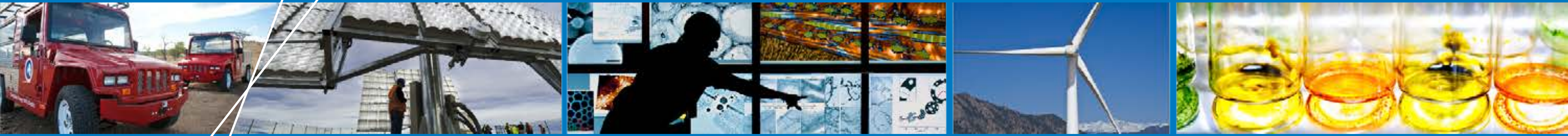
Report on Wind Turbine Subsystem Reliability – A Survey of Various Databases



Shuangwen (Shawn) Sheng

National Renewable Energy Laboratory

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Outline

- Introduction
- Experiences in Europe
- U.S. Efforts
- Observations
- Opportunities

Introduction

Project Purpose and Approach

- **Purpose:**

  To get updated reliability statistics of wind turbines and/or subsystems, to benefit current and future activities aiming to improve turbine/plant reliability and availability

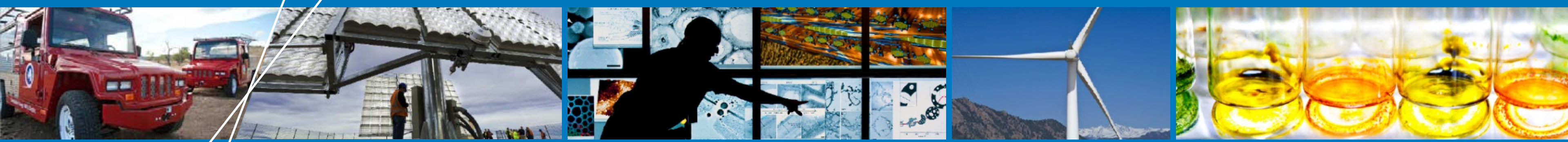
- **Approach:**

  Review reliability databases either directly or indirectly accessible

  Provide a brief summary of each database and highlight the key results that are deemed beneficial

- **Factors surveyed when possible:**

  Database population, lifespan, data collected, features & status, and selective results



Experiences in Europe

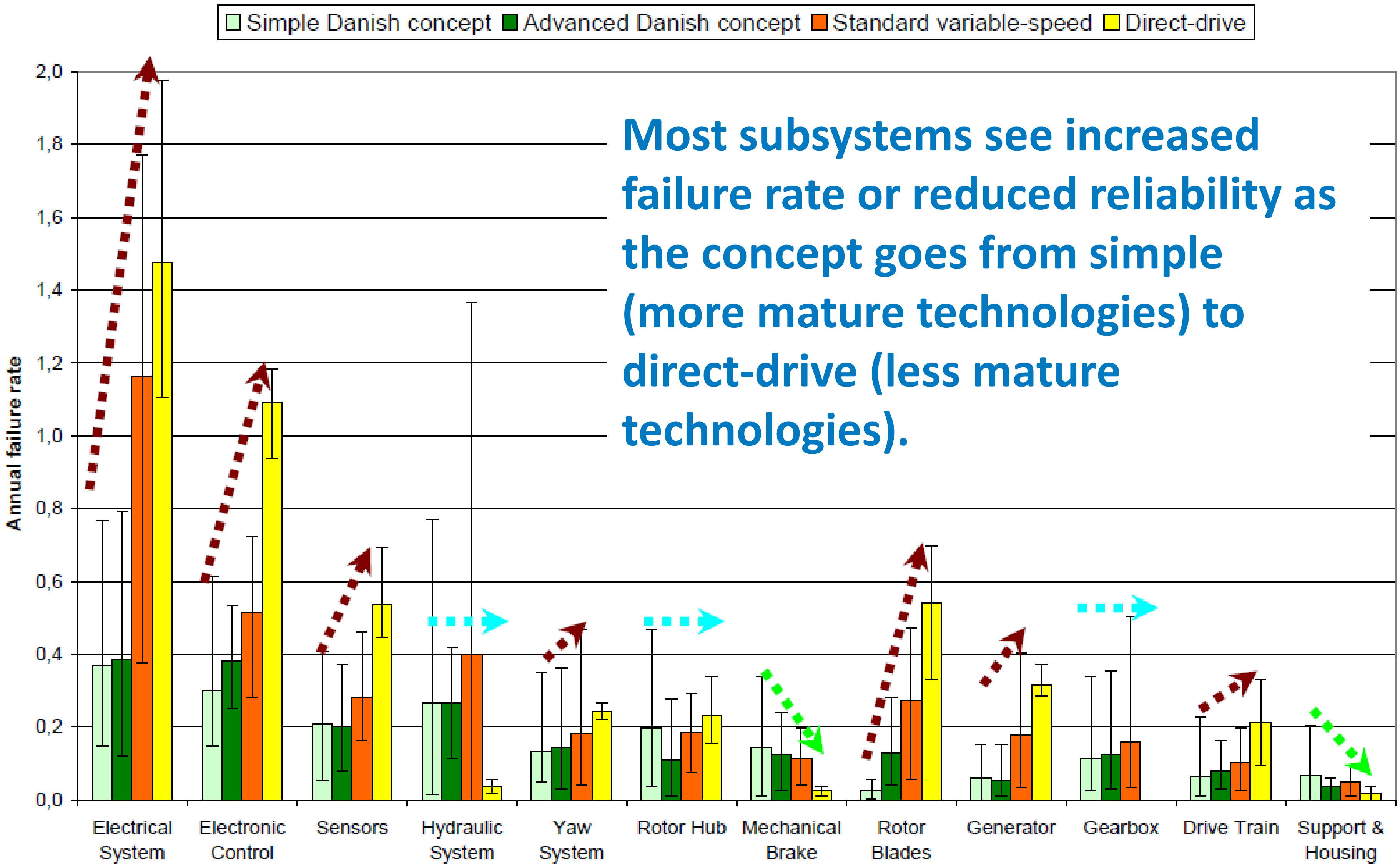
WMEP Database

- **A summary extracted from [1,2]:**

  A large monitoring program accomplished by ISET (now Fraunhofer IWES) from 1989 to 2006. The WMEP (Wissenschaftliches Mess- und Evaluierungsprogramm) database contains detailed information about reliability and availability of wind turbines (WTs) and subassemblies.

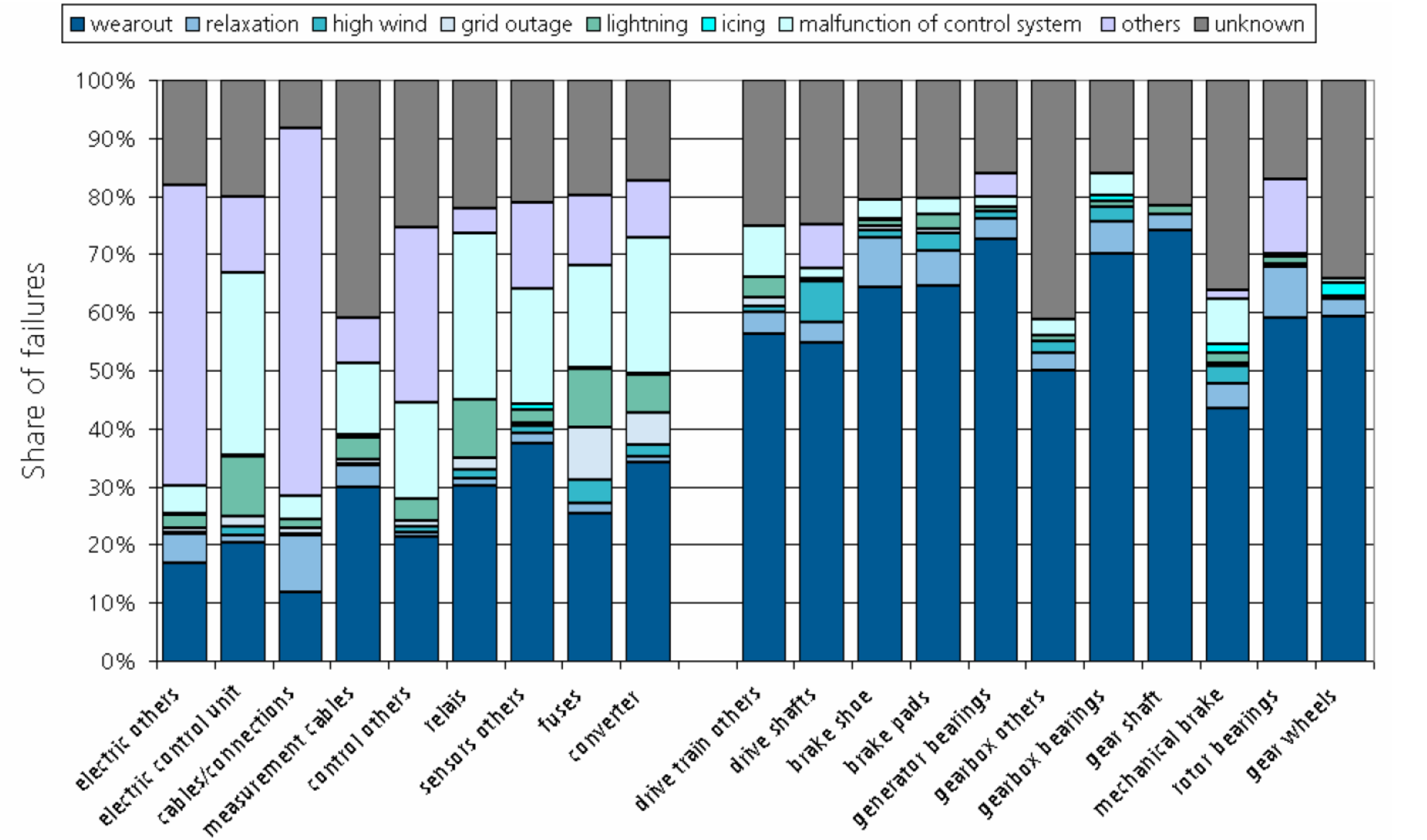
- **Features and status [1,2]:**
  - A total of 193,000 monthly operation reports and 64,000 incident reports from 1,500 onshore WTs.
  - Implemented using a logbook for each WT through manual documentation by the operators.
  - Closed in 2006.

WMEP: Failure Rates vs. Technical Concepts [1]



Most subsystems see increased failure rate or reduced reliability as the concept goes from simple (more mature technologies) to direct-drive (less mature technologies).

