Perceived Uncertainty Sources in Wind Power Plant Design

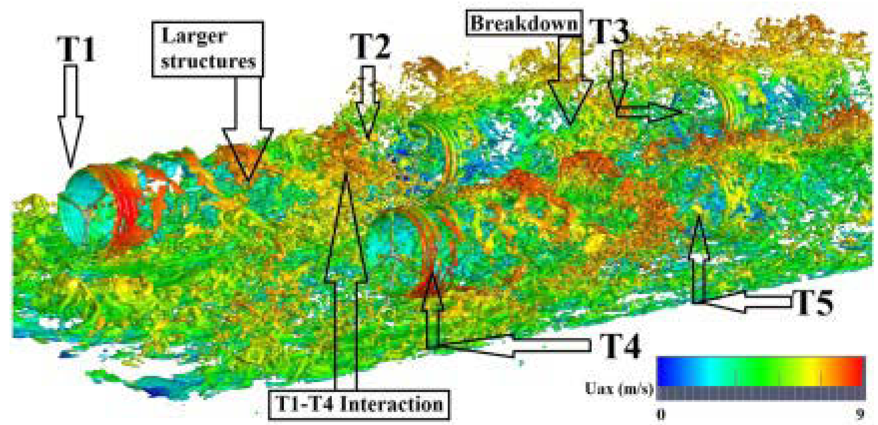
Rick Damiani

September 13–14, 2017
Fourth Wind Energy Systems Engineering Workshop
Danish Technical University, Roskilde, Denmark

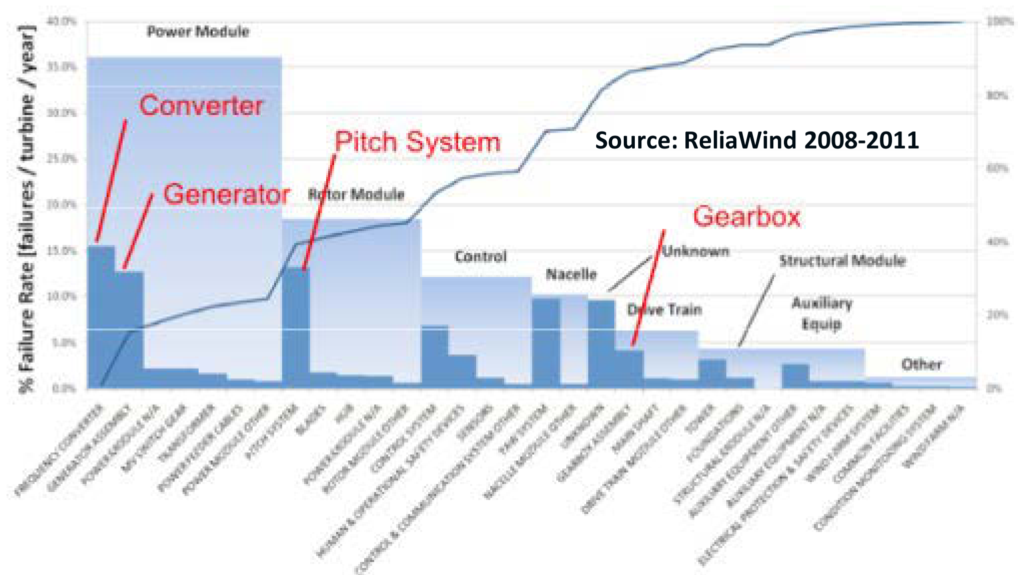
PR-5000-70653

Motivation

- Turbulent wind operation still laden with uncertainties
- Uncertainties affect design and structural reliability
- Failures still occur
- Risk/mitigation→ levelized cost of energy (LCOE)
- Downtime→LCOE.



