AWS Truepower®
Where science delivers performance.

Wind Turbine Performance: Issues and Evidence

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Chief Technical Officer

Company Overview

- Established in 1983
- Over 100 professional staff
- Activity
  - Resource mapping
  - Site assessment
  - Plant design and energy estimates
  - Operational plant assessment
  - Real-time forecasting
  - Grid impact studies

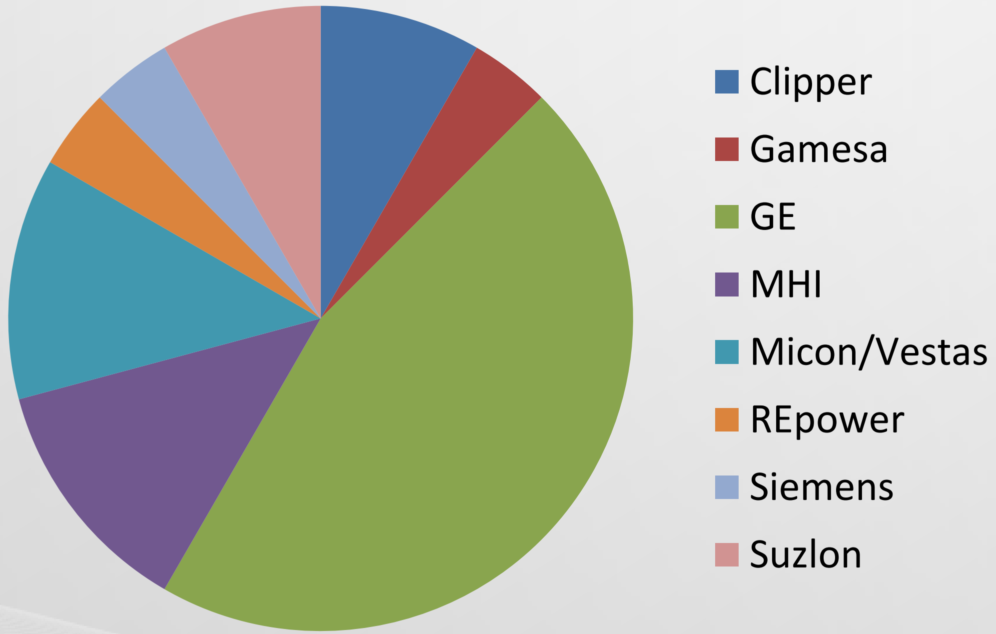
The Underperformance Gap

- The wind industry continues to suffer from an "underperformance gap"
  - This sounds better than an "overestimation gap"
- The gap was ~10% in 2008, reduced to 0%-5% by 2011 - better, still not perfect
- What are the main factors causing the gap, and how much does the performance of individual turbines contribute to it?

AWS Truepower “Backcast” Database

Parameter	Database
Wind Plants	24
Total Plant Years	106
Average Years per Plant	4.4
Min-Max Years per Plant	1 - 11
Average Plant Capacity	82 MW
Min-Max Plant Capacity	10 – 210 MW

AWS Truepower "Backcast" Database



Regions (all in North America)

- Texas & Southern Plains
- Upper Midwest
- Northeast
- Inter Mountain West
- California