WMEP: Causes of Failures [3]



- **Results compiled for Upwind project in the UK**
- **Wearout: main driver for gearbox, generator and rotor failures**

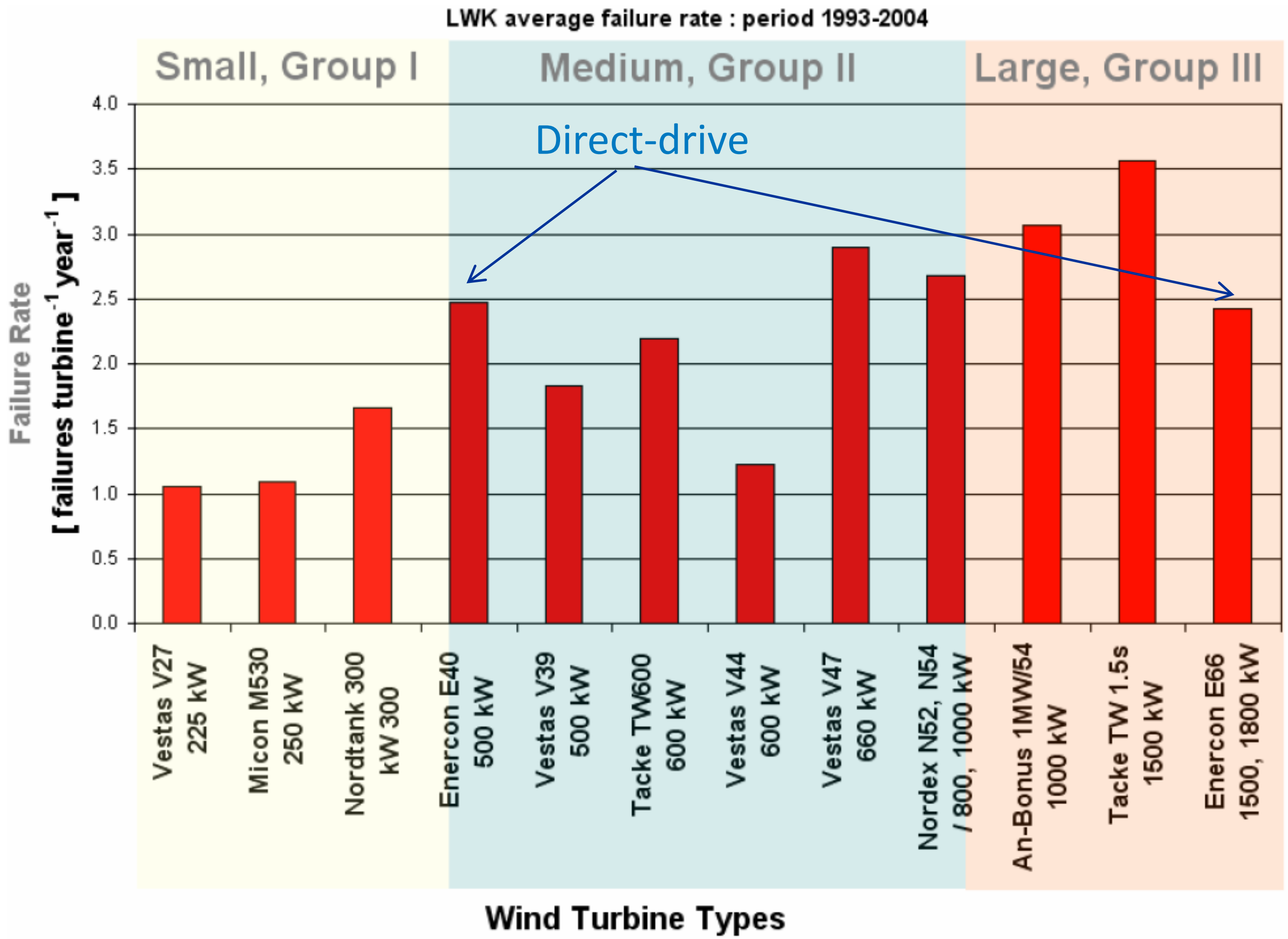
LWK Database

- **A summary extracted from [1,2]:**

  Failure statistics published by Landwirtschaftskammer Schleswig-Holstein (LWK) from 1993 to 2006. Its annual report contains output data and number of failures per system for all WTs in a province in the northern Germany.

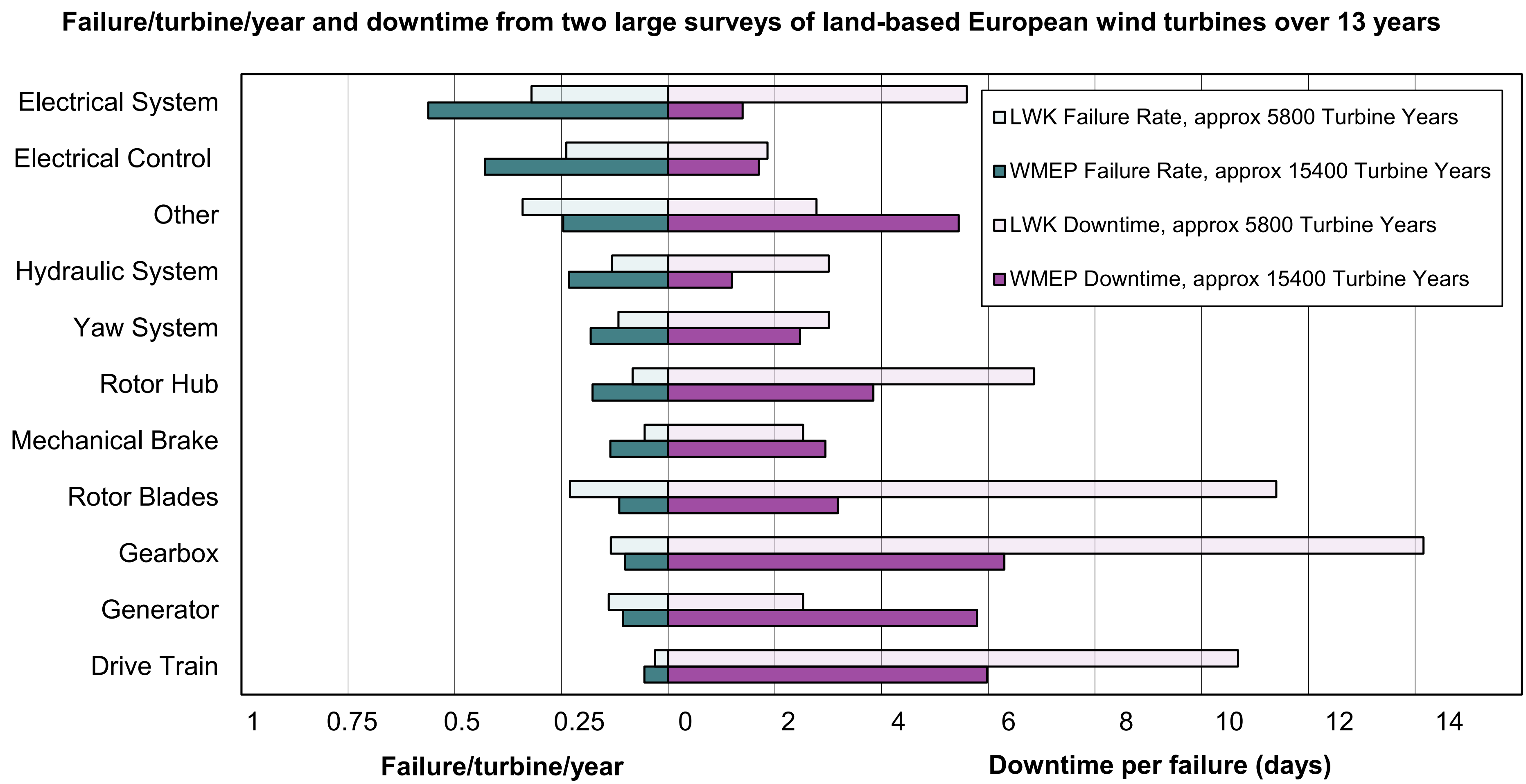
- **Features and status [2]:**
  - >650 WTs.
  - Closed 2006.

LWK: Failure Frequency vs. Turbine Types [1]



- Reliability tends to decrease from small to large group, representing mature to less mature technologies.
- Benefits from direct-drive WTs over geared WTs not conclusive; need more data collection to evaluate.

Failure Rate and Downtime from WMEP and LWK [4]



- **Electrical systems had highest failure rate.**
- **Gearboxes caused longest downtime per failure.**
- **75% faults caused 5% downtime and 25% faults caused 95% of downtime.**

VTT Database

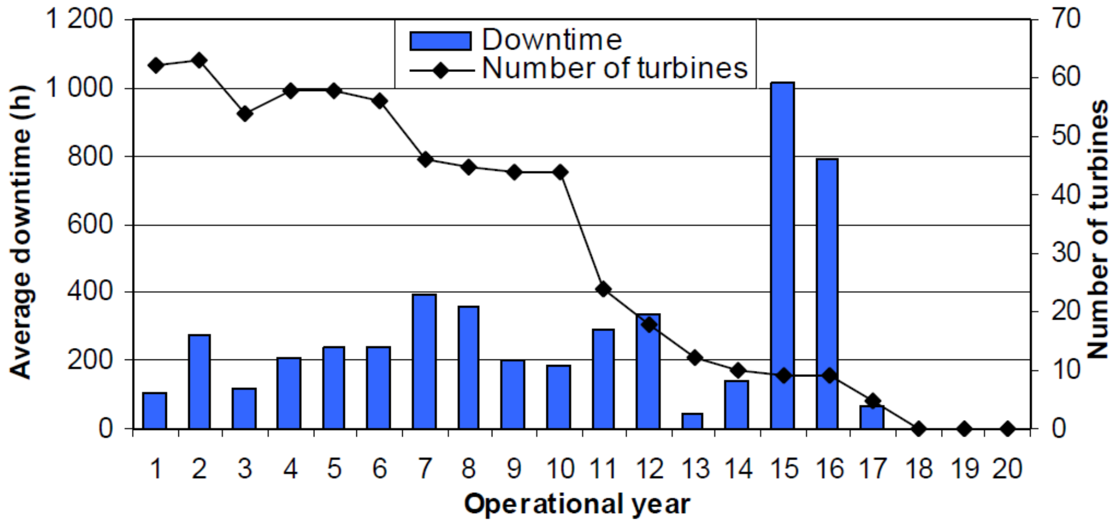
- **A summary extracted from [1,2]:**

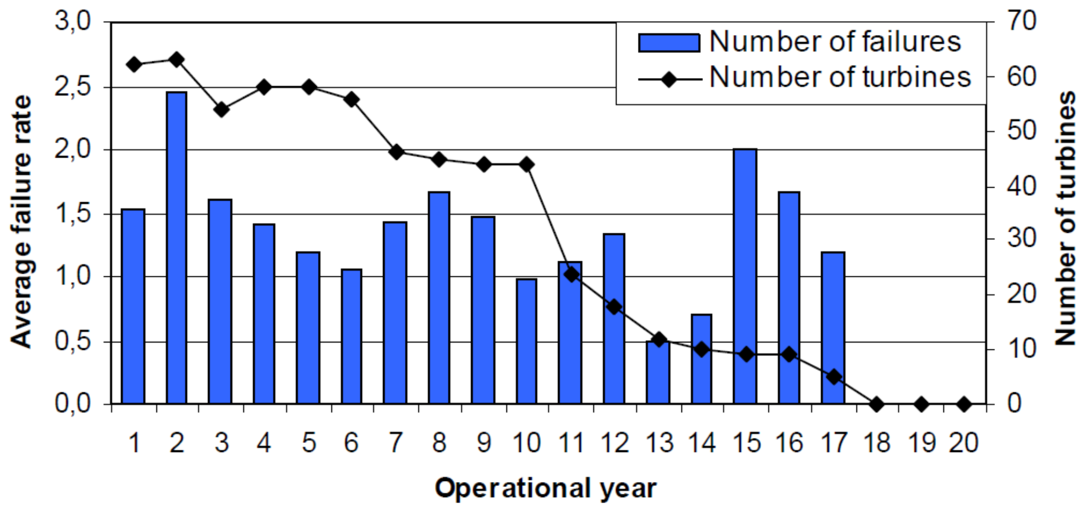
  WT performance and failure data collected by VTT, the Technical Research Centre of Finland, since 1992 based on wind power plants situated in Finland. Failure data includes such information such as cause, downtime, actions, and component.

- **Features and status:**
  - 162 WTs by the end of 2012 [5].
  - Detailed failure statistics between years 1996 and 2008 from 72 turbines examined and reported in [6].
  - Data still being collected [5].

VTT: Reliability vs. Operational Years [6]

- Total reported failures 898
- Downtime due to technical failures per turbine and operational year (top right):
  - Average ~170 hours/year /turbine
  - Rise in downtime when turbines reach age 15
  - Older turbines higher downtime mainly caused by hydraulic systems and tip brakes, and lack of spare parts
- Number of faults caused by technical failures per turbine and operational year (bottom right):
  - Average ~1.0 to 1.5 failures/year/turbine
- Results can not be generalized for older turbines due to the small number of samples.





