rated
- Generation: Rated, Wind: Moderate
- Generation: Rated, Wind: Below Cut In
- Generation: Moderate, Wind: Above Cut Out
- Generation: Moderate, Wind: Rated
- Generation: Moderate, Wind: Moderate
- Generation: Moderate, Wind: Below Cut In
- Generation: Low, Wind: Above Cut Out
- Generation: Low, Wind: Rated
- Generation: Low, Wind: Moderate
- Generation: Low, Wind: Below Cut In
- Generation: None, Up/Transition, Wind: Above Cut Out
- Generation: None, Up/Transition, Wind: Rated
- Generation: None, Up/Transition, Wind: Moderate
- Generation: None, Up/Transition, Wind: Below Cut In
- Generation: None, Down, Wind: Above Cut Out
- Generation: None, Down, Wind: Rated
- Generation: None, Down, Wind: Moderate
- Generation: None, Down, Wind: Below Cut In

Percent of Time		Wind				
		Above Cut Out	Rated	Moderate	Below Cut In	
Generation	Rated, Over-Rated	0.0%	10.1%	1.3%	0.0%	11.4%
	Moderate	0.0%	3.2%	46.7%	0.0%	49.9%
	Low	0.0%	0.0%	12.2%	2.8%	15.0%
	None (Up, Transition)	0.0%	0.9%	2.5%	16.1%	19.6%
	None (Down)	0.0%	0.3%	0.5%	3.3%	4.1%
		0.0%	14.4%	63.3%	22.2%	100.0%

Event & SCADA Data Source: ORAP ® for Wind

Unavailability Pareto: Systems

- **Unavailability:** combined impact of event frequency (how often) and downtime (how long)
- **Dominated by "Wind Turbine (Other)" events**
  - Whole turbine maintenance, generic or unexplained trips, etc.



System		Relative Contribution to Unavailability
WT Other	Wind Turbine (Other)	71.7%
Rotor	Rotor/Blades	7.0%
Gen	Electric Generator	5.2%
BoP	Balance of Plant	4.7%
Power	Power Distribution	2.7%
Controls	Controls	2.5%
Yaw	Yaw	2.0%
Gearbox	Gearbox	1.4%
Braking	Braking System	1.3%
Struct.	Structures - Enclosures	1.3%
Hydraulic	Hydraulic Control	0.1%
Drivetrain	Drivetrain	0.1%

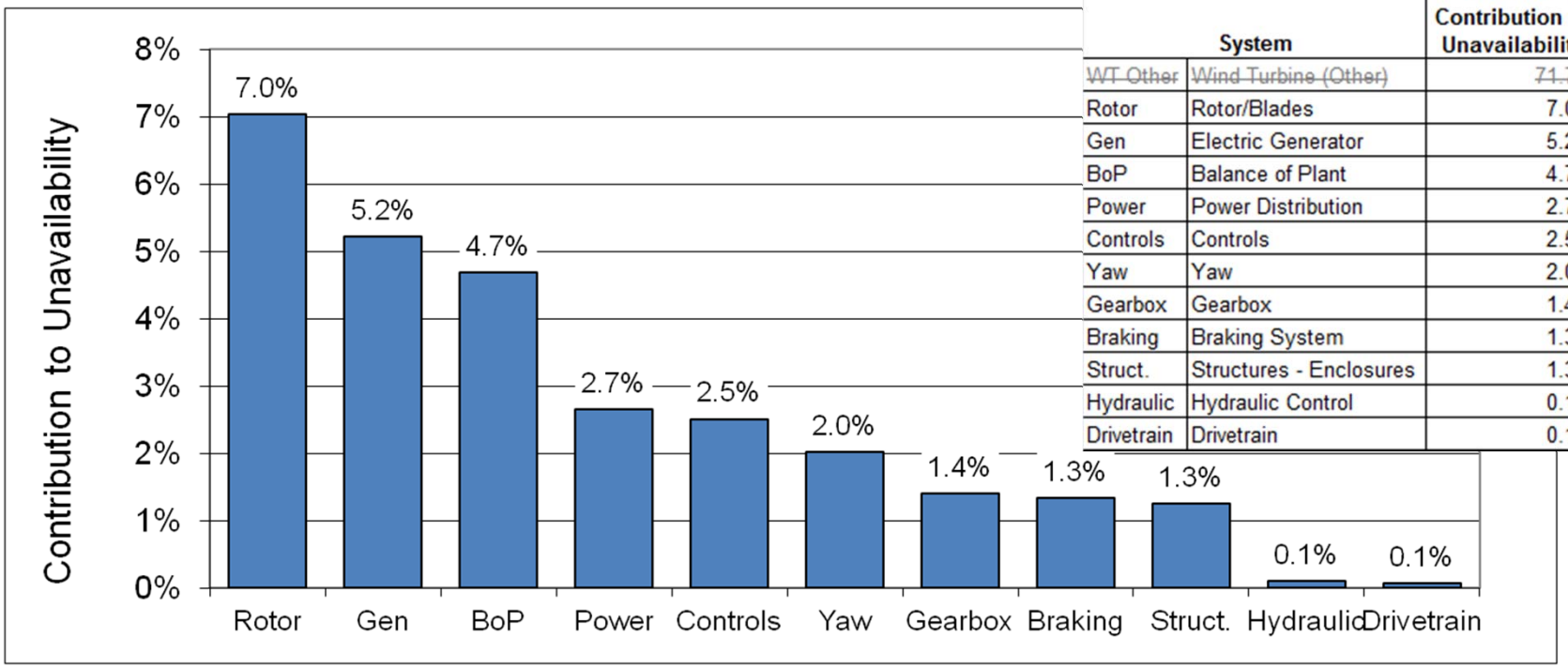
SCADA faults tend to indicate symptom, not necessarily root cause

Event & SCADA Data Source: ORAP ® for Wind

Without "Wind Turbine (Other)"