Source: Jha et al. (2015) "Unraveling the Mysteries of Turbulence Transport in a Wind Farm"



Goal and Methods

- Identify key sources of uncertainty and prioritization for research and development (R&D)

- Analysis of current procedures, industry best practice , standards, and expert opinions

- Design Criteria Identification and Ranking Table (DCIRT)

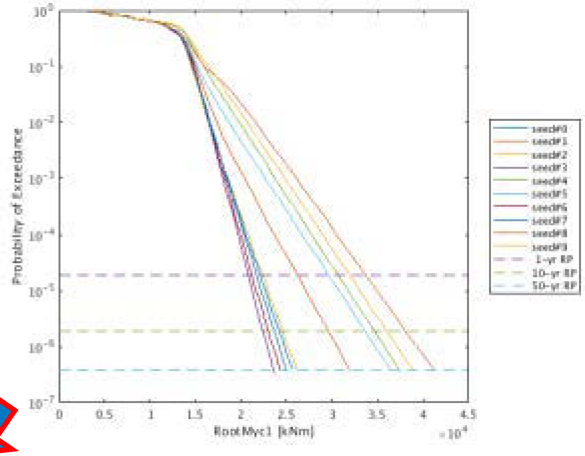
Design Criteria Identification and Ranking Table (DCIRT)

Design Criteria	Level of Understanding of the...			Expert Opinion: Impact on System Risk and Reliability
	Process Physics	Load Modeling	Uncertainty	
As-Built and Nonconformities	• As-built nonconforming to specs • Pitch errors • Yaw errors • Mass/inertia errors • Temperature effects on material and system properties • Material properties/manufacturing quality and variability • Failures 'outside the box'	• Raise QA/QC level vs. design for lower QC → focus on increasing QC • Cascading effects of errors (e.g., pitch/yaw)	Uncertainty, its propagation, and impacts are known, but they do not diminish	Human error filtered by QA/QC, but not covered by PSFs
Standard Design Conditions	• Dimensionality of design space • Beyond tu, how do you handle other conditions (shear, veer, and so on) • How do we improve turbine classes to be more representative of real site conditions? • Perhaps develop new design classes to address location-specific issues • Offshore DLC 6.2: how can the yaw error be better defined? What is missing?	• Extrapolation modeling (methods being used by OEM may be proprietary) • Account for time spent under different-than-standard conditions (stability/shear, and so on)	This ties to site suitability: mapping capacity to particular site	• V_{ref} issue as in site suitability; • Current standard not explicit in the intent of goals • Expected values of gust factors vs. considering uncertainty • PRUF-like exercise for loads • Site-suitability standards? • Adjustable products are the trend: mix and match components suitable for site-specific design