Vindstat Database

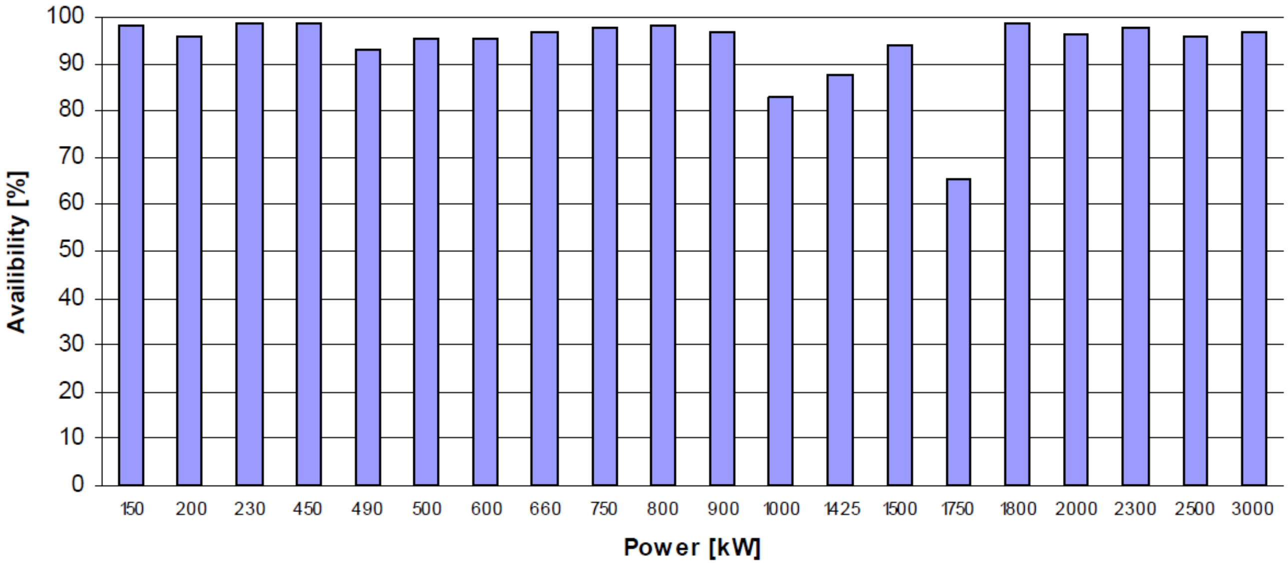
- **A summary extracted from [2,7]:**

  A database with production and downtime information from a majority of wind turbines installed in Sweden. It was started in 1988 with manual data reporting through faxes. Automatic daily data reporting was implemented in 2002. Before 2005, all major incidents were reported and failures were specified in type and cause. In recent years, only production and downtime data, along with turbine manufacturer, installation year and rated power, are reported.

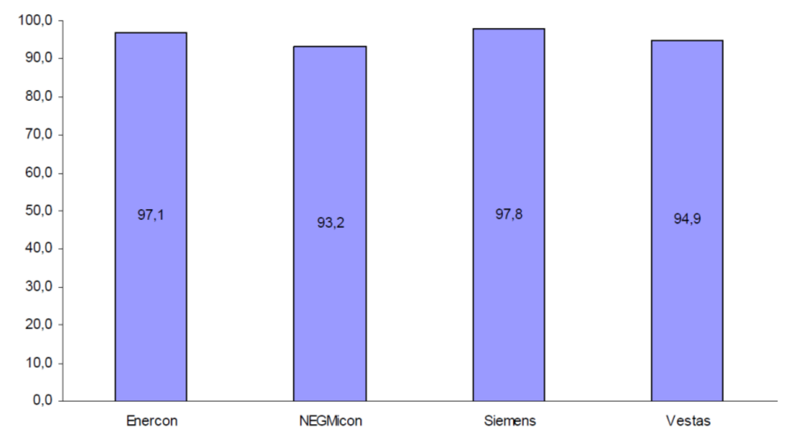
- **Features and status [7]:**
  - ~800 WTs out of total ~ 1300 installed WTs are reporting.
  - Data collection still active.

Vindstat: Availability [7]

- Availability vs. power class based on 2009 data (top right):
  - Independent of turbine size
  - Most over 90%
  - Only three power classes have a lower availability



- Availability vs. turbine manufacturers based on 2009 data for turbines > 1.5 MW (bottom right):
  - Difference is not significant.
  - Reported data may overestimate the real availability and should be treated cautiously.



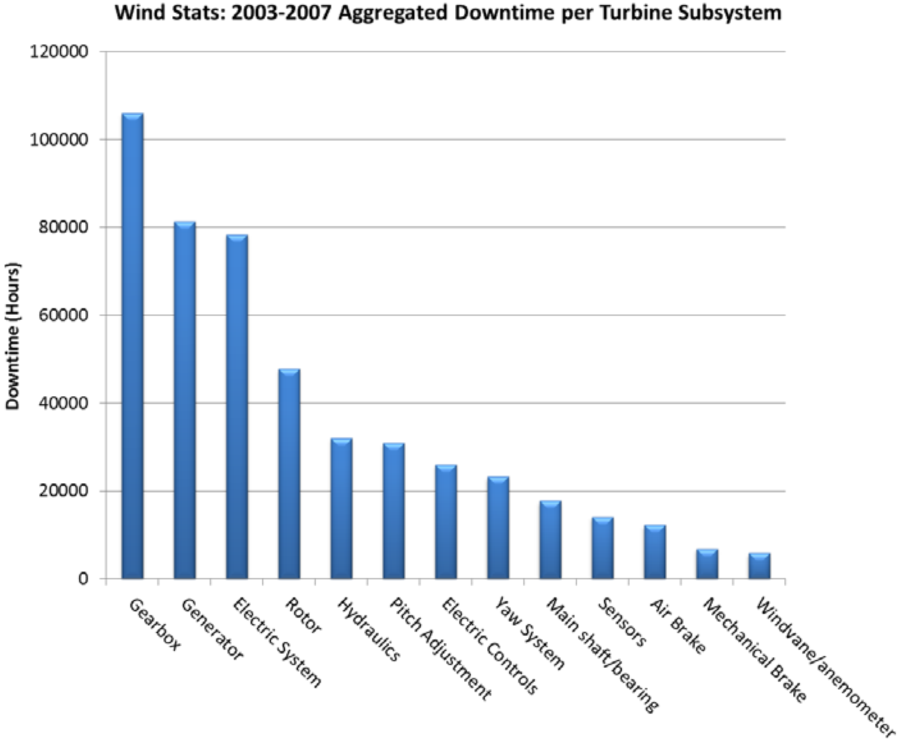
WindStats Newsletter

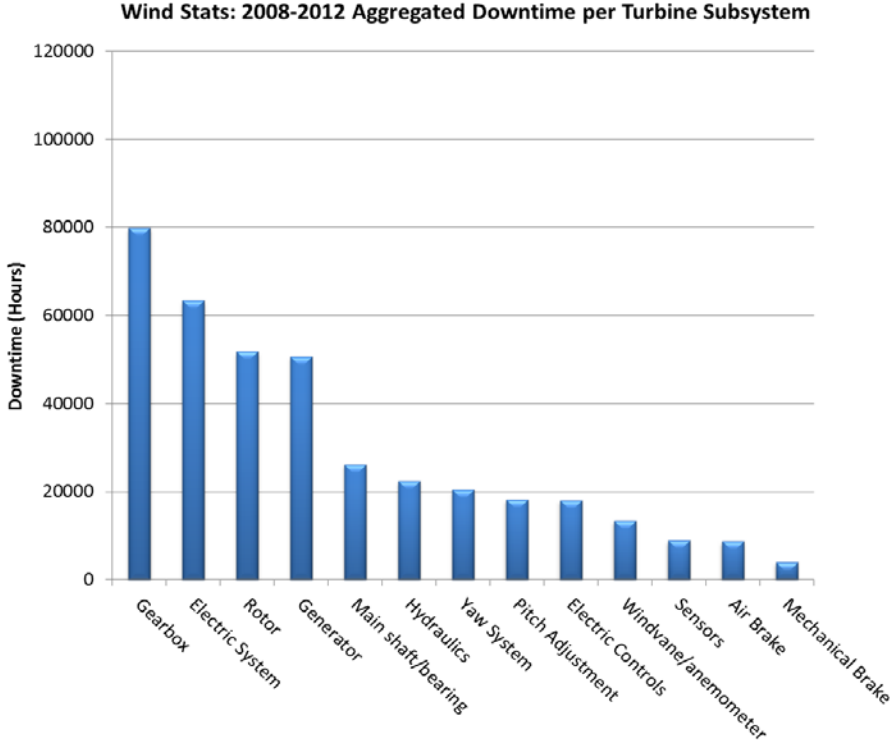
- **A summary extracted from [1,2,7]:**

  A quarterly international wind energy publication with news, reviews, and wind turbine production and operating data from turbines in Sweden, Denmark, Germany and Finland. The data are in a similar format to Vindstat. The total number of downtime for individual turbines is available and German turbines also have number of stops reported. These data can be related to the cause of the stops (Weather, Grid, etc.) and the failed turbine subsystems (Gearbox, Rotor etc.). The failure data are not specified for wind turbine size, type or manufacturer. Information on wind turbine age is not available.

- **Features and status [8]:**
  - Registered turbines in December 2012: ~5,000 in Denmark, ~24,000 in Germany, and ~1,200 in Sweden.
  - Not much reporting from Finland in recent years.
  - Active data collection and reporting.

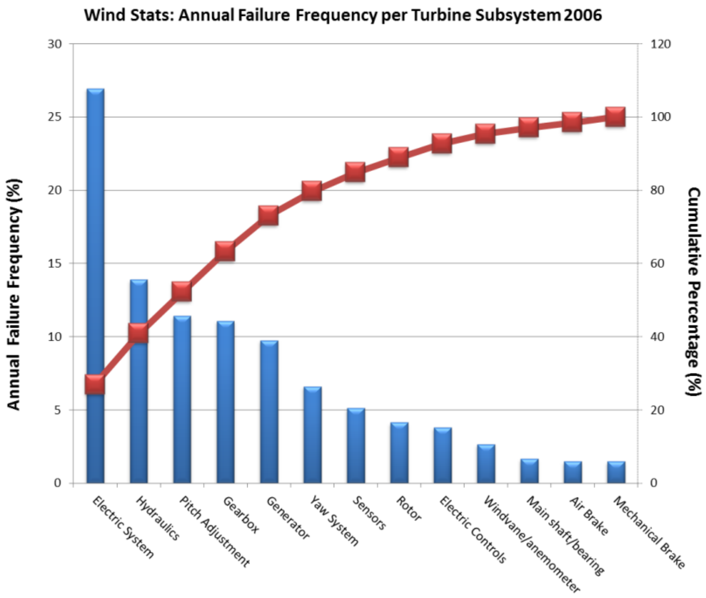
WindStats: Downtime [9]

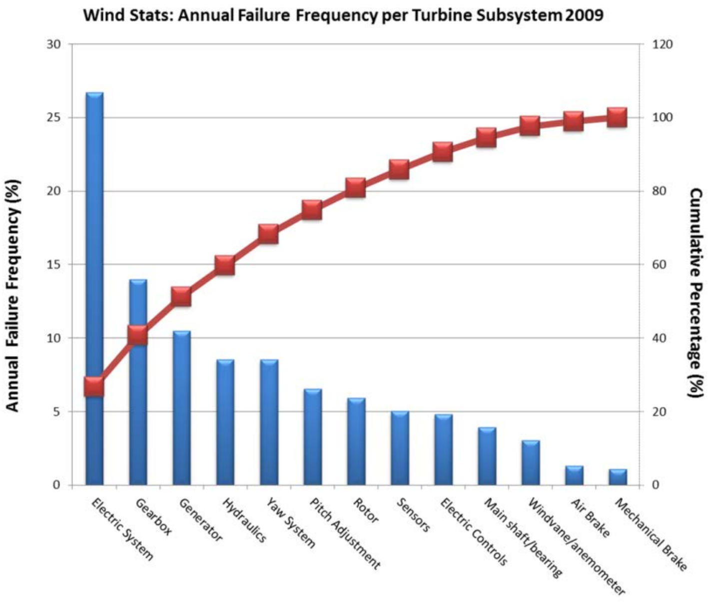




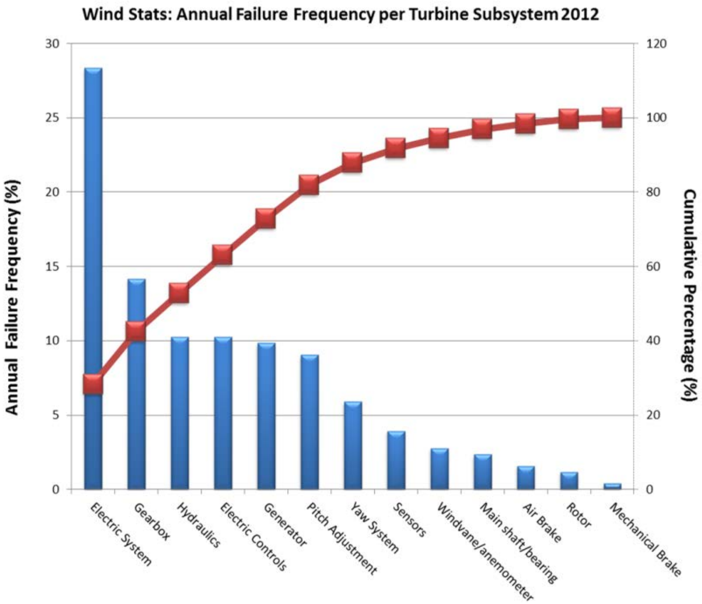
- Aggregated downtime per turbine subsystems 2003 – 2007 (left) and 2008 – 2012 (right):
  - Both periods indicate gearbox as the highest downtime driver.
  - Recent period shows less downtime than old period for most subsystems.
  - Top four drivers stay the same with a little variation in sequence: gearbox (1=>1), generator (2=>4), electric systems (3=>2), and rotor (4=>3).
  - Middle four drivers vary: hydraulics, pitch adjustment, electric controls, and yaw (old) => main shaft/bearing, hydraulics, yaw system, and pitch adjustment (recent).