Unavailability Pareto: Systems

- **Redrawn, to better see differences among remaining systems**
- **Top 3: Rotor/Blades, Electric Generator, Balance of Plant**
  - Rotor/Blades & Electric Generator similar in event frequency and downtime
  - Balance of Plant has much longer, but less frequent, events

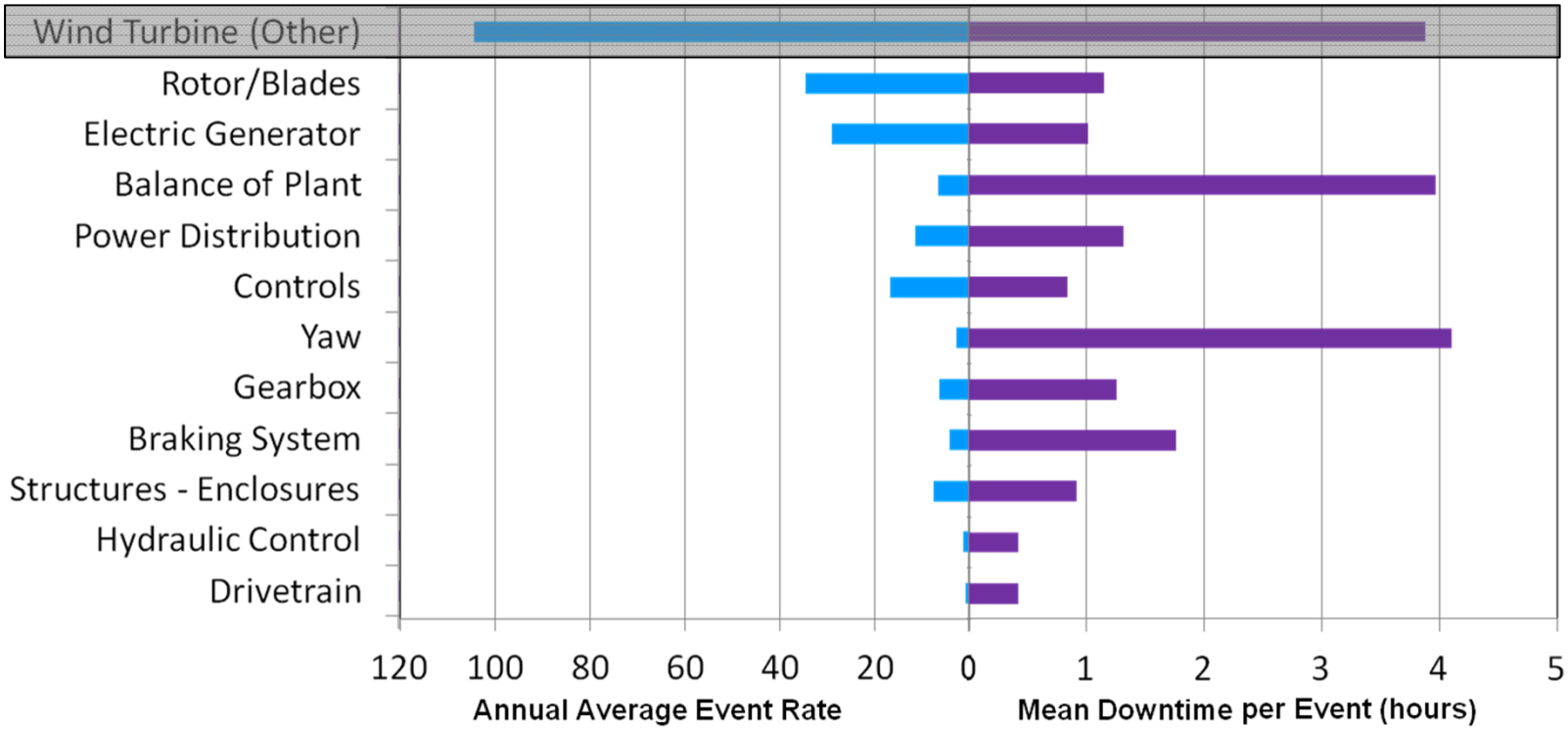


System		Relative Contribution to Unavailability
~~WT Other~~	~~Wind Turbine (Other)~~	~~71.7%~~
Rotor	Rotor/Blades	7.0%
Gen	Electric Generator	5.2%
BoP	Balance of Plant	4.7%
Power	Power Distribution	2.7%
Controls	Controls	2.5%
Yaw	Yaw	2.0%
Gearbox	Gearbox	1.4%
Braking	Braking System	1.3%
Struct.	Structures - Enclosures	1.3%
Hydraulic	Hydraulic Control	0.1%
Drivetrain	Drivetrain	0.1%