Excerpt

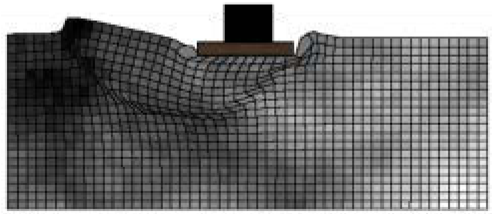
Uncertainty Category I

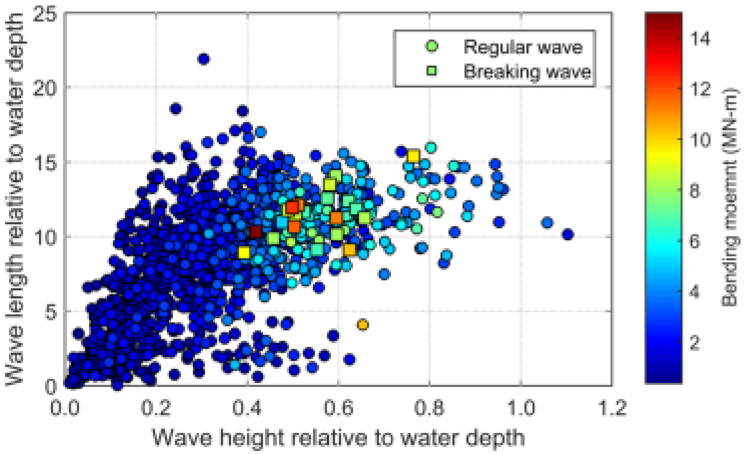
$$\gamma_L L \leq \frac{R}{\gamma_R}$$



1. Inflow and Environmental BCs (direct impact on Loads)

Bearing Capacity





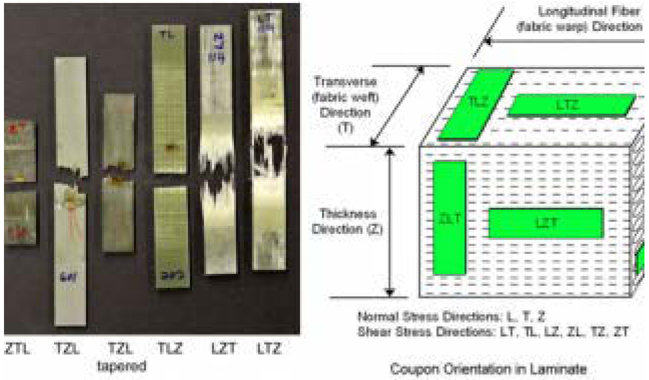
- Turbulence spectrum, coherence, shear, veer, stability, wakes, terrain effects, wave field, higher order hydrodynamics, breaking waves
- Deterministic vs. Stochastic Turbulence parameters
- Extreme Events
- Soil-structure interaction
- Load Extrapolation.

Uncertainty Category II

$$\gamma_L L \leq \frac{R}{\gamma_R}$$

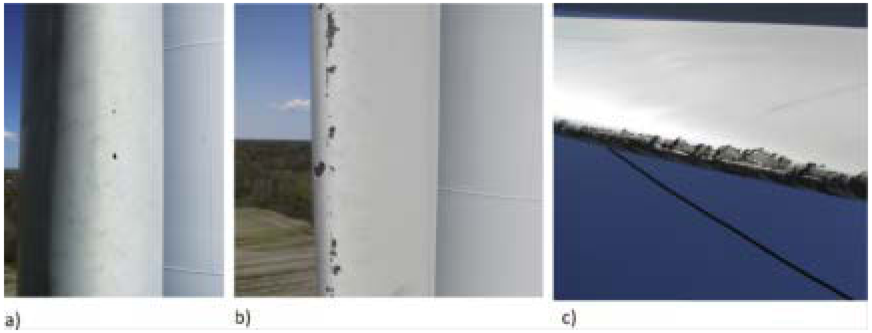
2. Material behavior and strength (direct impact on Resistance)

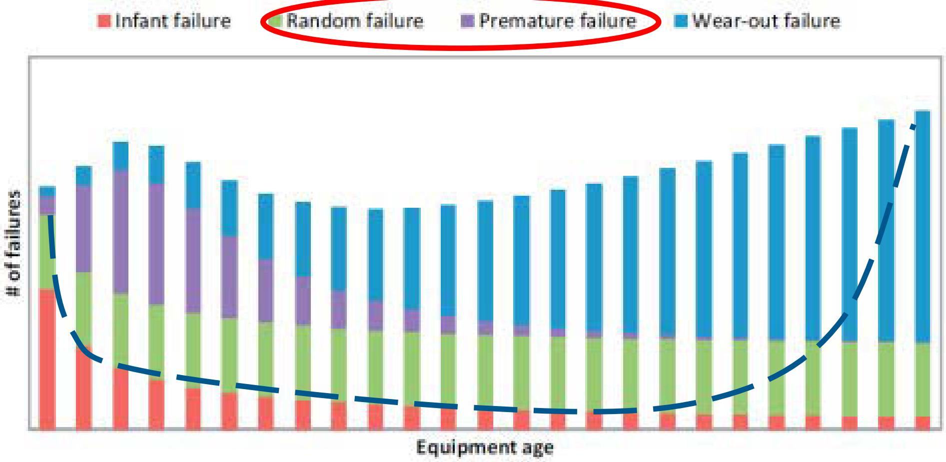
- Quality assurance and control → need codification
- Nonconformities (e.g., pitch settings, surface characteristics)
- Human error (applications outside the envelope)
- Thermal effects and humidity effects on power electronics.