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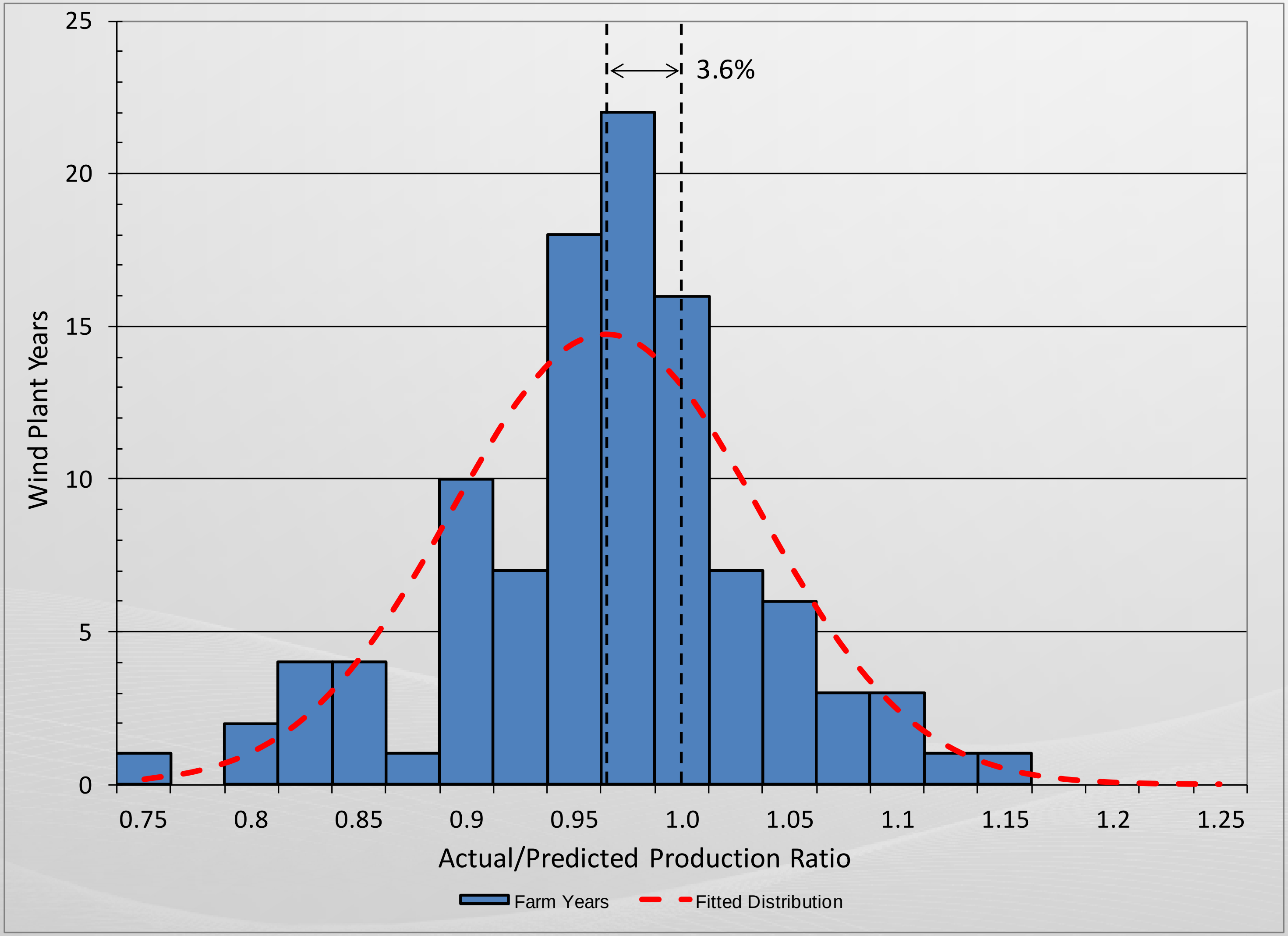
Production Ratio Histogram



What Could Be Contributing to the Gap?

- Availability
  - Assumptions align with experience
- Resource assessment and wind flow modeling
  - “Smart” resource assessment practices remove most sources of bias
- Wake losses
  - AWST “deep-array” wake model (DAWM) aligns with available data (onshore and offshore)
  - Wakes in thermally stable conditions may still be a problem
- Performance of turbines…?

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Turbine Performance Is a Problem

- Performance under nominal (IEC-compliant) conditions
  - “Warranted” v. “advertised” output
- Turbine operation and maintenance practices
- Impacts of non-ideal conditions
  - High/low shear
  - High/low turbulence
  - Non-horizontal flow

Performance Under Nominal Conditions Falls Short

- Typical performance gap of 1-4% in power curve tests
  - Supported by AWST and other industry test data
- IEC compliant, so not caused by site conditions
- Usually contractually allowed
  - The results exceed the minimum guaranteed production minus the uncertainty
  - *Really?*