Event & SCADA Data Source: ORAP ® for Wind

Event Frequency vs. Downtime

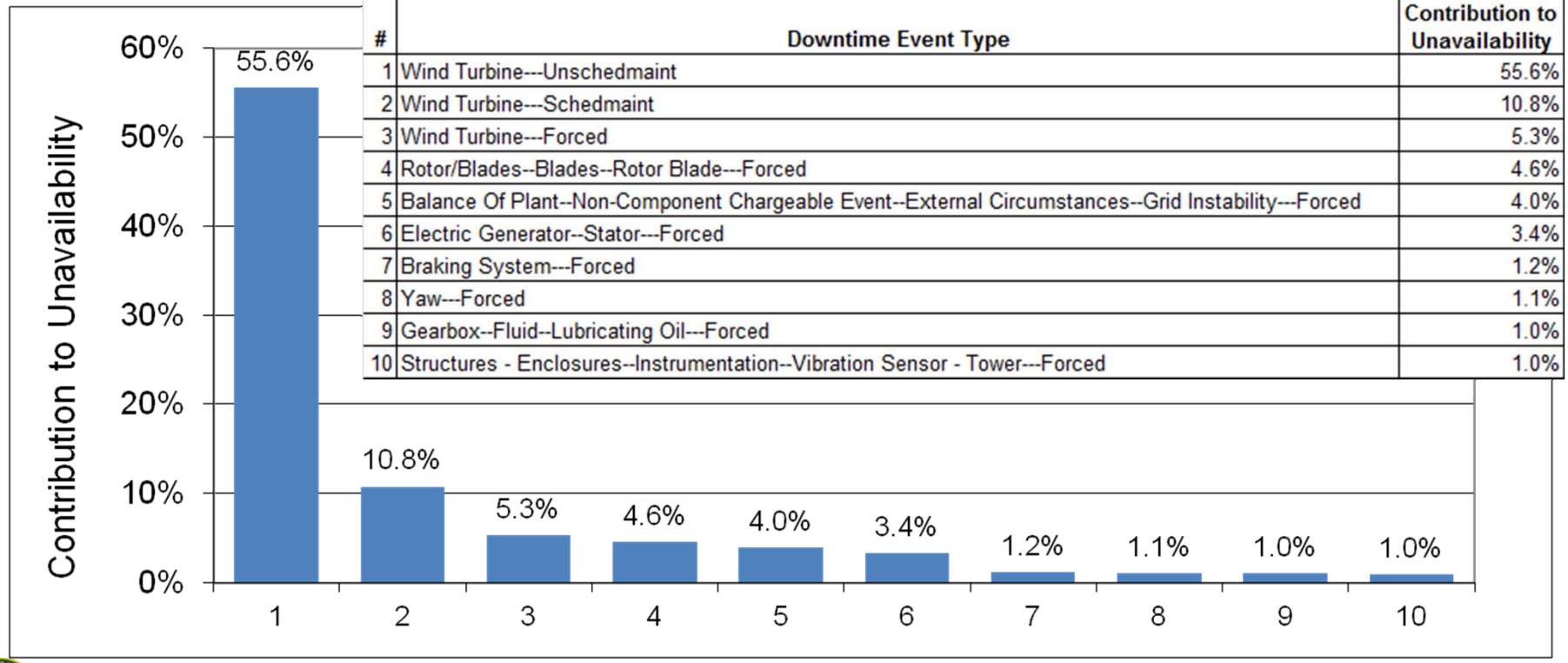
- **Sorted by Unavailability Contribution**
- **Aside from "Wind Turbine (Other)"**
  - Rotor/Blades, Electric Generator have most frequent events
  - Lengthy, but infrequent, Balance of Plant and Yaw events have largest mean downtime



Event & SCADA Data Source: ORAP ® for Wind

Unavailability Pareto: Component + Event Type

- **Dominated by general events**
  - "Wind Turbine" (Other) = top 3; over 70% of unavailability
  - Work Orders are critical for filling in these blanks about true root cause



#	Downtime Event Type	Relative Contribution to Unavailability
1	Wind Turbine---Unschedmaint	55.6%
2	Wind Turbine---Schedmaint	10.8%
3	Wind Turbine---Forced	5.3%
4	Rotor/Blades--Blades--Rotor Blade---Forced	4.6%
5	Balance Of Plant--Non-Component Chargeable Event--External Circumstances--Grid Instability---Forced	4.0%
6	Electric Generator--Stator---Forced	3.4%
7	Braking System---Forced	1.2%
8	Yaw---Forced	1.1%
9	Gearbox--Fluid--Lubricating Oil---Forced	1.0%
10	Structures - Enclosures--Instrumentation--Vibration Sensor - Tower---Forced	1.0%

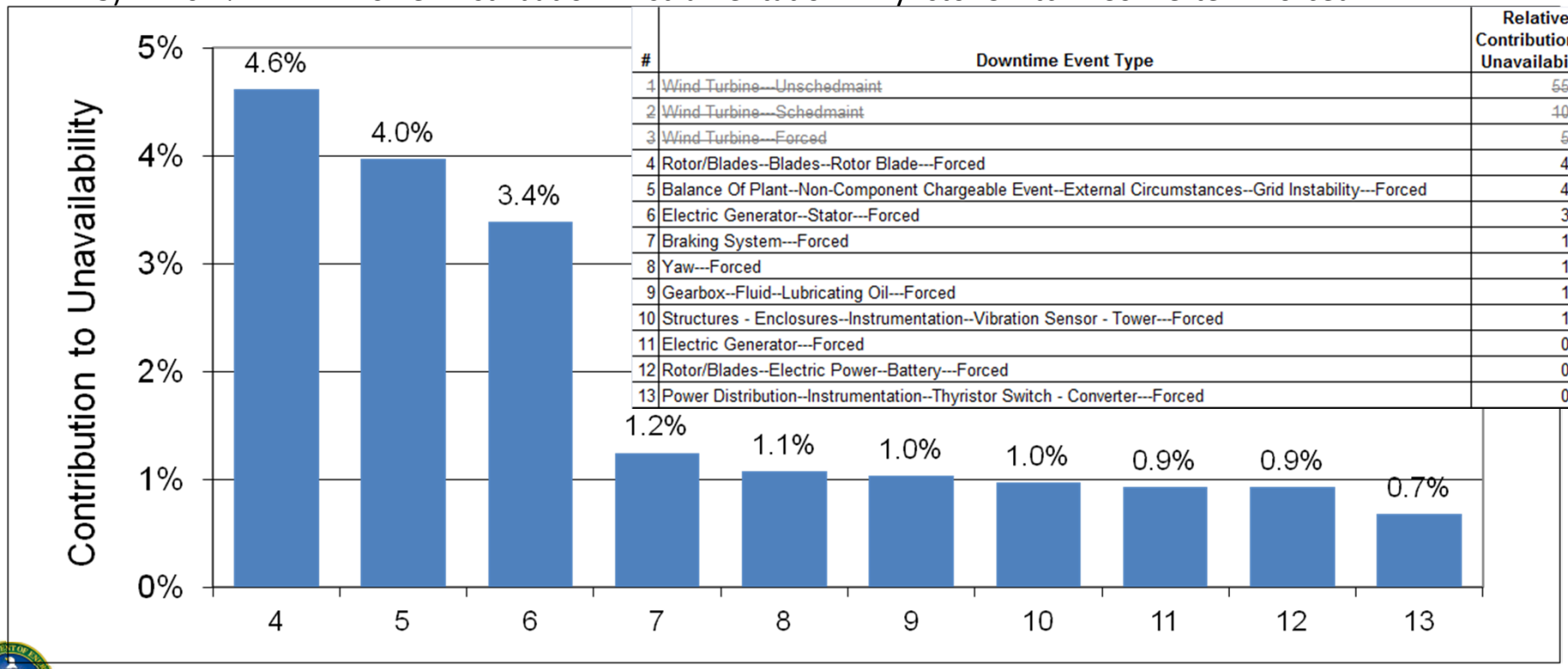
Without "Wind Turbine (Other)"