Source: Sandia National Laboratories (SNL)

Source: Forte Renewables



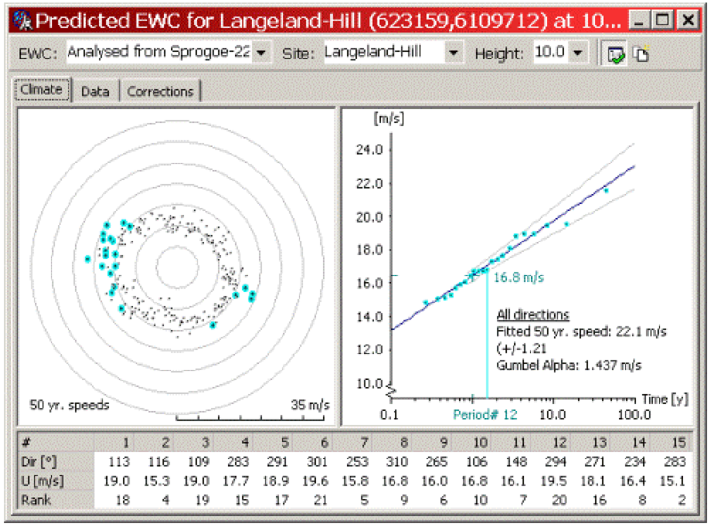


Uncertainty Category III

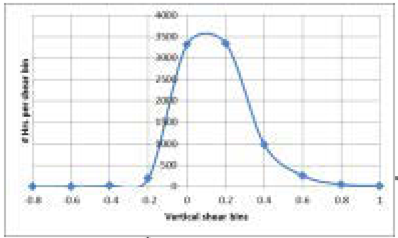
$$\gamma_L L \le \frac{R}{\gamma_R}$$

3. Site Suitability and Due Diligence

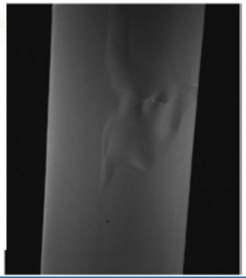
- Lack of transparency between manufacturer and independent engineer (e.g., controller algorithms, site assessment)
- New failure modes (e.g., edgewise vibrations and chordwise cracking)
- Suitability lags design progress
- Variable vs. averaged shear
- Plant underperformance
    - No correlation between predicted uncertainty and AEP predicted error.

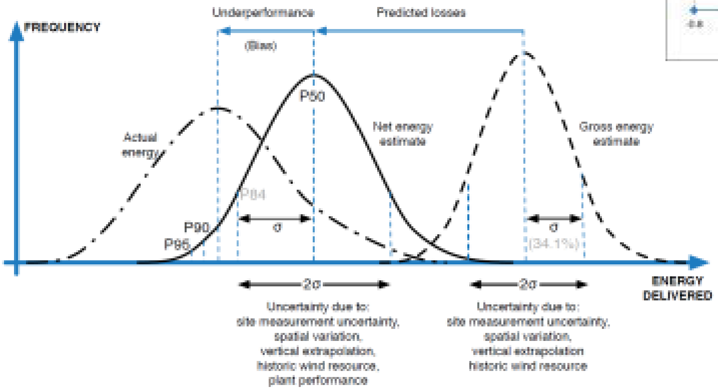


Source: WaspEngineering



	m	% increase in loads resulting from Variable method relative to Standard method
Blade root Mx	4	0.10%
	10	0.10%
Blade root My	4	6.40%
	10	2.40%
Blade root Mz	4	1.90%
	10	3.30%
Blade root Fx	4	6.30%
	10	2.90%
Blade root Fy	4	0.00%
	10	0.00%
Blade root Fz	4	0.30%
	10	3.60%