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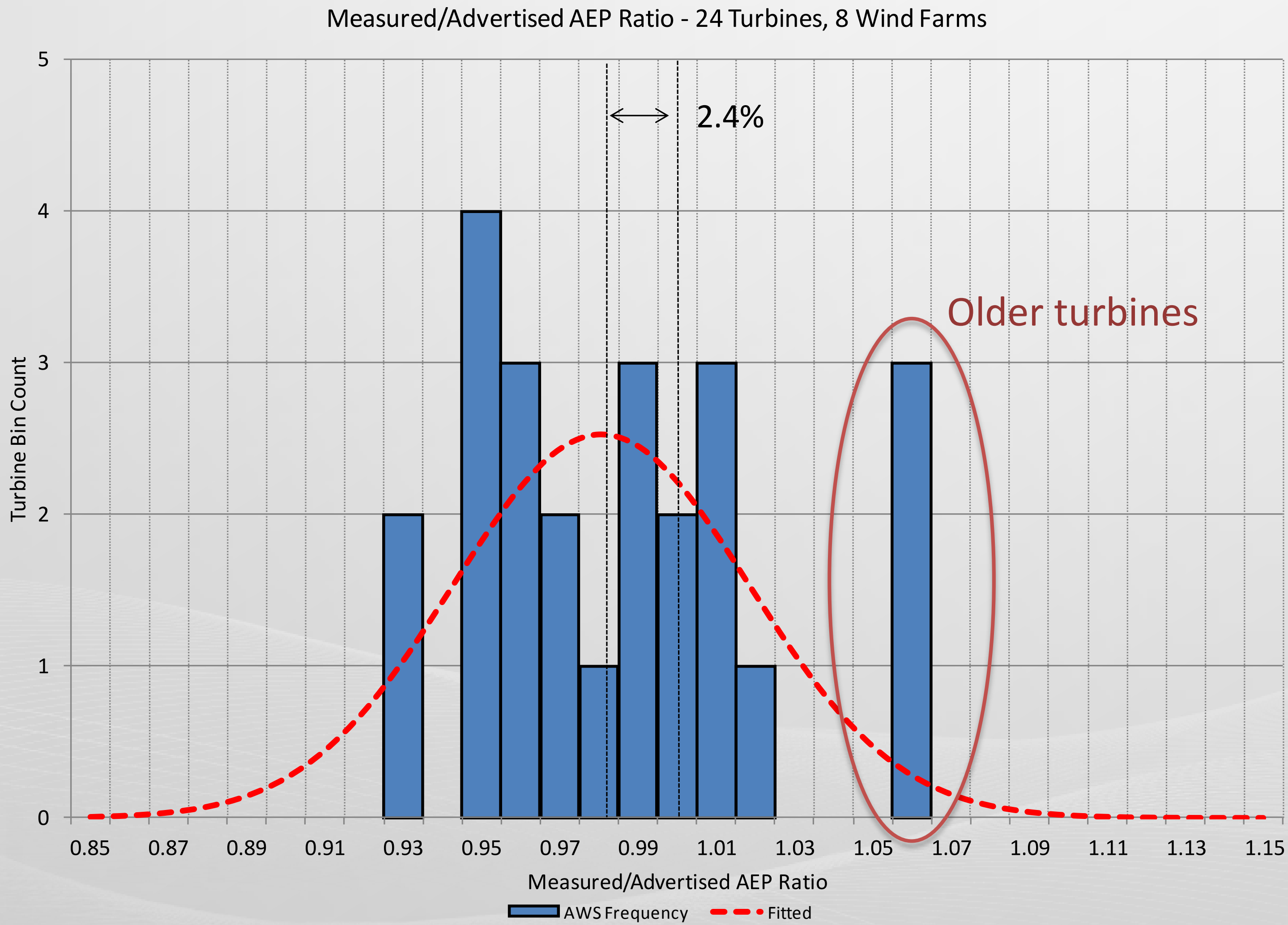
24 Turbine Power Performance Tests