Unavailability Pareto: Component + Event Type

- **Top Component + Event Type, for Systems not in the top 3**

(i.e, not in Rotor/Blades, Generator, Balance of Plant; not Wind Turbine (Other))

7) 1.2% Braking System---Forced
8) 1.1% Yaw---Forced
9) 1.0% Gearbox--Fluid--Lubricating Oil---Forced
10) 1.0% Structures - Enclosures--Instrumentation--Vibration Sensor - Tower---Forced
13) 0.7% Power Distribution--Instrumentation--Thyristor Switch - Converter---Forced



#	Downtime Event Type	Relative Contribution to Unavailability
~~1~~	~~Wind Turbine---Unschedmaint~~	~~55.6%~~
~~2~~	~~Wind Turbine---Schedmaint~~	~~10.8%~~
~~3~~	~~Wind Turbine---Forced~~	~~5.3%~~
4	Rotor/Blades--Blades--Rotor Blade---Forced	4.6%
5	Balance Of Plant--Non-Component Chargeable Event--External Circumstances--Grid Instability---Forced	4.0%
6	Electric Generator--Stator---Forced	3.4%
7	Braking System---Forced	1.2%
8	Yaw---Forced	1.1%
9	Gearbox--Fluid--Lubricating Oil---Forced	1.0%
10	Structures - Enclosures--Instrumentation--Vibration Sensor - Tower---Forced	1.0%
11	Electric Generator---Forced	0.9%
12	Rotor/Blades--Electric Power--Battery---Forced	0.9%
13	Power Distribution--Instrumentation--Thyristor Switch - Converter---Forced	0.7%

Event & SCADA Data Source: ORAP ® for Wind

Wind Turbine Reliability Model

	All Events		Forced		Scheduled Maintenance		Unscheduled Maintenance		Reserve (Non-Wind)	
System	**MTB**	**DT**	**MTB**	**DT**	**MTB**	**DT**	**MTB**	**DT**	**MTB**	**DT**
Turbine	**28**	**2.5**	**34**	**1.0**	**308**	**3.0**	**324**	**16.0**	**20,117**	**2.0**
Balance of Plant	957	4.0	957	4.0						
Braking System	1,492	1.8	1,492	1.8						
Controls	386	0.9	386	0.9						
Drivetrain	6,401	0.4	6,401	0.4						
Electric Generator	219	1.0	219	1.0						
Gearbox	1,004	1.3	1,004	1.3						
Hydraulic Control	4,678	0.4	4,678	0.4						
Power Distribution	558	1.3	558	1.3						
Rotor/Blades	184	1.1	186	1.2	12,402	0.9				
Structures - Enclosures	829	0.9	829	0.9						
Yaw	2,234	4.0	2,513	4.3					20,117	2.0
Wind Turbine (Other)	*61*	*3.9*	*98*	*0.5*	*316*	*3.0*	*324*	*16.0*		

MTB: Mean Time Between Events (generating hours); DT: Mean Downtime (hours)

Event & SCADA Data Source: ORAP ® for Wind

Closing

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Conclusions

In order to understand the entire reliability picture, it is critical to provide insight into Unknowns

- **Turbine Unavailability is dominated by "Wind Turbine (Other)" events**
  - These events are whole turbine maintenance, generic or unexplained trips, etc.
  - Unspecified events dominate system and component Unavailability Paretos
  - **CMMS Data is critical**
    - Enable identification of primary failures through insight at component level
    - Provide visibility into "Wind Turbine (Other)" events

- **IT Communication and SCADA issues are key drivers of Unknown Time**
  - ORAP® for Wind data quality assessments are driving focus to addressing communication issues

Insights

- **Top 3 contributors to Turbine Unavailability, excluding "Other": Rotor/Blades, Electric Generator, Balance of Plant**
  - Gearbox not in top 5 systems
    - Have not collected data long enough to estimate impact of major repairs
    - Benchmarking day-to-day performance, at this point
  - Balance of Plant and Yaw have approximately 4 hour mean downtimes

- **Although details are not provided in the public benchmark, reliability performance varies tremendously from plant to plant**
  - Event frequency, event downtime
  - System and component metrics

- **Overall performance in line with expectations**
  - Operational Availability 94.8%
  - Capacity Factor 33.4%
    - 2010 Wind Technologies Market Report estimates 34% for 2008 and 30% for 2009 & 2010 (U.S. Department of Energy/Lawrence Berkeley National Laboratory, Wiser & Bolinger)

Event & SCADA Data Source: ORAP ® for Wind

Data Access

- **Sandia keeps an archive of our past wind turbine reliability publications at http://energy.sandia.gov/?page_id=3057#WPR**
- **The data in the CREW database is proprietary to our partners. We are not able to disclose non-aggregated data.**
  - Due to a large volume of requests and limited funding, Sandia is not able to provide customized subsets of aggregated data outside the Department of Energy's Energy Efficiency and Renewable Energy program.
  - Strategic Power Systems, our corporate partner in this effort, may be able to assist with more information about this and other products and programs related to wind turbine reliability. For more information, please contact