WindStats: Failure Frequency [10]





- Failure frequencies of turbine subsystems for 2006 (top left), 2009 (top right) and 2012 (bottom right):
    - Top four subsystems identified in all three years: electric systems (consistently being the 1st driver), gearbox, hydraulics, and generator.
    - Top seven drivers contributed more than 80% of failure events each year. Their corresponding subsystems change over time.



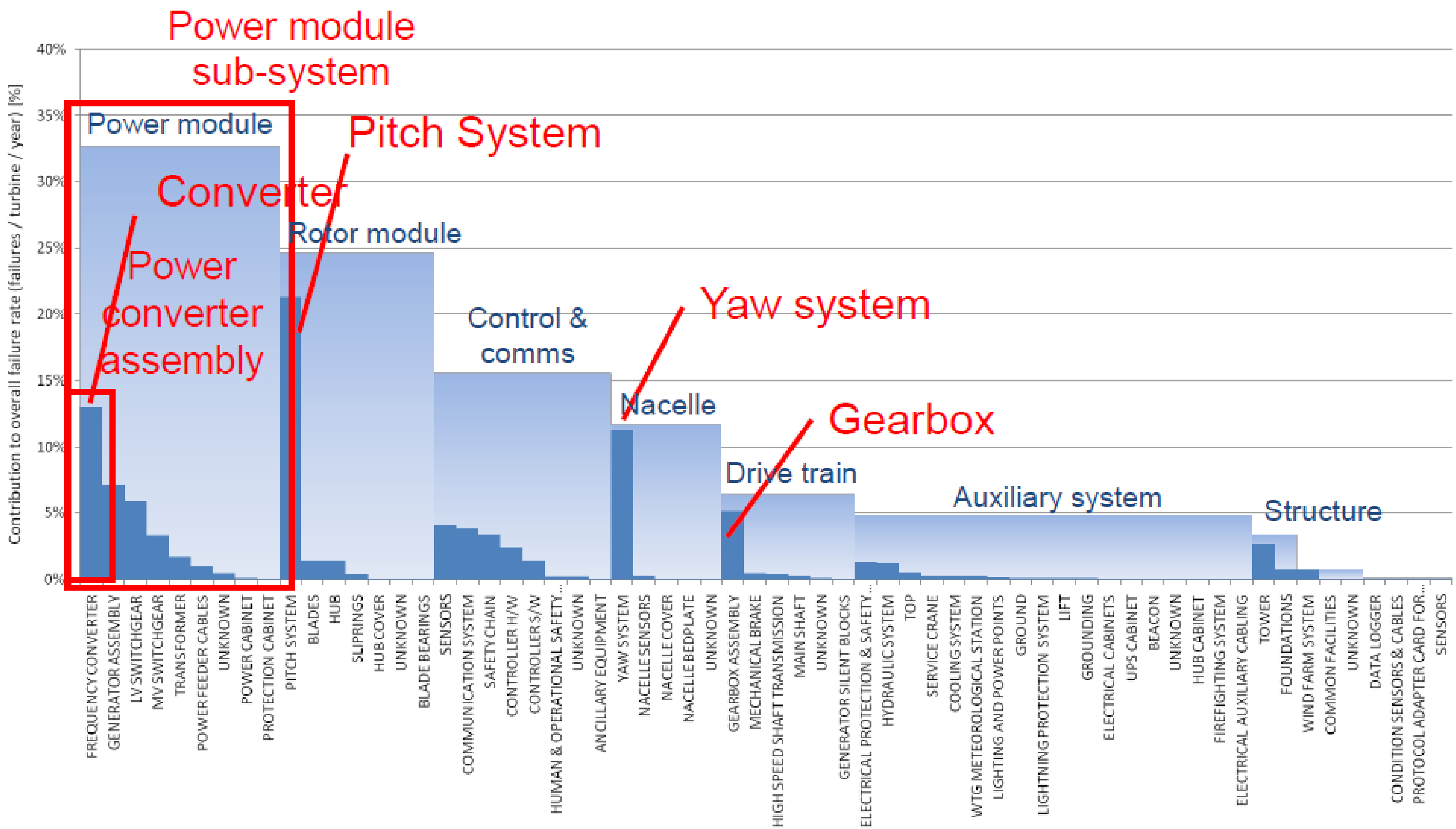
ReliaWind

- **A summary extracted from [2,11]:**

  ReliaWind is an European Union project, involving 10 industrial and academic partners. It has the goals of improving the general understanding of wind turbines and farm reliability, and developing reliability models specific to wind turbines. The database takes account of all operational data recorded at modern wind farms, including: 10-minute average SCADA data; fault / alarm logs; work orders / service reports; and O&M contractor reports.

- **Features and status:**
  - ~ 350 WTs, aging 1 ~6 years, all pitch-regulated, ~ 35,000 downtime events [4].
  - Closed in 2011 [2].

ReliaWind: Normalized Failure Rates [4]

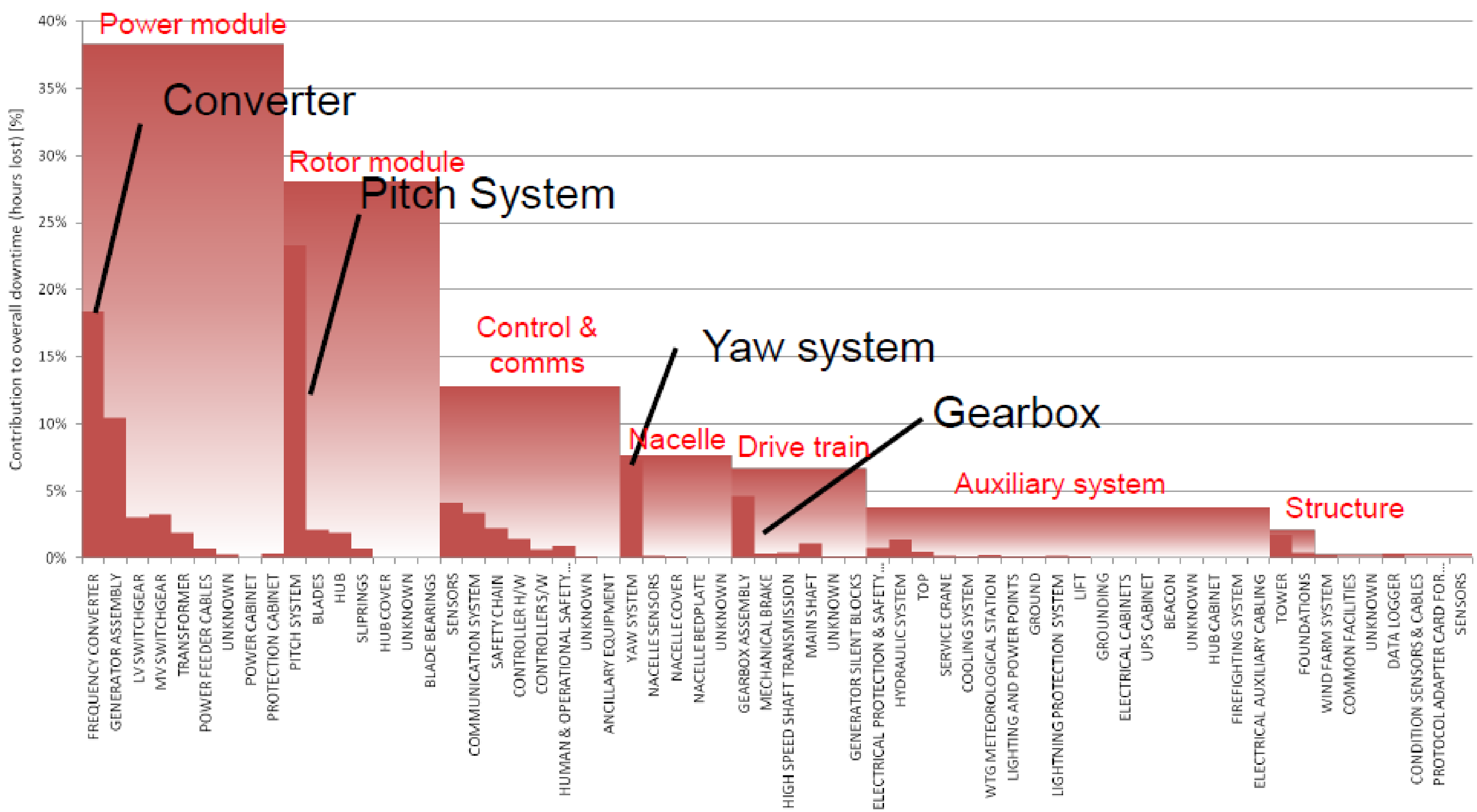


Percentage contribution to overall failure rate

Data source: turbines from multiple manufacturers

- **Top contributing subsystems: converter, pitch, yaw, and gearbox**

ReliaWind: Normalized Hours Lost [4]

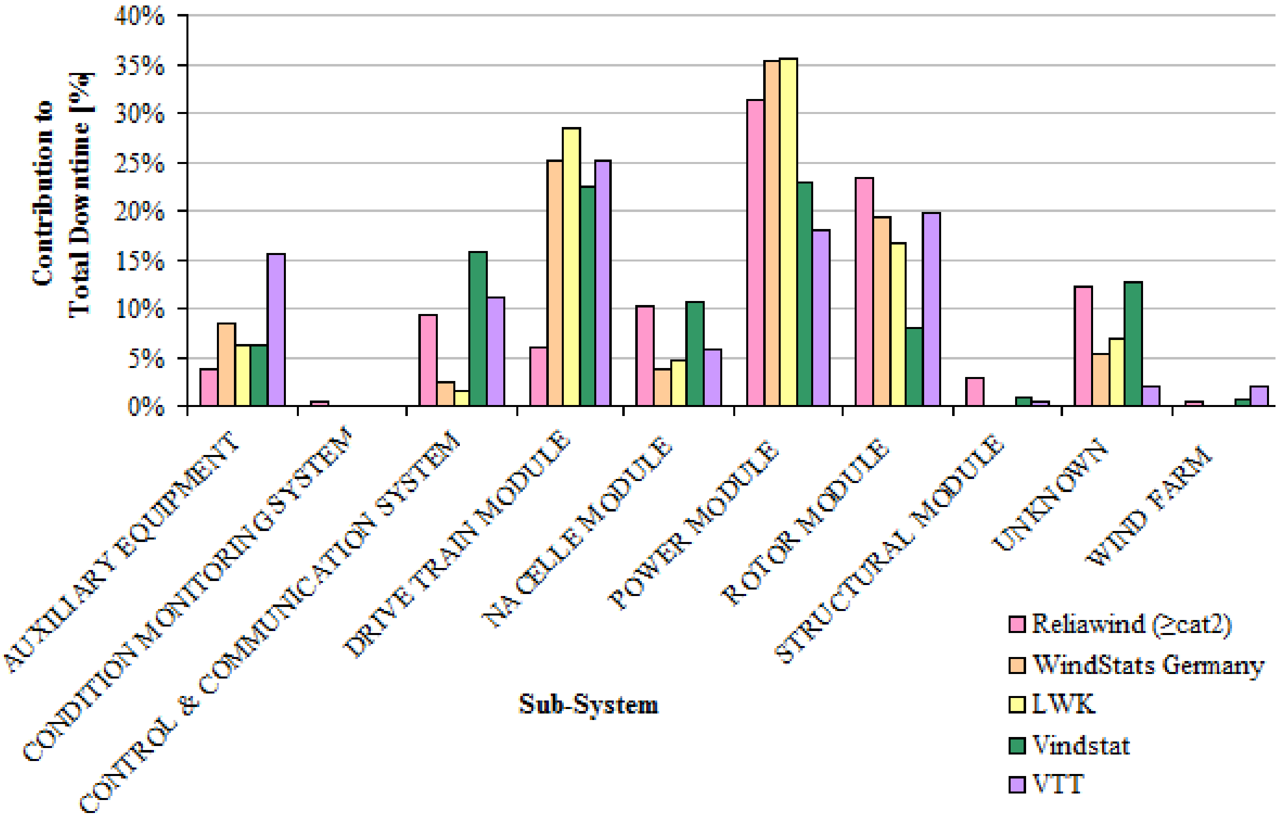


Percentage contribution to overall failure rate

Data source: turbines from multiple manufacturers

- **Top contributing subsystems same as to failure rates: converter, pitch, yaw, and gearbox**