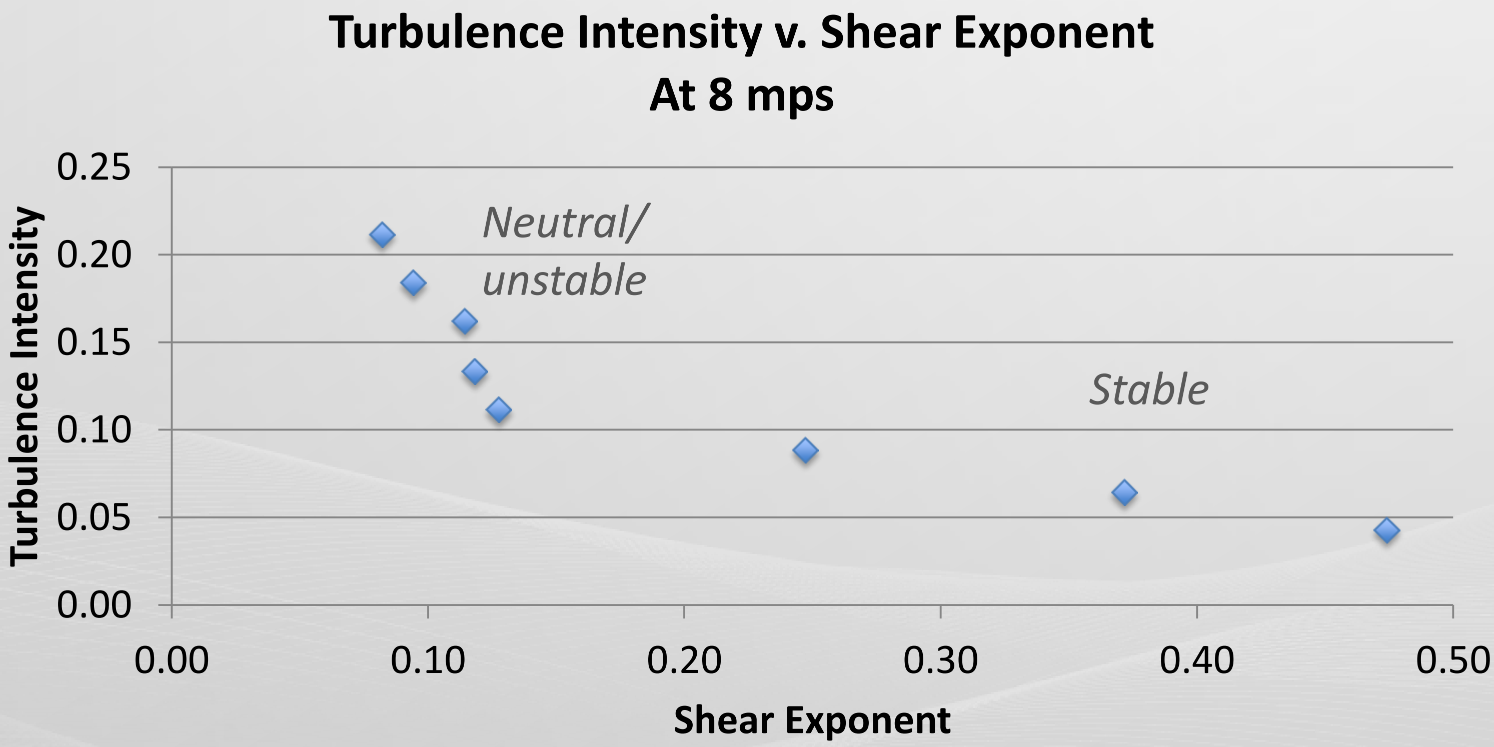


Operation and Maintenance Practices

- Software settings, e.g.,
  - Anemometer calibration constants
  - Pitch, yaw errors
- Physical condition, e.g.,
  - Wear and tear of moving parts
  - Blade degradation
  - Icing, soiling
- Plant operators must have the incentive to address such problems
- Operators must be able to measure the benefits of fixing the problems

Site Conditions: Shear and Turbulence

At a given site, shear and turbulence are usually closely linked, making their effects on output hard to separate