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Strategic Power Systems, Inc.
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Increasing Benchmark Representation

- **The benchmark's ability to accurately represent the performance of the U.S. wind fleet is based on the amount and variety of operating data received by the CREW database.**
- **All U.S. wind plant owners, operators and OEM's are invited to participate. Please contact:**

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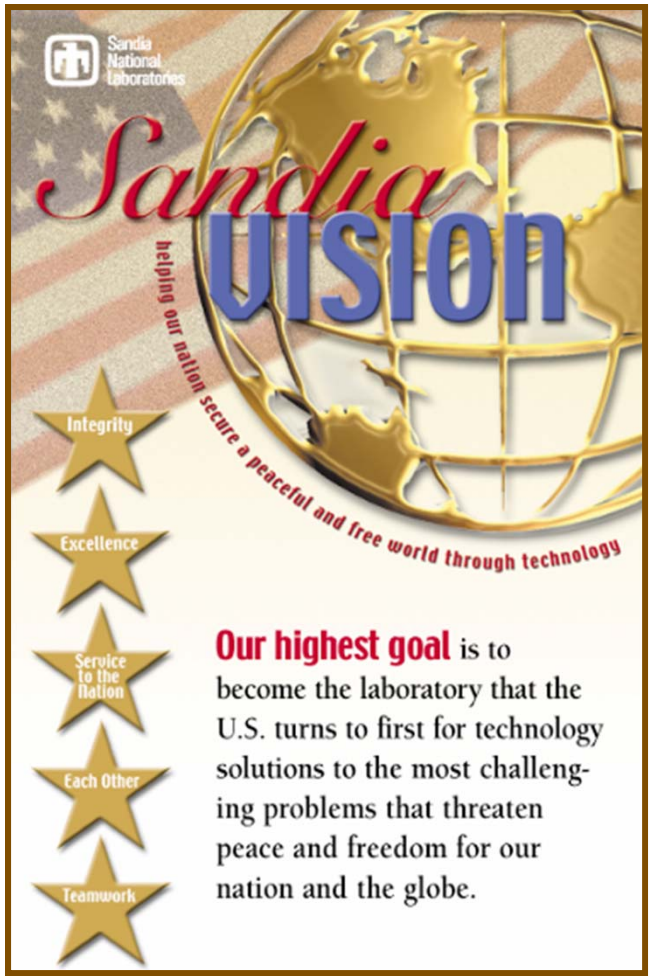
- **Plans for expanded Fall 2012 benchmark include:**
  - Larger section of fleet
  - Increased variety of plants and turbines
  - Metrics filtered by geography, turbine age, etc.

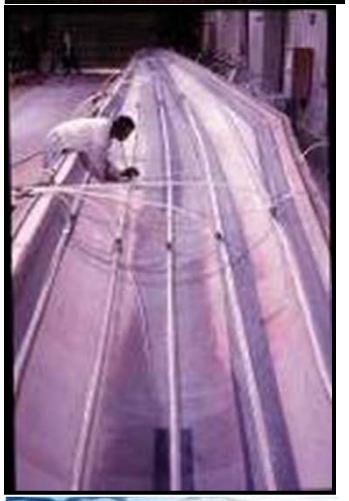
Appendix
Background and Methodology

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

"Exceptional Service in the National Interest"