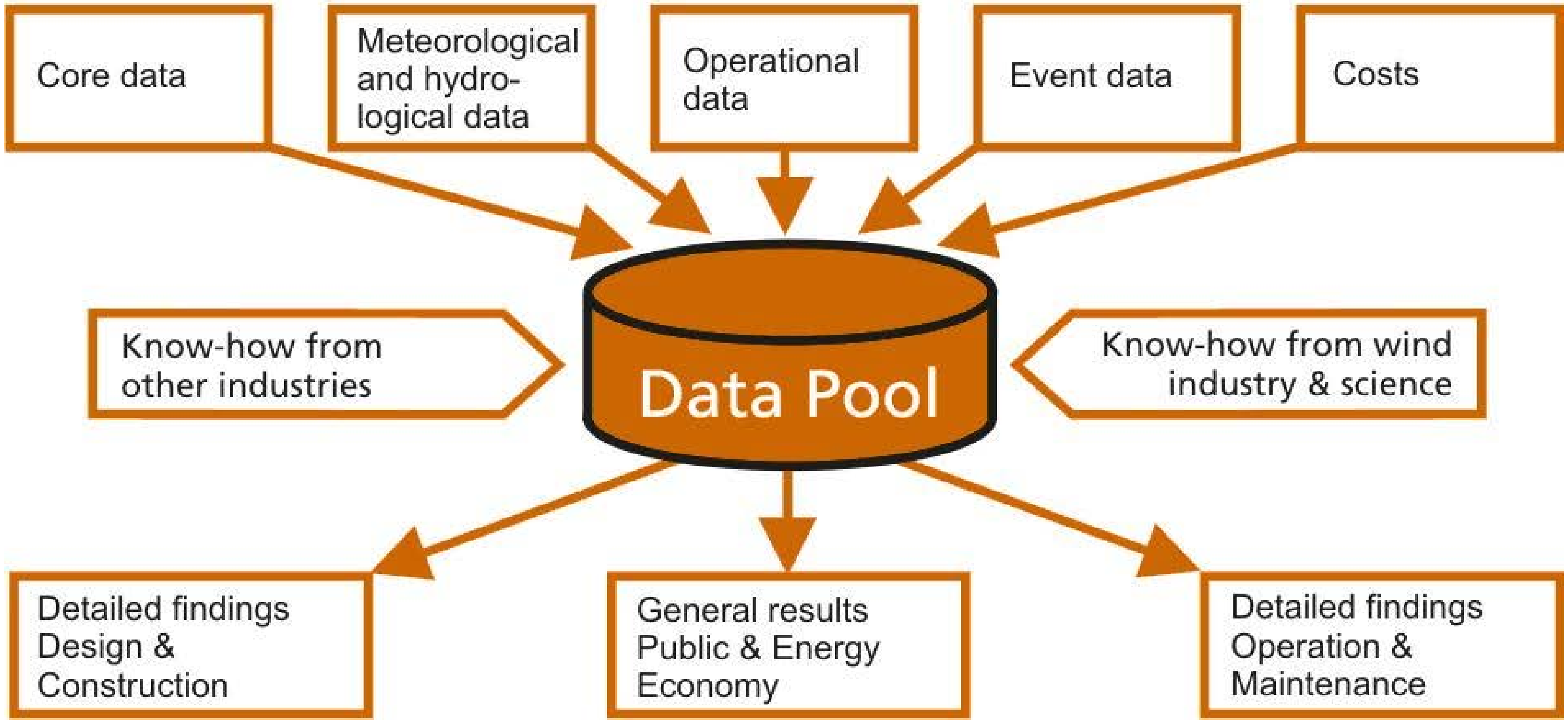
Downtime Summary by Several Efforts [12]

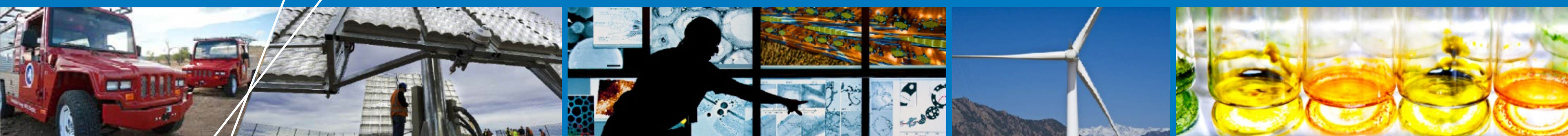


- Top three contributors indicated by most of these databases: power module, drive train module, and rotor module, among which drive train and rotor modules are typically more expensive to repair due to the crane costs.
- To correctly understand variations in the results from different databases: need to consider the population of turbines recorded by each database, such as turbine ages, technologies, site location and characteristics, etc.

Offshore WMEP

- A follow-up project of the onshore WMEP [13] demonstrating the value of reliability data collection efforts for O&M and reliability research.
- Concepts phase started in 2007 and ended in 2011 [14].
- Some results reported in [14].

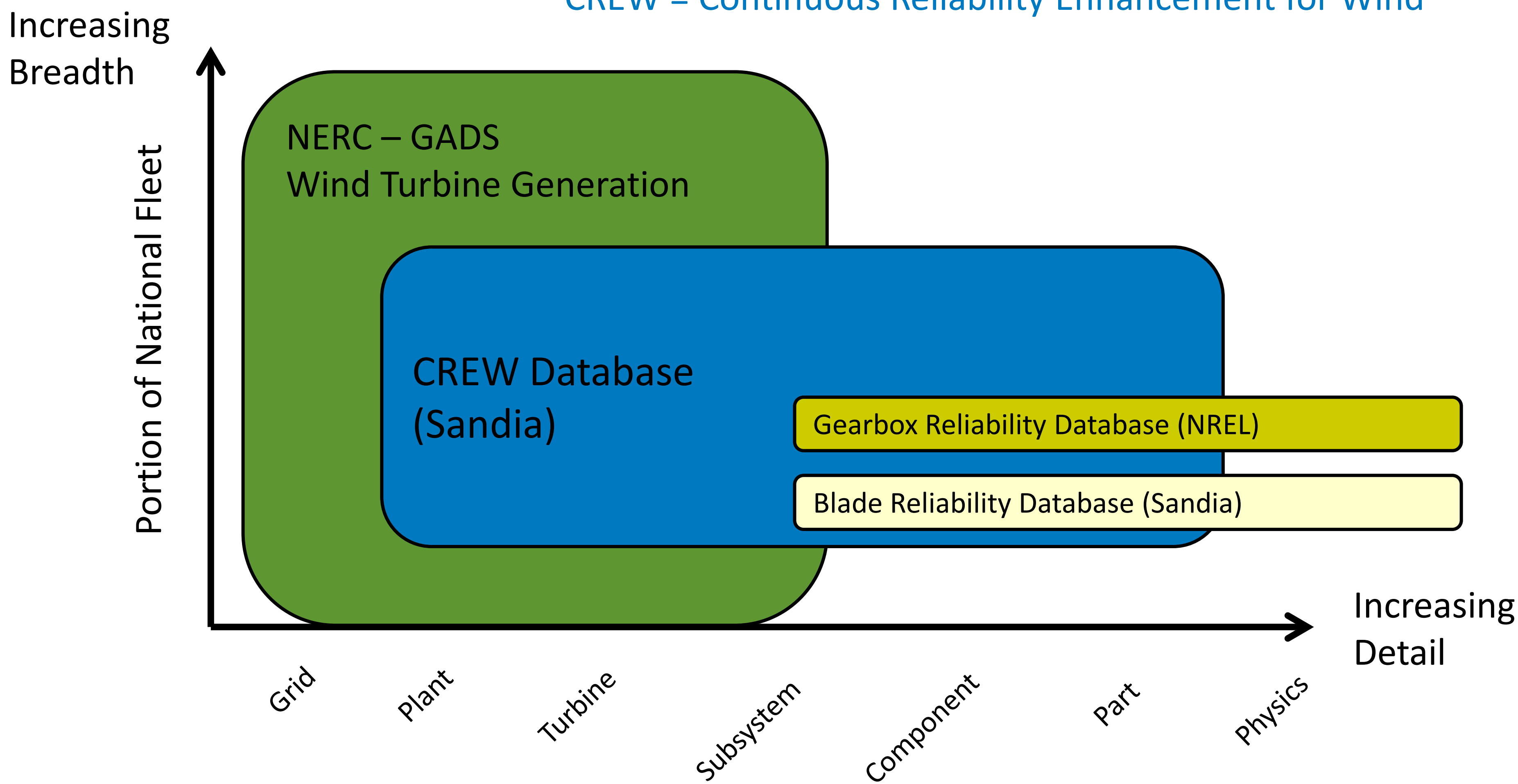




U.S. Efforts

U.S. Databases

NERC = North American Electric Reliability Corporation
GADS = Generating Availability Data System
CREW = Continuous Reliability Enhancement for Wind



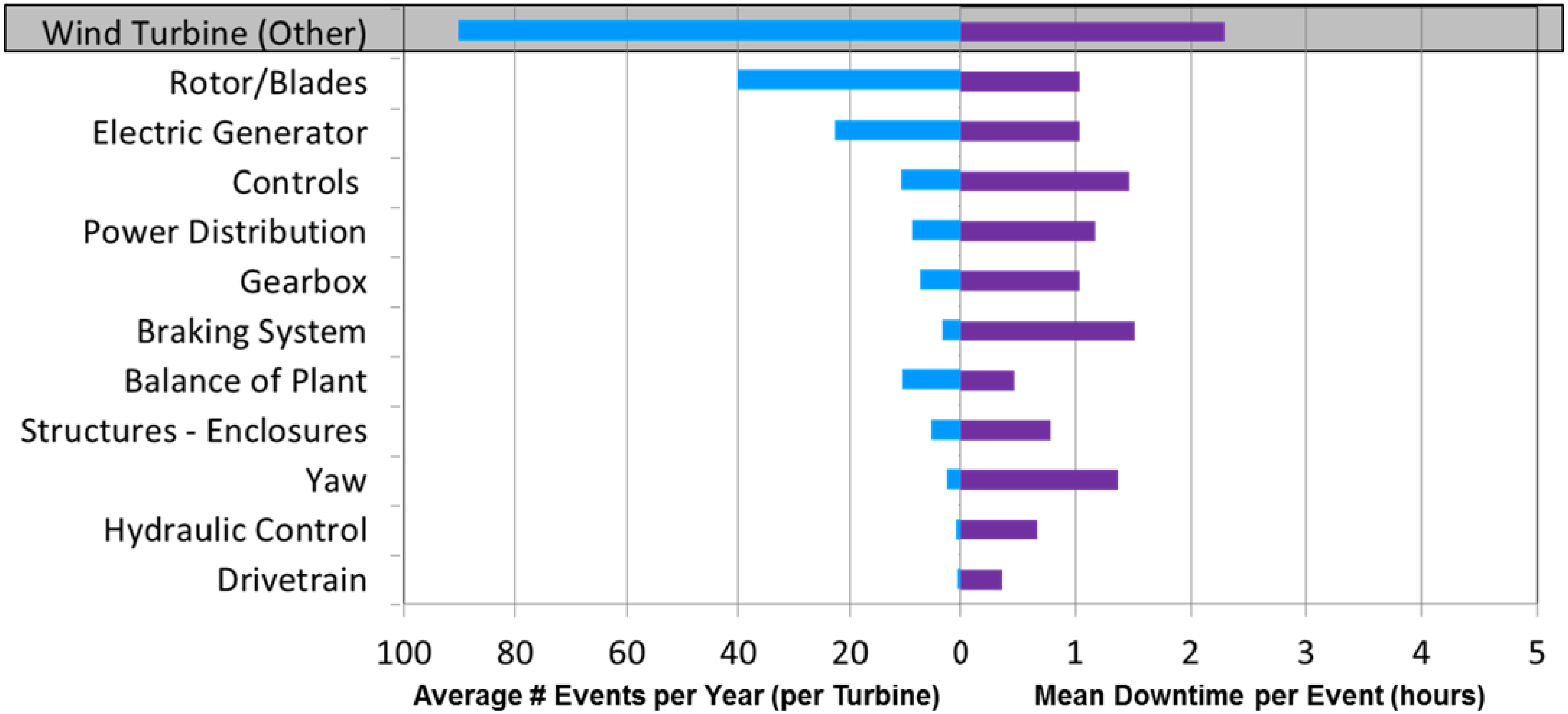
SNL CREW Database [15]