Shear

- Stability is not the root problem…
- Power curves are specified for "normal" shear (0.2)
- High shear means more power is theoretically available (~½ ρv^3), so that should boost output…
- But turbines cannot use the extra power as efficiently as possible because the blade pitch is not optimal for speeds encountered in the top half of the rotor plane
- Individually pitched blades would address this problem

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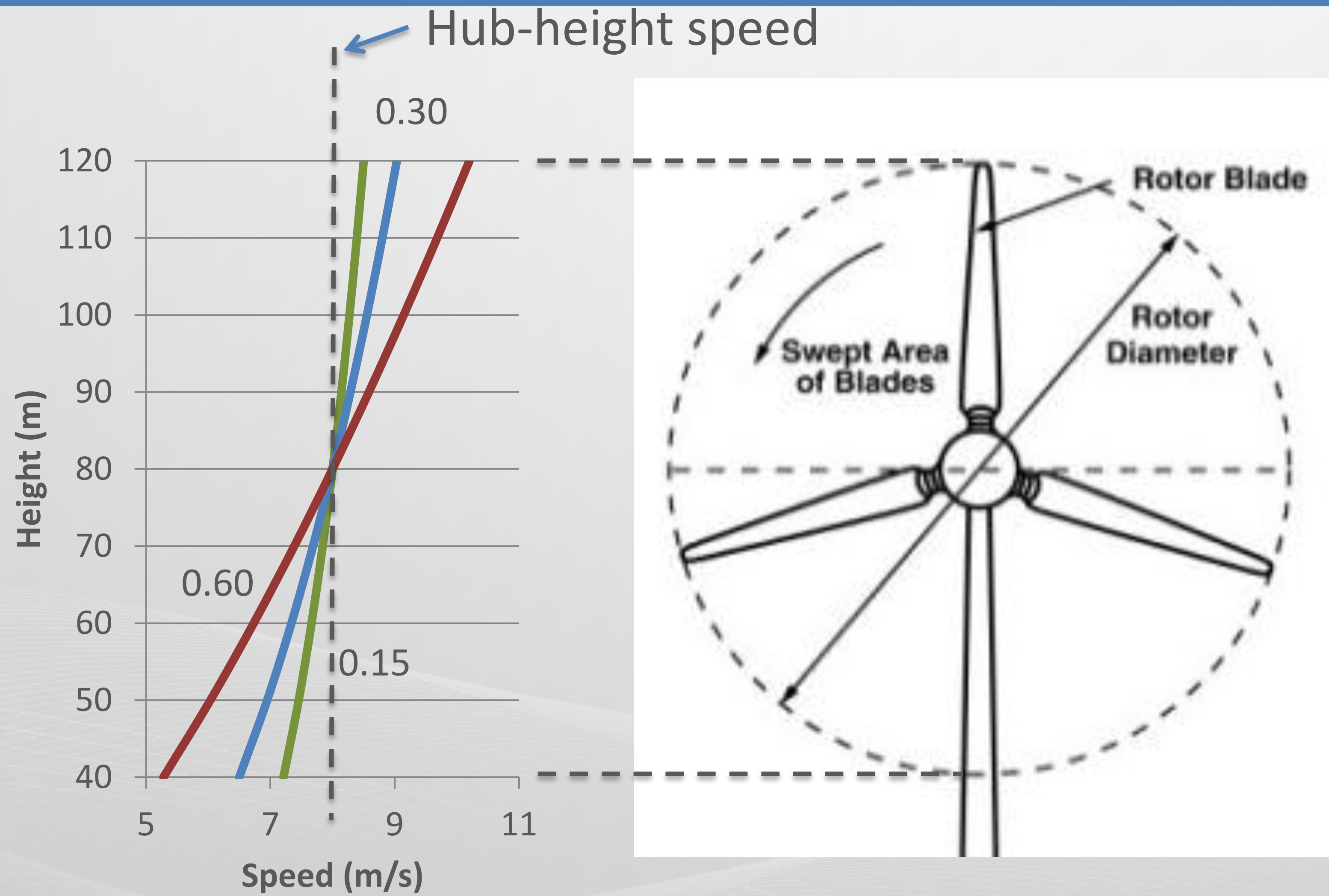
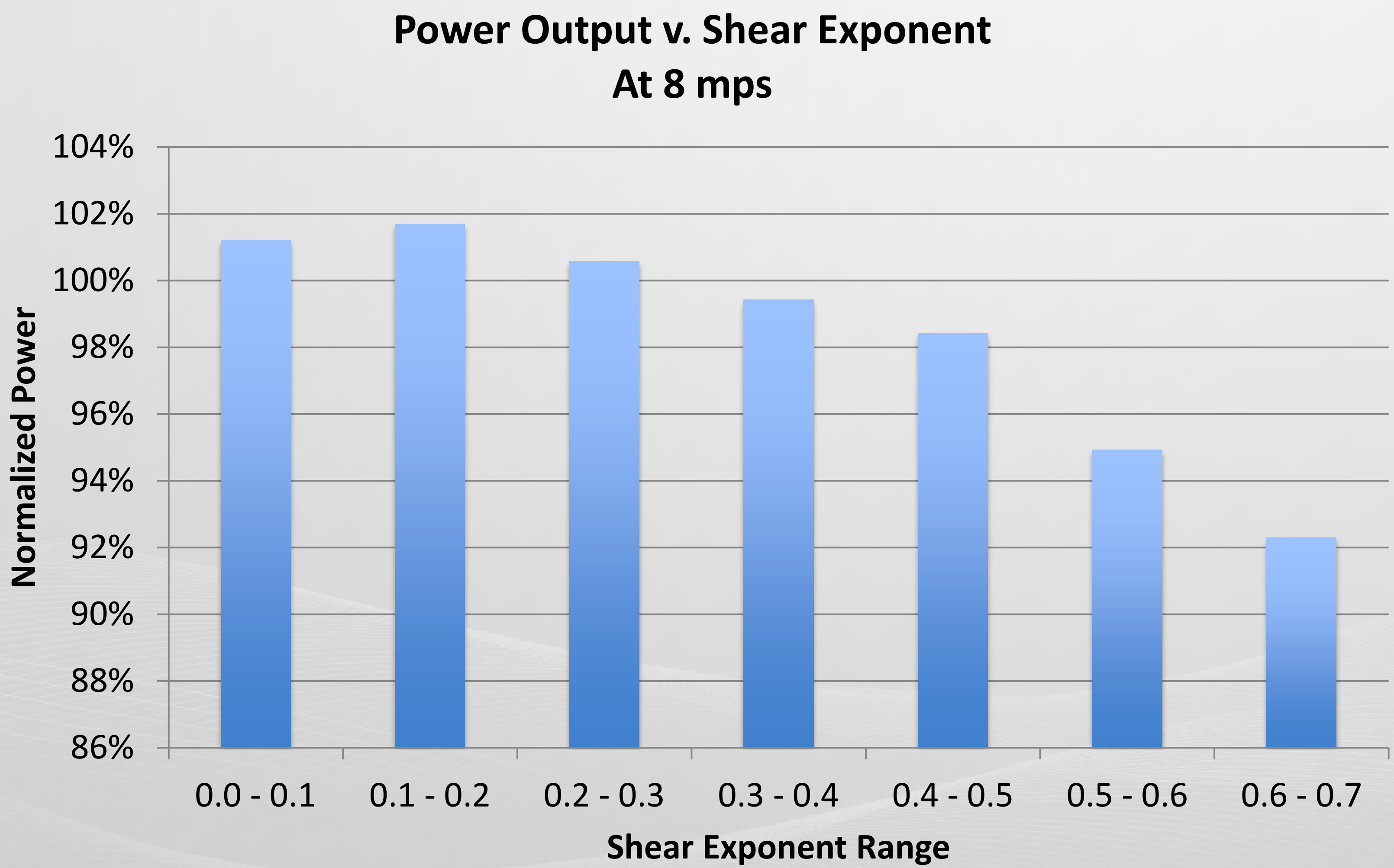
Effect of Shear on Aerodynamic Efficiency