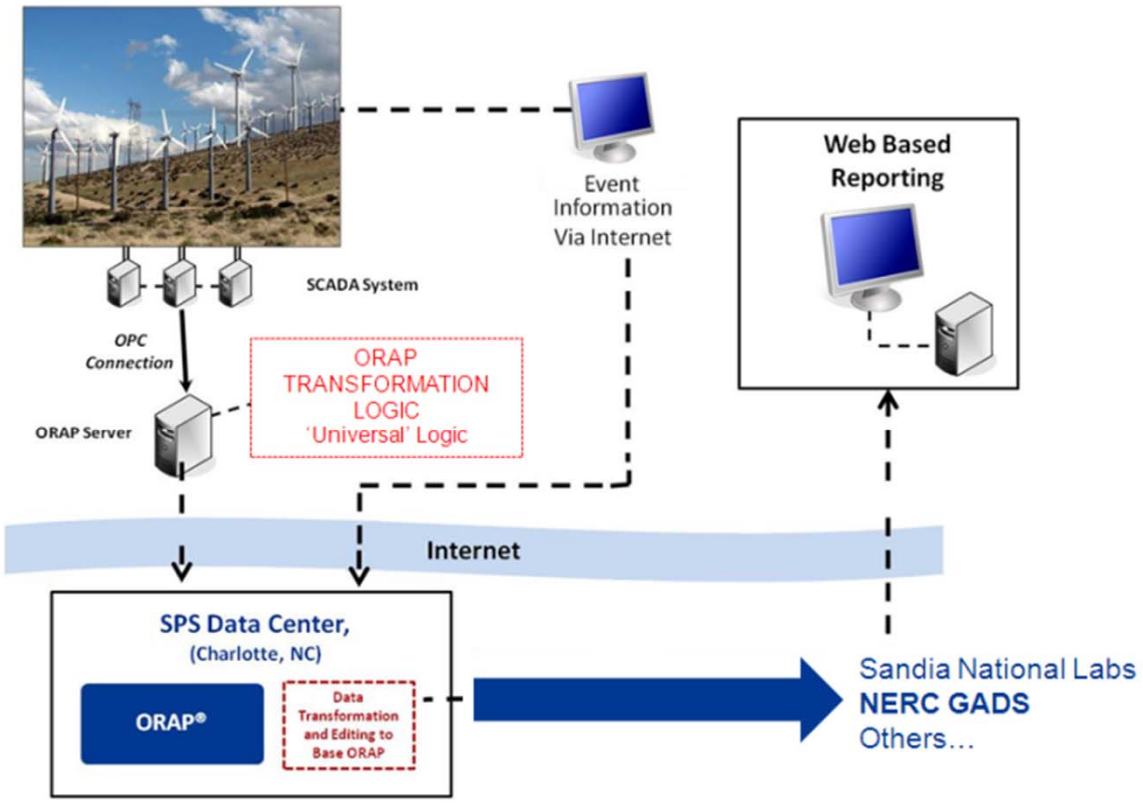
Wind Energy Technologies

Funded by Department of Energy

Energy Efficiency and Renewable Energy

- Wind Technology
  - Materials and Manufacturing
  - Structural, Aerodynamic, and Full System Modeling
  - Sensors and Structural Health Monitoring
  - Advanced Blade Concepts
  - Lab - Field Testing and Data Acquisition
- **System Reliability**
  - **Industry Data Collection**
  - **Improve reliability of the existing technology and future designs**
  - Blade Reliability Collaborative
- System Integration & Outreach
  - Wind/RADAR Interaction
  - Integration Assessment
  - SNL Wind Energy Test Facility

Data Collection via ORAP® for Wind by Strategic Power Systems

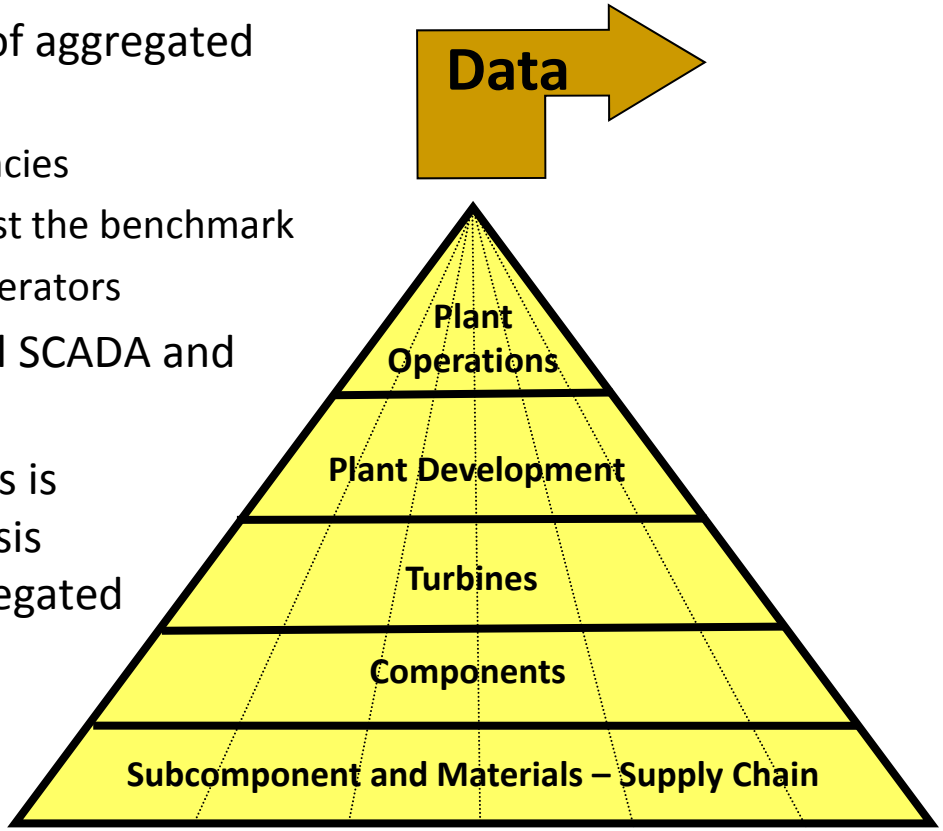


Operational Reliability Analysis Program (ORAP®)

- ❑ Capture Reliability, Availability, Maintainability (RAM) data at component level
- ❑ Close relationship with Turbine Manufacturers (OEMs) and operators
- ❑ Customer-specific data treated as proprietary
- ❑ Minimize human input
- ❑ Internet-enabled reporting and feedback RAM database
- ❑ Industry-driven methodology
  - IEEE, IEC and ISO standards
  - NERC compliant

CREW Benchmark Approach

- Establish a national reliability database containing a sufficiently large sample of wind plants to benchmark the operation and maintenance experience of the US fleets.
- Provide regular public-domain reporting of aggregated fleet reliability data metrics.
  - Provide specific failure sources and frequencies
  - Enable comparison of a plant or fleet against the benchmark
  - Will NOT compare companies, OEMs, or operators
- Analysis will be based on sub-system level SCADA and event data.
- Data gathered from individual participants is proprietary and will only be used in analysis reporting when it can be sufficiently aggregated so that individual participants cannot be identified.



Reliability Improves from the bottom up

Methodology: Data Foundation

- **CREW uses transformed data from ORAP® for Wind software**
  - Algorithms transform raw plant SCADA data into ORAP® data, summarized into time, capacity and events
    - Time data = daily time-based accounting of turbine status
    - Capacity data = energy-based accounting
    - Event data = details on downtime events and wind reserve time

Example of ORAP® for Wind Events

Turbine ID	Event ID	Event Type	Begin Date	End Date	EBS Component	Outage Mechanism	Trip Load	…
123	5688	Forced Outage Automatic Trip	1/3/11 15:16	1/4/11 11:34	Pitch Controller	Erratic (electrical)	-10	
123	5678	Reserve Shutdown	1/1/11 01:23	1/1/11 04:56	Yaw Cable Twist Counter	Position, Incorrect	-11	

- **CREW also uses SCADA time series data from SPS** (Ex: acceleration, vibration, ambient temperature, wind speed)
  - Captured 5-30x/minute
  - Key goals: enhanced time accounting; understanding of leading failure indicators