- **A brief summary:**

  Continuous Reliability Enhancement for Wind (CREW) database is developed by Sandia National Laboratories (SNL) with the objective to benchmark the current U.S. wind turbine fleet reliability performance and identify the major contributors to component-level failures and other downtime events. It collects Supervisory Control and Data Acquisition (SCADA) data, downtime and reserve event records, and daily summaries of Generating, Unavailable, and Reserve time for each turbine.

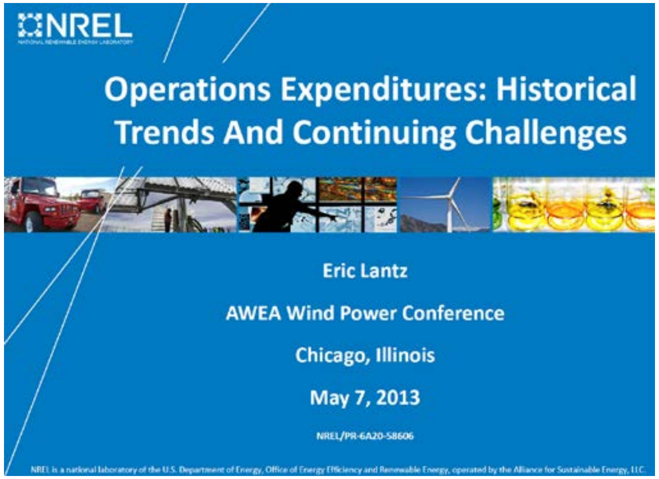
- **Features and Status:**
  - 800 ~ 900 WTs rated above 1 MW.
  - Active data collection and reporting .

SNL CREW: Failure Rate and Downtime [15]



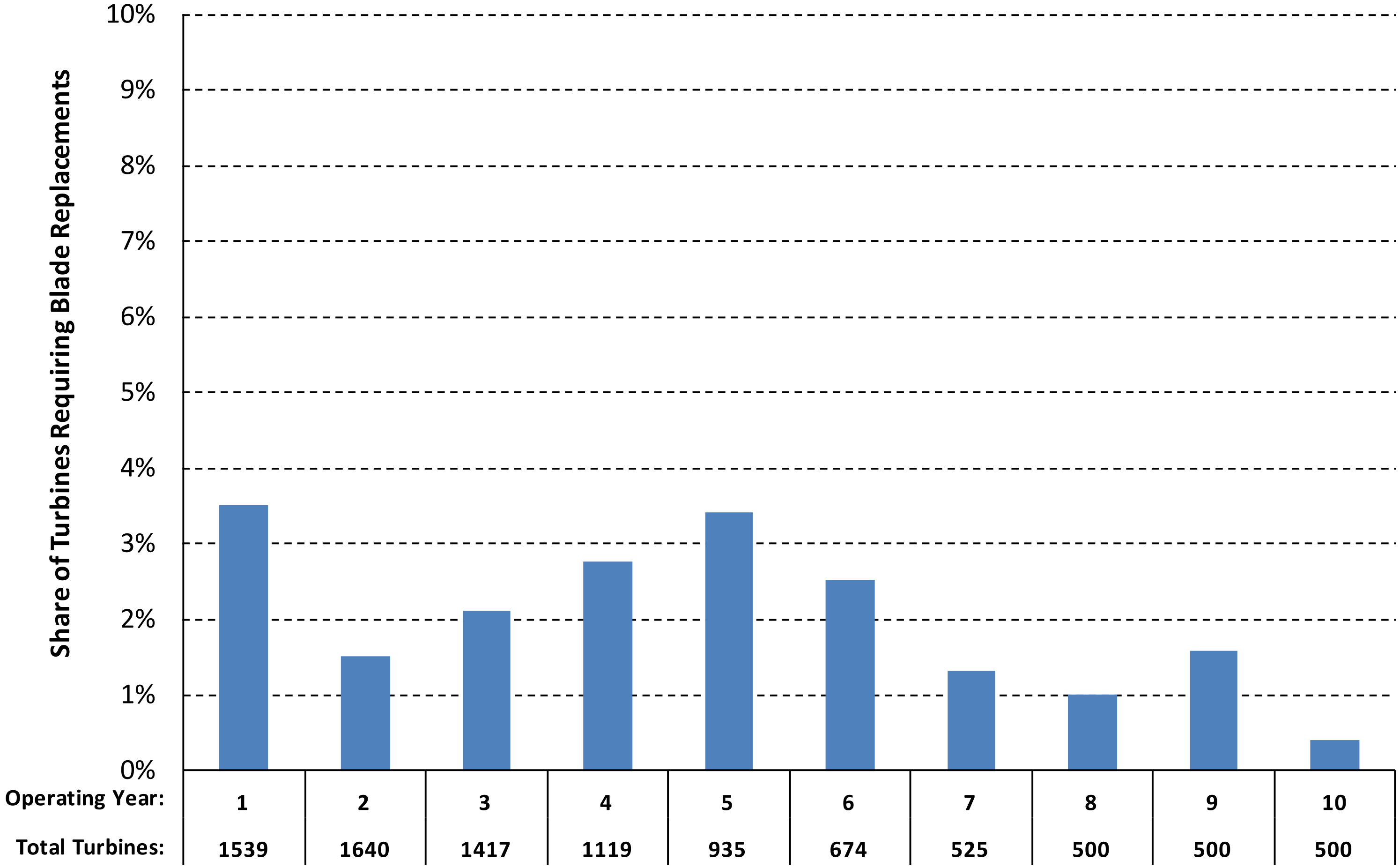
- "Other" caused longest down time per event: need to clarify what it covers, specifically
- Average # of events per turbine top four identifiable drivers: rotor/blades, electric generator, balance of plant, and controls.
- Mean downtime per event top four identifiable drivers: braking system, controls, yaw, and power distribution.

Data Collected by DNV-KEMA and GL Garrad Hassan for NREL [16]



- Main objective is to track costs, plant availability, and component failures over technology improvements.
- The combined GL Garrad Hassan and DNV KEMA sample represents about 10 GW of operating wind plants.
- Replacement rates of major subsystems including blades, gearboxes, and generators will be presented. For other information please check [16].
- Critical caveats:
  - Datasets studied are not comprehensive and data quality varies by project and across time.
  - Data are skewed toward recent builds (as that is when the capacity has come online); however, these projects only offer 1-3 years of operating data.
  - Operating data beyond 5 years are sparse and may not be fully represent industry experience.

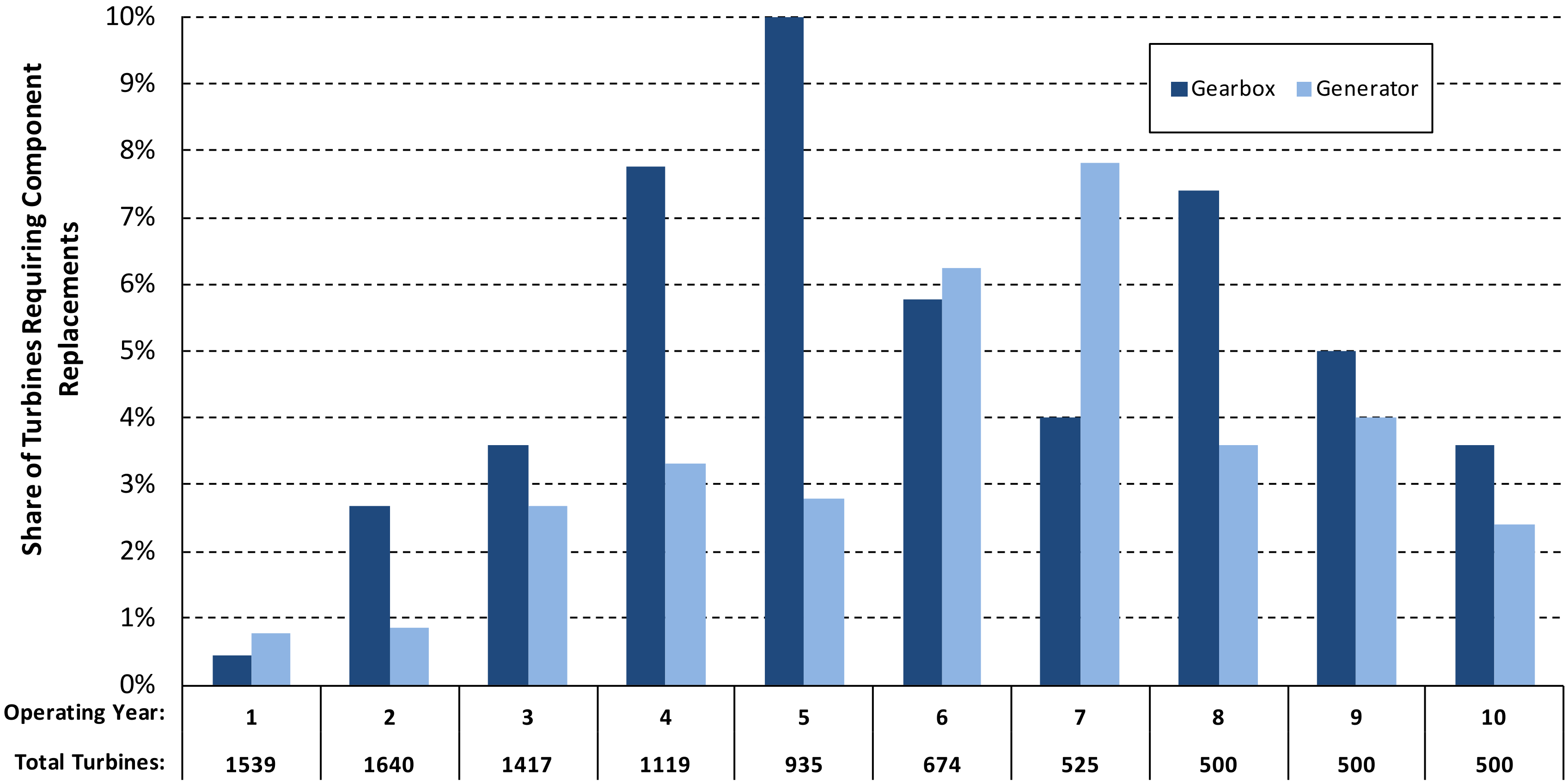
Annually, 1 to 3% of Turbines Require Blade Replacements with Spikes in Years 1 and 5 [16]



Data Source: DNV KEMA

- **Blade replacements in years 1 and 2 are typically the result of manufacturing defects or damage that occurs during transport and construction.**
- **On average, about 2% of turbines per year (through 10 years of operations) require blade replacements; lightning strikes are the most commonly noted cause of failure.**

More Turbines Require Gearbox and Generator Replacements [16]