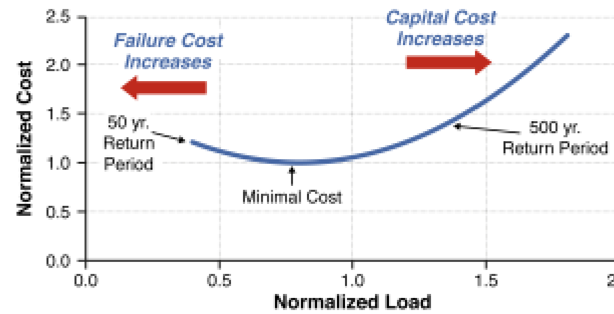




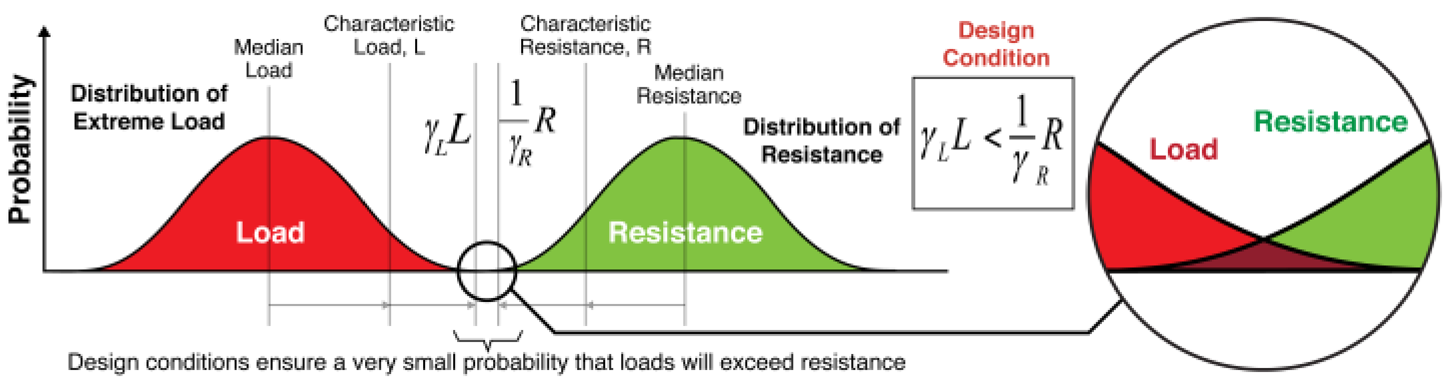
$$\gamma_L L \le \frac{R}{\gamma_R}$$

4. Partial Safety Factors and Reliability Target

- Limit State Approach
- Moderate Consequence of Failure and Mid-High Cost of Safety Measures
- Partial Safety Factors Not Adequately Representing Actual Uncertainty
- Reliability-Based Design
  - Requires knowledge of uncertainty distributions and effects on design parameters
- Load Factors could be reduced if COV(X_{aero}-X_{str}) can be reduced.