Methodology: Aggregation

- **Gather statistically appropriate sample**
  - Sufficient data (duration, breadth) to aggregate without violating anonymity
- **Create individual plant models, by summarizing ORAP ® for Wind events into:**
  - Event frequency & duration for each component + event type
  - Time accounting based on summing hours across turbines
- **Aggregate results from plant models**
  - Event frequency & duration: weight plant model results by turbine-days
    - Creates greater impact from plants that have a large number of turbines, have a longer data history, or both
  - Time Accounting: take summed turbines hours from plant models, then sum across plants
    - Naturally provides greater impact from larger plants and/or plants with longer data history

Methodology: Key Definitions

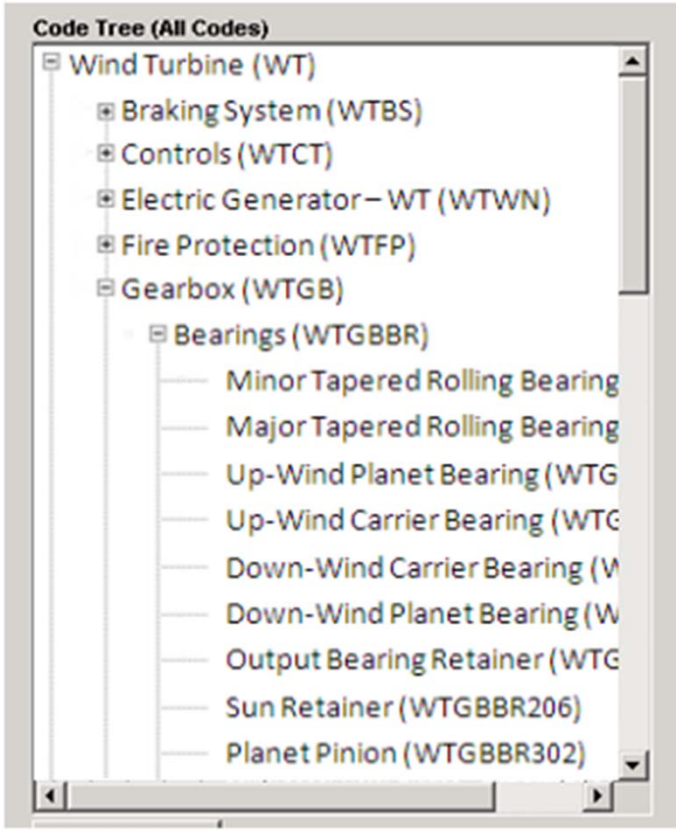
- **Systems**: Top-level component groups that comprise a turbine (ex: Rotor/Blades)
- **Generating**: time when turbine has a grid connection
- **Reserve Shutdown – Wind**: time when wind conditions are not appropriate for generation AND turbine is not down for an event
- **Unknown Time**: time when turbine state is not clear
- **Event**: SCADA fault state that stops the turbine or takes it out of service (both automatic & manual stops)
  - **Reserve Shutdown – Other**: event that indicates turbine is not in service, but has no equipment problems (ex: cable unwind)
  - **Scheduled Maintenance**: planned maintenance event, scheduled well in advance, which puts the turbine in a down state (ex: annual maintenance)
  - **Unscheduled Maintenance**: maintenance event which cannot be deferred for any significant length of time (ex: major maintenance, troubleshooting)
  - **Forced (Outage or Unavailability)**: unplanned event indicating a fault or failure (ex: automatic trip; manual stop by operator)

Methodology: Calculations

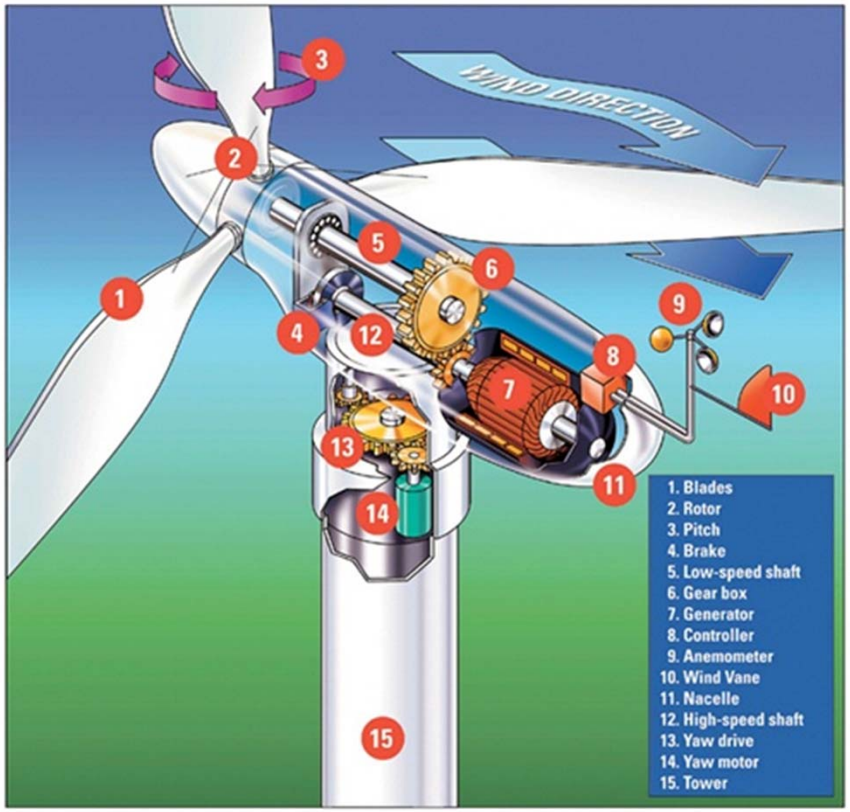
- **Operational Availability:** percent of known time turbine is NOT down for events
  = (Generating Time + Reserve Shutdown Wind Time)/Known Time
  - Calculated from time accounting
- **Generating Factor:** percent of known time that turbine is generating (a.k.a. Utilization)
  = Generating Time/Known Time
  - Calculated from time accounting
- **Mean Downtime:** average duration of an event (in hours, unless otherwise specified)
  - Calculated by plant in Sandia reliability simulation model; then aggregated
- **Event Frequency**: the expected number of events per unit time (per generating hour, unless otherwise specified)
  - Calculated by plant in Sandia reliability simulation model; then aggregated
- **Annual Average Event Rate:** the expected number of events per calendar year
  = Generating Hours Per Year * Event Frequency per generating hour
  - Generating Hours Per Year = Utilization * 8760 hrs/year
- **MTBE:** Mean Time Between Events (in hours, unless otherwise specified)
  = 1/Event Frequency
- **Capacity Factor:** percent of nameplate capacity that turbine generated
  = Generated Power / Nameplate Capacity
  - Calculated from energy accounting