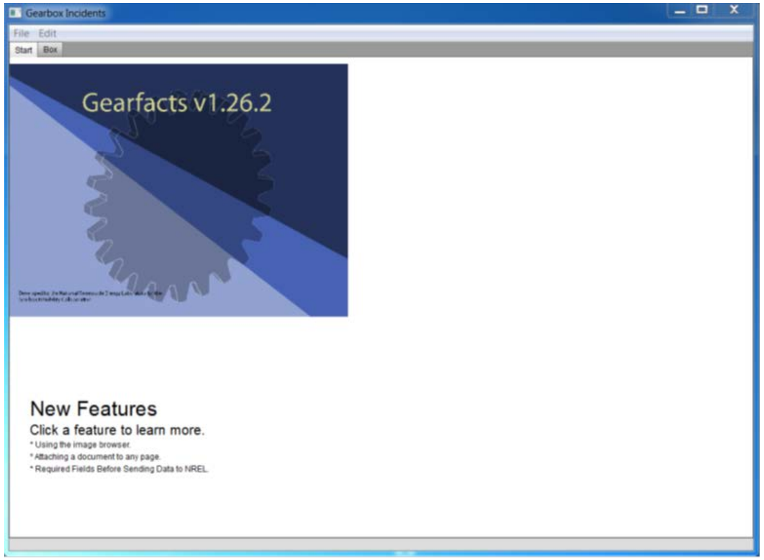


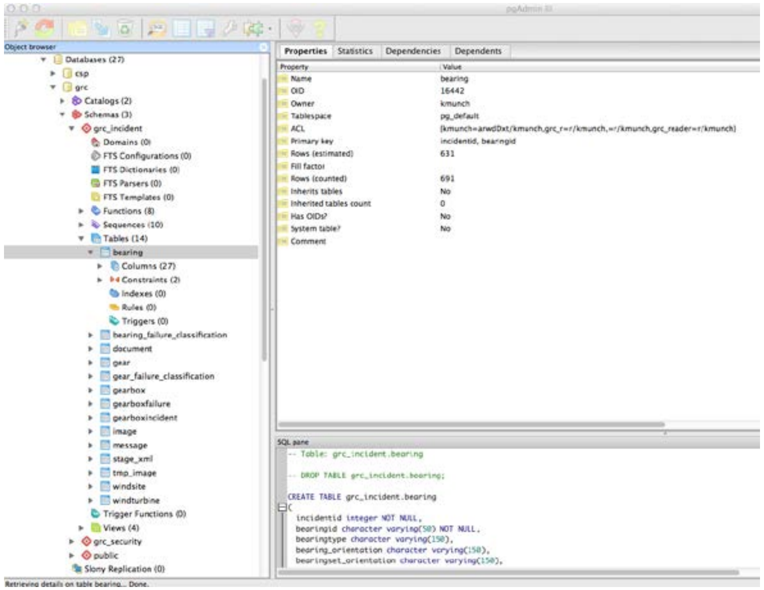
Data Source: DNV KEMA

- **Average gearbox failure rate over 10 years of operations is estimated at 5%, peaked in years 4, 5 and 8.**
- **The average generator failure rate is somewhat lower and over 10 years of operations is estimated at 3.5%, peaked in years 6 and 7.**
- **Serial failures were observed to have a noteworthy effect on gearbox and generator failure rates, potentially skewing the results.**

NREL Gearbox Failure Database

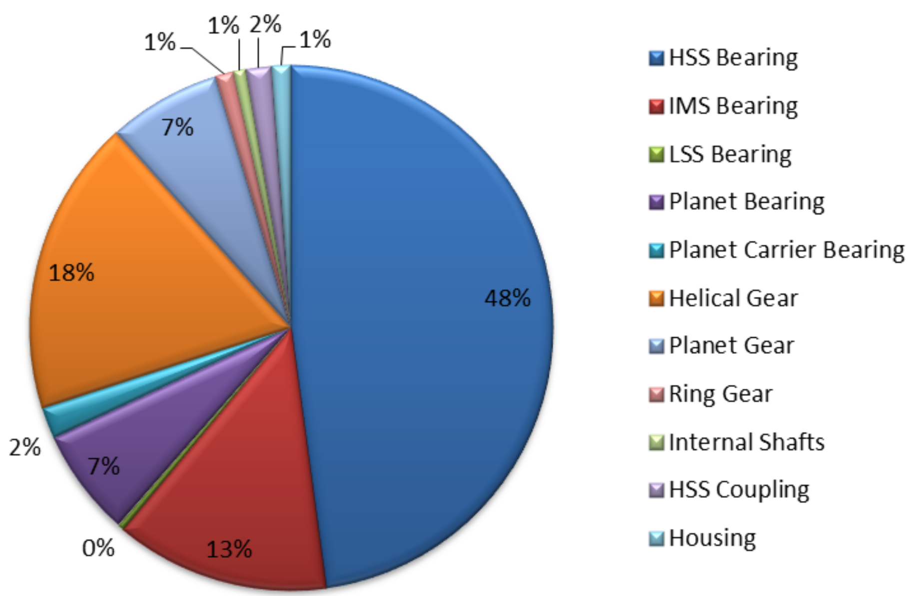
- Main objectives are to categorize top gearbox failure modes, identify possible root causes, and direct future gearbox reliability R&D activities.
- Gearbox failure event data at very detailed and summary levels highlighting damaged components, failure modes and possible root causes.
- About 20 partners including turbine/gearbox manufactures, owners/operators, gearbox rebuild shops, and O&M service providers.
- Started in 2009 and currently active.
- Assets owned by owner/operator partners on this database represent ~31% of the U.S. end of 2012 capacity.





Gearbox Damage Distribution

- The database contains 289 gearbox failure incidents with 257 confirmable damage records (Note: one incident may have multiple damage records).
- Gearboxes could fail in drastically different ways.
- Bearings: ~ 70%; Gears: ~ 26%; and Others: ~ 4%
- Current data show:
  - Both bearing and gear faults are concentrated in the parallel section.
  - Top gearbox failure mode is high or intermediate speed shaft bearing axial cracks.



<table>
<tr><th></th><th>Damage Records</th><th>Bearings</th><th>Gears</th><th>Others</th></tr>
<tr><td>Planetary</td><td>44</td><td>23</td><td>21</td><td rowspan="3">9</td></tr>
<tr><td>IMS</td><td>N/A</td><td>34</td><td rowspan="2">47</td></tr>
<tr><td>HSS</td><td>N/A</td><td>123</td></tr>
<tr><td>Total</td><td>257</td><td>180</td><td>68</td><td>9</td></tr>
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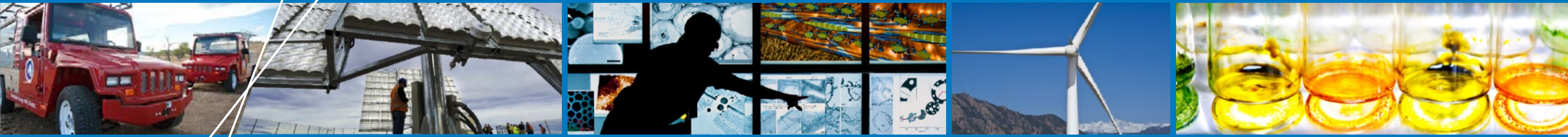


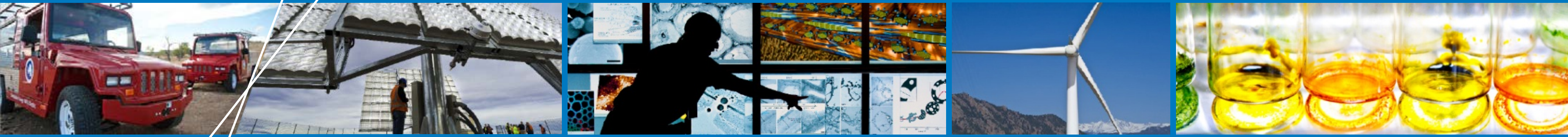
Observations

Data Collection Efforts

- Experiences in Europe
  - Many years of experiences with various efforts
  - Explored various data analysis methods and presented valuable statistics for the industry as a whole
  - Reliability database value demonstrated for O&M and reliability research
- U.S. Efforts
  - SCADA data valuable for benchmarking purpose
  - Historical replacement statistics instructive for future O&M planning
  - Gearbox failure database supports reliability R&D activities
- Trend to tie different data streams together
- Challenges with data sharing by partners and need for standardization of terminology and data collection protocols
- Opportunities to collaborate at a global level

Statistics

- Experiences in Europe:
  - Most databases show the most frequently failed subsystem is power electronics or power module.
  - Most databases indicate gearboxes caused the highest downtime per failure.
  - Other subsystems may also need attentions include: generators, hydraulics, converters, pitch, yaw, rotor/blades, and main bearings.
  - Reliability tends to reduce for larger WTs, which represent less mature technologies.
  - Benefits from direct-drive WTs based on available data not conclusive and need more data to evaluate.
- U.S. Efforts:
  - For the U.S. fleet, average yearly replacement rates: gearboxes ~5% peaked in years 4, 5 and 8, generators ~3.5% peaked in years 6 and 7, and blades ~ 2% peaked in years 1 and 5.
  - Gearboxes can fail in drastically different ways and it appears that bearing/gear failures concentrate in parallel stage.
  - For the U.S. fleet, the top gearbox failure mode is high speed or intermediate shaft bearing axial cracks.