$$g = z\delta_R R - X_{dyn} X_{exp} X_{aero} X_{str} L_x \ge 0$$

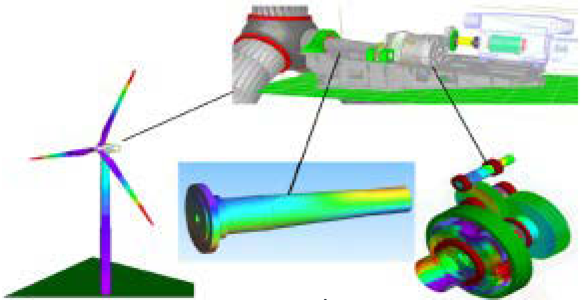


Uncertainty Category V

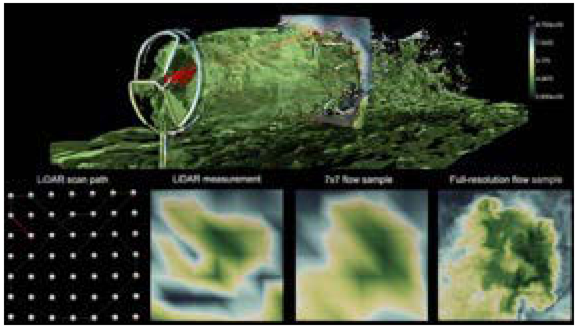
$\gamma_L L \le \frac{R}{\gamma_R}$

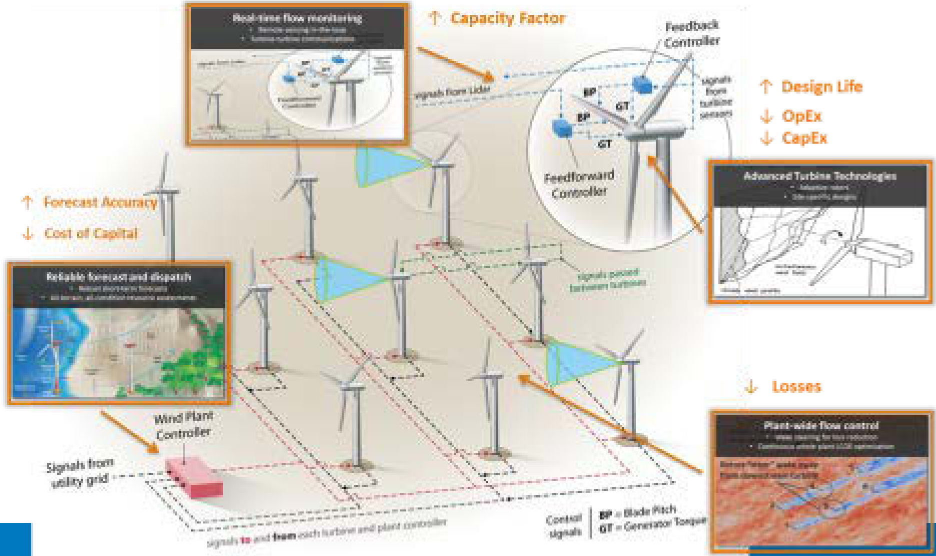
5. Computational Modeling

- Multi-fidelity Requires Risk & Uncertainty Assessment
  - Uncertainty quantification (UQ) and verification and validation (V&V)
- UQ➔ Efficient and Robust Design Optimization
- Codified V&V➔Prioritize Gaps and Needs for Model Improvement
- Surrogate Models
- System Management of Atmospheric Resources through Technology (SMART) Wind Plants
  - Improved load mitigation and performance.



Source: Jin et al. 2016





Higher Priority Recommended Actions from DCIRT

- Modeling
  - HPC + UQ + V&V → renewed basis for standards development
  - Improve engineering models for "ultra-large" composite structures
  - Design event definition
  - Design time scale reassessment (10-min, 3-s enough?).

- Site Suitability
  - Account for non-mean shear and site actual conditions
  - Evaluate reference wind speed and its impacts on survivability and number of shutdowns (U.S. vs. non-U.S.)
  - Increase transparency OEM-IE (surrogate modeling, control strategy informed exchanges)
  - Include manufacturing tolerances in the verification and certification process
  - Improve understanding of damping levels.

- Standards & Standard Classes
  - Improve class description to reflect site-specific conditions
  - Revisit partial safety factors through systems engineering of socio-techno-economic risk analyses
  - Improve definitions and modeling of shear, veer, stability
  - "Load Extrapolation" assessment
  - Assess soil temporal variability.

Thank you!

Acknowledgments

- Attendees of the *Mini-Workshop on Uncertainty in Design for Wind (July 2016)*:

Jomaa Ben-Hassine, Res Americas; **John Bosche**, Chinook Wind; **John Dalsgaard Sørensen**, Aalborg University/Technical University of Denmark; **Katherine Dykes**, NREL; **Jason Fields**, NREL; **D.V. Griffiths**, Colorado School of Mines; **William Holley**, former GE; **Nick Johnson**, U.S. Department of Energy; **Mike Robinson**, U.S. Department of Energy; **Jason Jonkman**, NREL; **Lance Manuel**, University of Texas; **Frank Lombardo**, University of Illinois; **Julie Lundquist**, University of Colorado; **Dave Maniaci**, Sandia National Laboratories; **Emil Moroz**, AWS Truepower; **Juan Pablo Murcia**, Technical University of Denmark; **Walter Musial**, NREL; **Amy Robertson**, NREL; **Michael Sprague**, NREL; **Peter Vickery**, Applied Research Associates; **Rochelle Worsnop**, University of Colorado at Boulder.

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory. Funding for the work was provided by the DOE Office of Energy Efficiency and Renewable Energy, Wind Energy Technologies Office.

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