Methodology: Equipment Breakdown Structure

- Equipment Breakdown Structure (EBS) developed by Strategic Power Systems for ORAP® for Wind



Source: Strategic Power Systems



Source: http://wind-turbine.tripod.com/id13.html

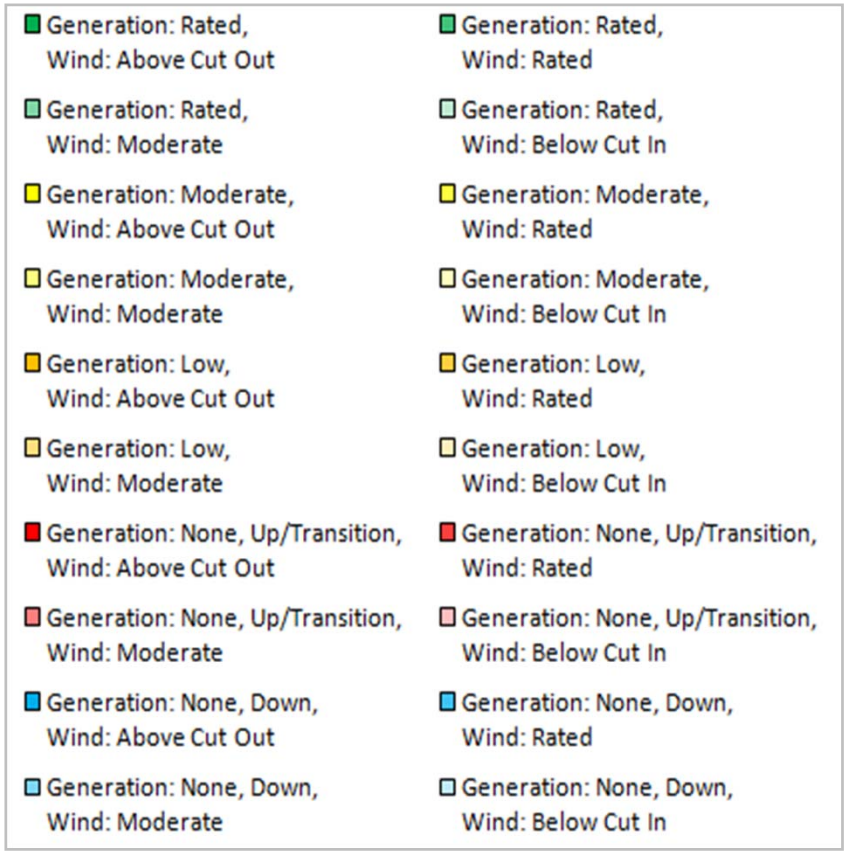
The full EBS used for CREW is proprietary to Strategic Power Systems, Inc

Methodology:
Wind Speed & Generation Time Accounting

- **For each turbine, for each 10 minute period, determine the Wind Speed & Generation category**
  - Based on Wind Speed (average), power Generation (average), and Turbine State (most common)

Wind	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

Generation	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



- **Sum the total amount of time (10 minute periods) for each category combination (Wind Speed + Generation + State)**

Methodology:
Wind Speed & Generation Time Accounting, continued

- **Exceptions**
  - Transition
    - Turbine State is not clear (not up, not down) AND Generation is positive
      - (If no generation, time counted elsewhere)
  - Down with Generation
    - Turbine State is down, while Generation is positive
  - Unknown-No Data
    - Data is entirely missing
  - Unknown-Incomplete Data
    - Missing Wind Speed
    - Missing Generation
    - Missing Turbine State AND conflict between Wind Speed and Generation

Methodology:
Availability Time Accounting

Total Hours = (Last Date – First Date + 1) * 24

- **Generating Hours**
  = Sum of ORAP® Contact Hours
- **Reserve Shutdown – Wind**
  = Sum of Duration, Events with Type "Reserve Shutdown - Wind"
- **Reserve Shutdown – Other**
  = Sum of Duration, Events with Type "Reserve Shutdown - Other"
- **Scheduled Maintenance**
  = Sum of Duration, Events with Type "Scheduled Maintenance"
- **Unscheduled Maintenance**
  = Sum of Duration, Events with Type "Unscheduled Maintenance"
- **Forced Outage & Unavailability**
  = Sum of Duration, Events with Type "Forced Outage Automatic Trip," "Forced Outage Manual Trip," or "Forced Unavailability
- **Unknown Hours:** All time not captured in other categories
  = Total Hours – (Generating Hours + Reserve Shutdown Wind + Reserve Shutdown Other + Scheduled Maintenance + Unscheduled Maintenance + Forced)

Methodology: Assumptions

- **If a plant does not experience any instances of a given kind of event, then the event frequency is considered to be 0 for that plant for that kind of event**
  - Impact: May slightly decrease the event frequency for events that have not yet occurred at all plants
- **Unknown time is treated as neither up time nor down time**
  - Essentially treated as if it never existed; did not assume
- **"Clustered" (back-to-back) events are counted separately**
  - Each event is included in the analysis & contributes to the event frequency
- **Events with no durations are given 0.0001 hours (0.36 seconds) downtimes**
  - These events contribute to event frequency & downtime