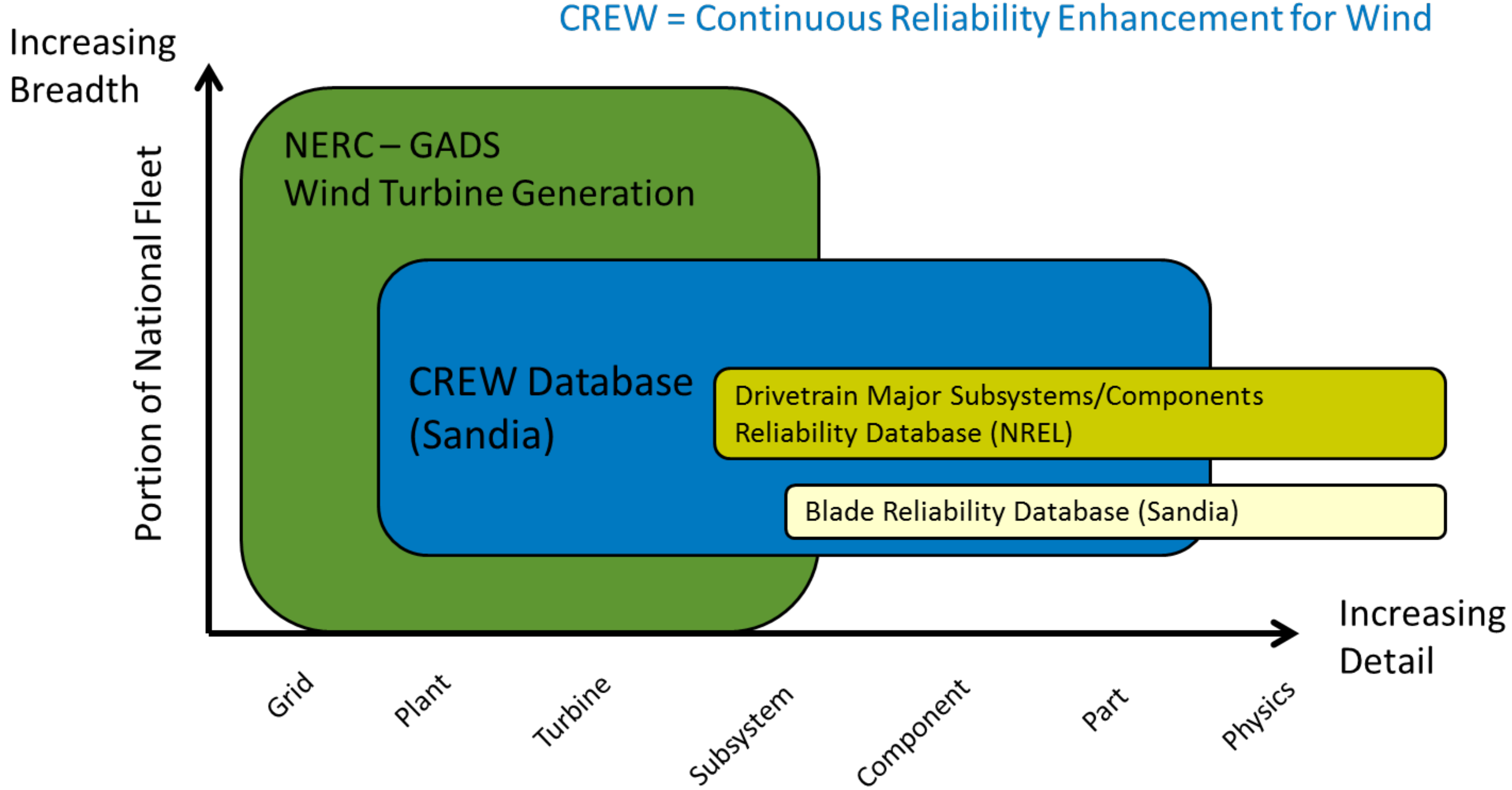


Opportunities

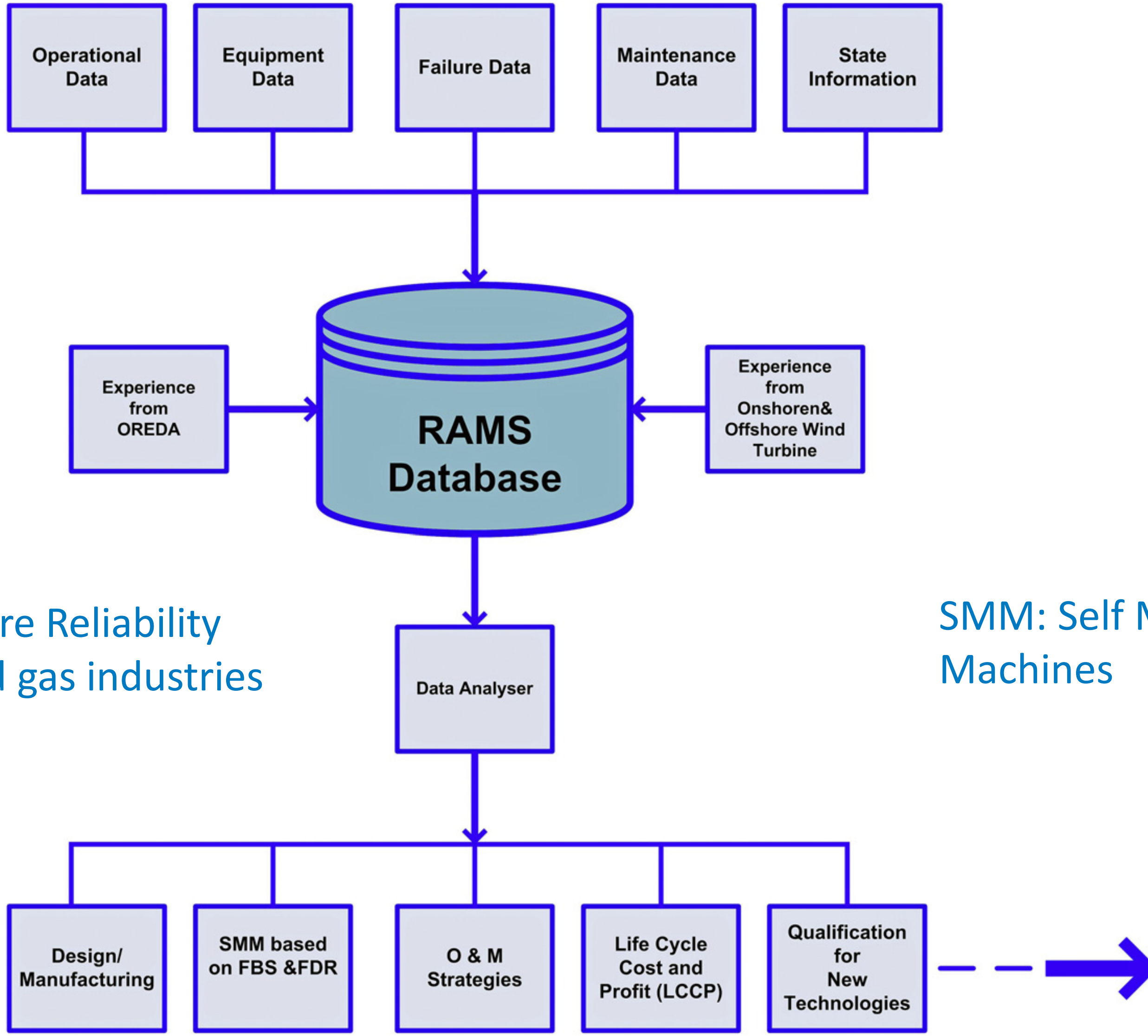
NREL Drivetrain Major Subsystems/Components Reliability Database

- **Expand the current effort on gearboxes to major drivetrain subsystems/components => reliability research and field operation activities**

NERC = North American Electric Reliability Corporation
GADS = Generating Availability Data System
CREW = Continuous Reliability Enhancement for Wind



A Proposed RAMS Database Schematics



OREDA: Offshore Reliability Data for oil and gas industries

SMM: Self Maintenance Machines

A Reliability, Availability, Maintainability, and Serviceability (RAMS) Database Schematics Proposed in [17]

NREL Wind O&M Database

- **Use O&M reports and keep the proposed RAMS schematics in mind => optimized O&M strategies**

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GADS = Generating Availability Data System
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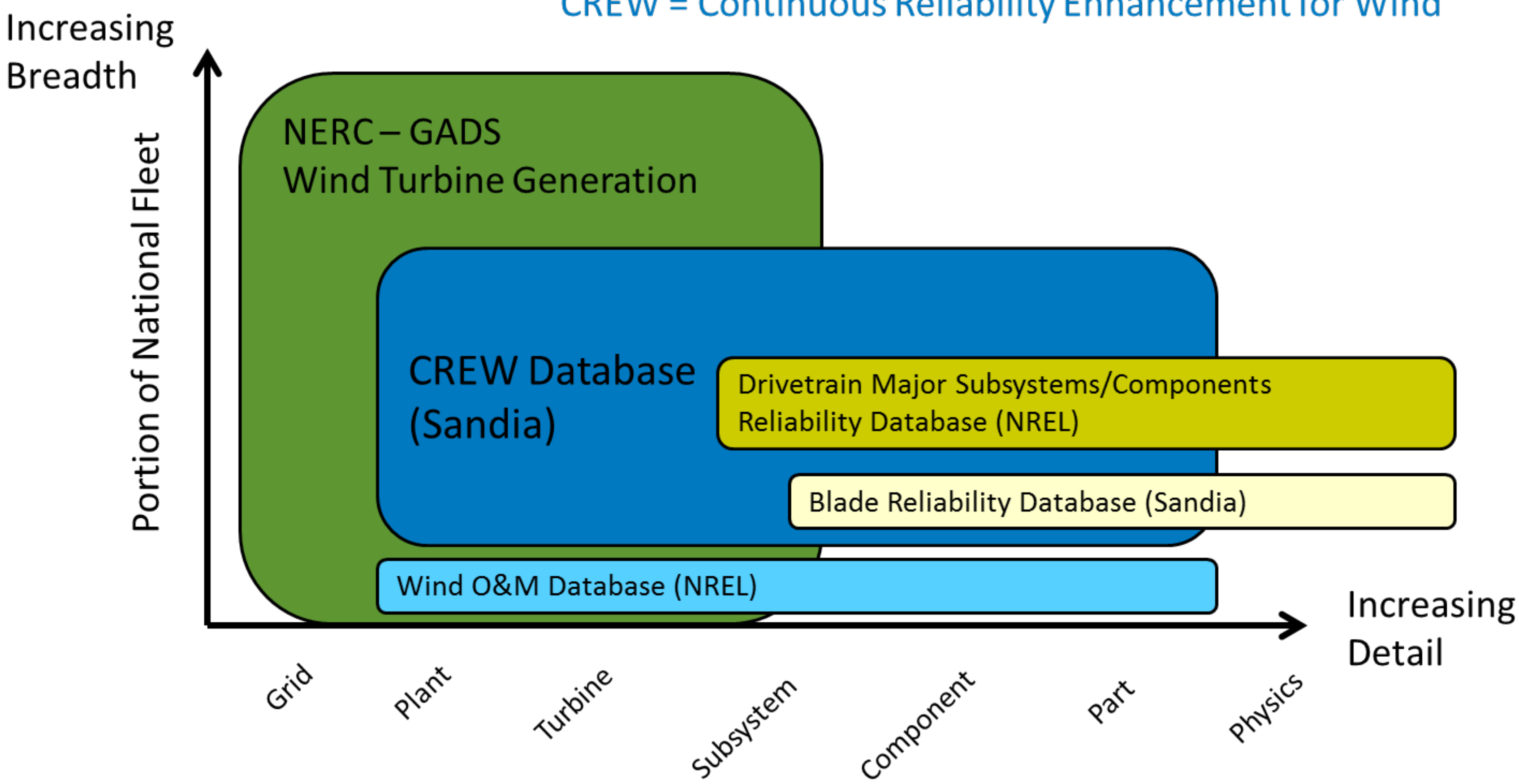

References

1. Tavner, P., Spinato, F., van Bussel, G.J.W., Koutoulakos, E. (2008). Reliability of Different Wind Turbine Concepts with Relevance to Offshore Application, presented at the European Wind Energy Conference, March 31 – April 3, Brussels, Belgium.
2. Pettersson L., Andersson J-O., Orbert C., and Skagerman S. (2010), RAMS-Database for Wind Turbines – Pre-study, Elforsk Report 10:67.
3. Faulstich, S.; Lyding, P.; Hahn, B. (2010), Component Reliability Ranking with Respect to WT Concept and External Environmental Conditions, Upwind Deliverable WP7.3.3.
4. Tavner, P. (2011), How Are We Going to Make Offshore Wind Farms More Reliable?, presented at the 2011 SUPERGEN Wind General Assembly, March 20, Durham University, United Kingdom.
5. Wind energy statistics in Finland: http://www.vtt.fi/proj/windenergystatistics/?lang=en [accessed 06/11/2013].
6. Stenberg, A.; Holttinen, H. (2010), Analysing Failure Statistics of Wind Turbines in Finland, presented at the European Wind Energy Conference, April 20-23, Warsaw, Poland.
7. Carlsson, F.; Eriksson, E.; Dahlberg, M. (2010), Damage Preventing Measures for Wind Turbines – Phase 1 Reliability Data, Elforsk Report 10:68.
8. Windstats Report, Vol. 26, No. 1, Q1 2013.
9. Windstats Reports, Vol. 16 – Vol. 25, Q1 2003 – Q4 2012.

References (*Cont.*)

10. Windstats Reports, Vols. 19, 22, and 25, Q1 – Q4 in 2006, 2009, and 2012.
11. Wilkinson, M.; Hendriks, B. (2011), Report on Wind Turbine Reliability Profiles, ReliaWind Deliverable D.1.3.
12. Lange, M.; Wilkinson, M.; van Delft, T. (2010), Wind Turbine Reliability Analysis, presented at the 10th German Wind Energy Conference, November 17-18, Bremen, Germany.
13. Offshore WMEP: http://offshorewmep.iwes.fraunhofer.de/index.html?page=concept&lang=en [accessed 06/14/2013].
14. Pfaffel, S. (2012), Offshore ~ WMEP Monitoring Offshore Wind Energy Use in Germany and Europe: from Concept to Execution, presented at the Research at Alpha Ventus (RAVE) International Conference, May 8-10, Bremerhaven, Germany.
15. Peters, V.; Ogilvie, A.; Bond, C. (2012), CREW Database: Wind Plant Reliability Benchmark, SAND2012-7328.
16. Lantz, E. (2013), Operations Expenditures: Historical Trends and Continuing Challenges, presented at AWEA Wind Power Conference, May 5-8, Chicago, IL. NREL/PR-6A20-58606.
17. Hameed, Z.; Vatn, J.; Heggset, J. (2011), Challenges in the Reliability and Maintainability Data Collection for Offshore Wind Turbines, Renewable Energy, Vol. 36, pp. 2154-2165.

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HC Sorensen, Middelgrunden Wind Turbine Cooperative/PIX17855

shuangwen.sheng@nrel.gov
303-384-7106