Effect of Shear in a Typical Power Curve Test



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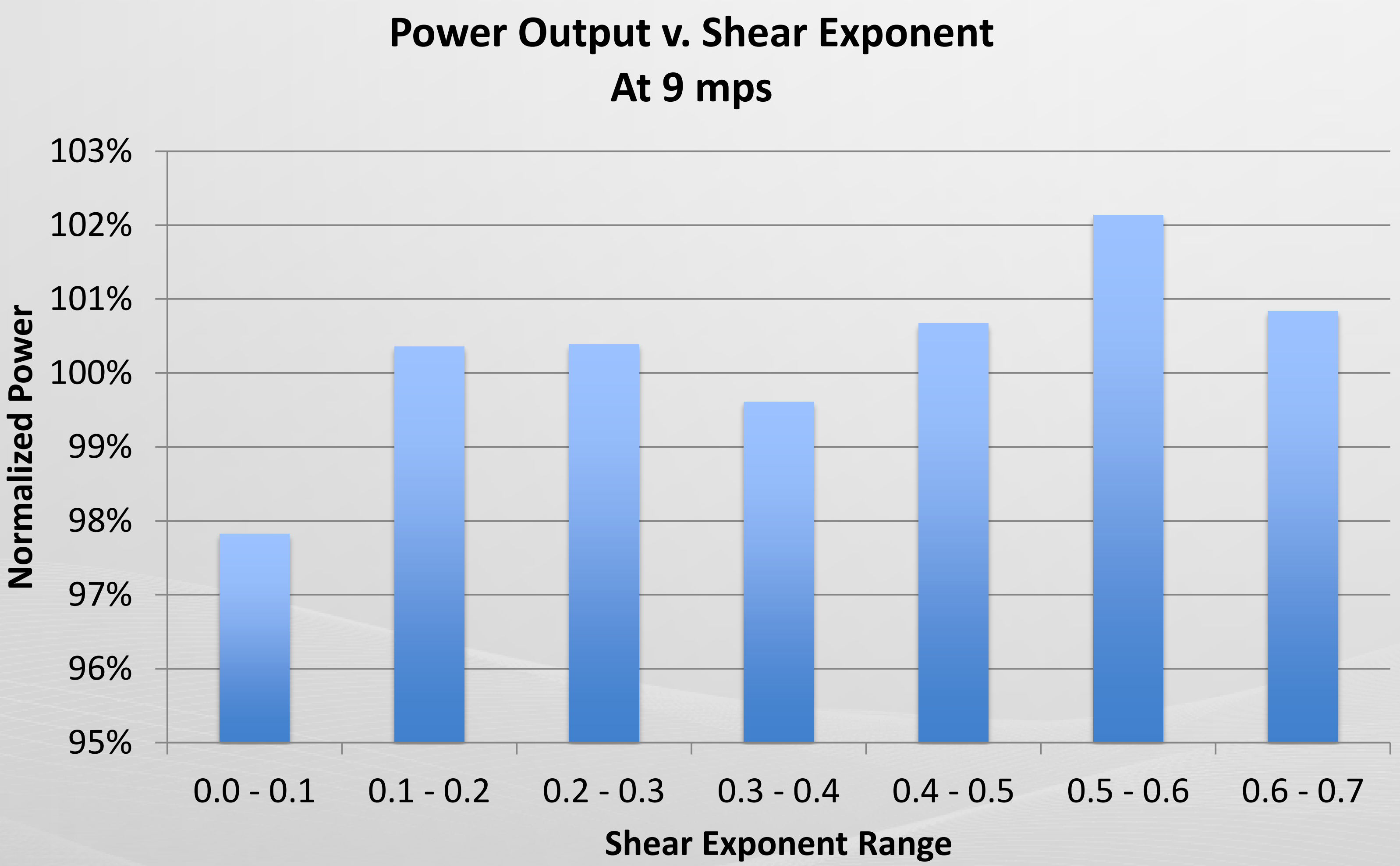

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Turbulence

- Turbulence = rapid fluctuations in speed
- If not too fast, such fluctuations make a turbine move up and down its power curve
- Whether it means a net gain or loss depends on where the turbine is on the curve and the size of the speed deviations
- A portion of turbulent kinetic energy cannot be converted to power
- Turbulent changes in direction create more losses, hard to track and respond to

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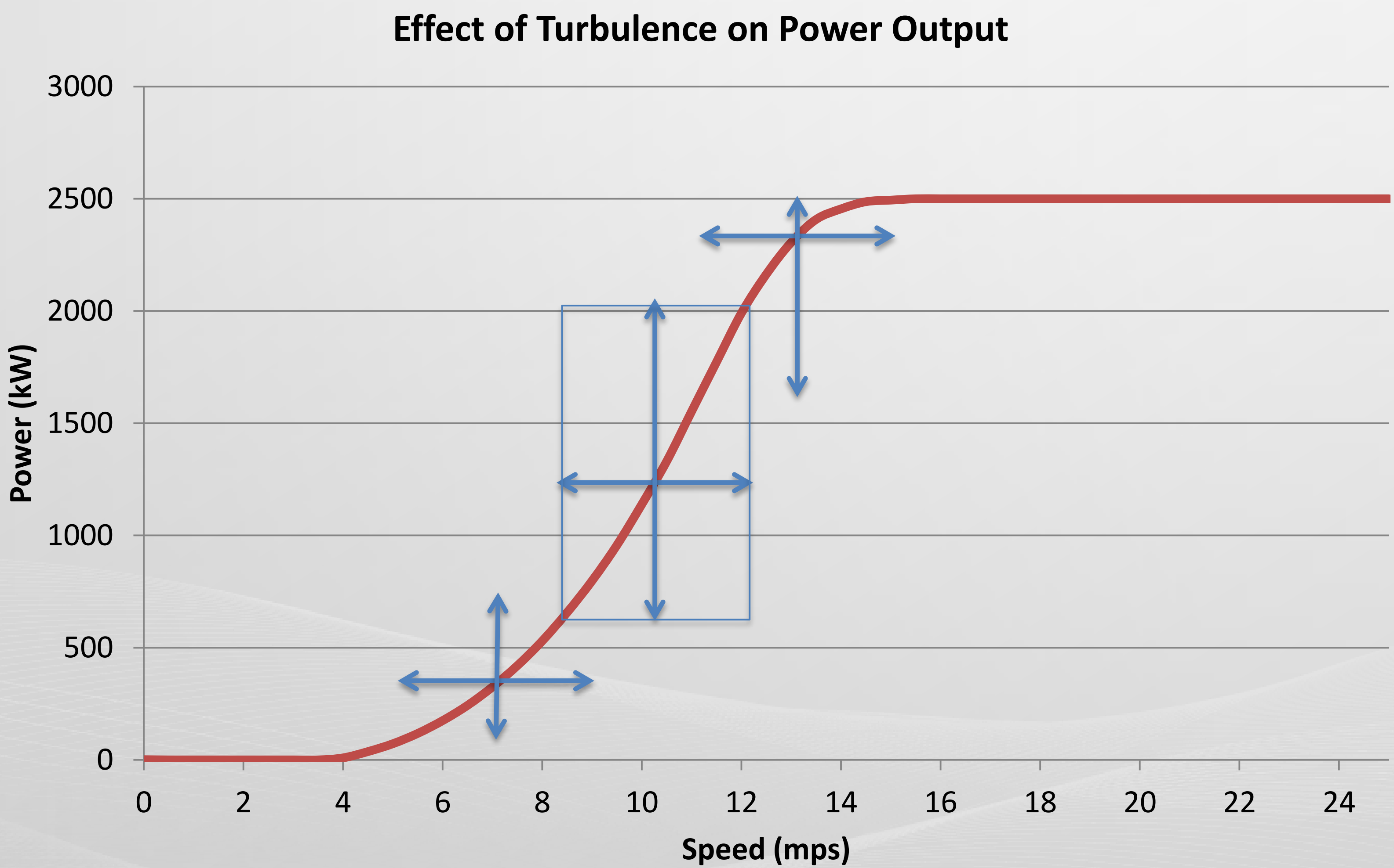
Turbulence



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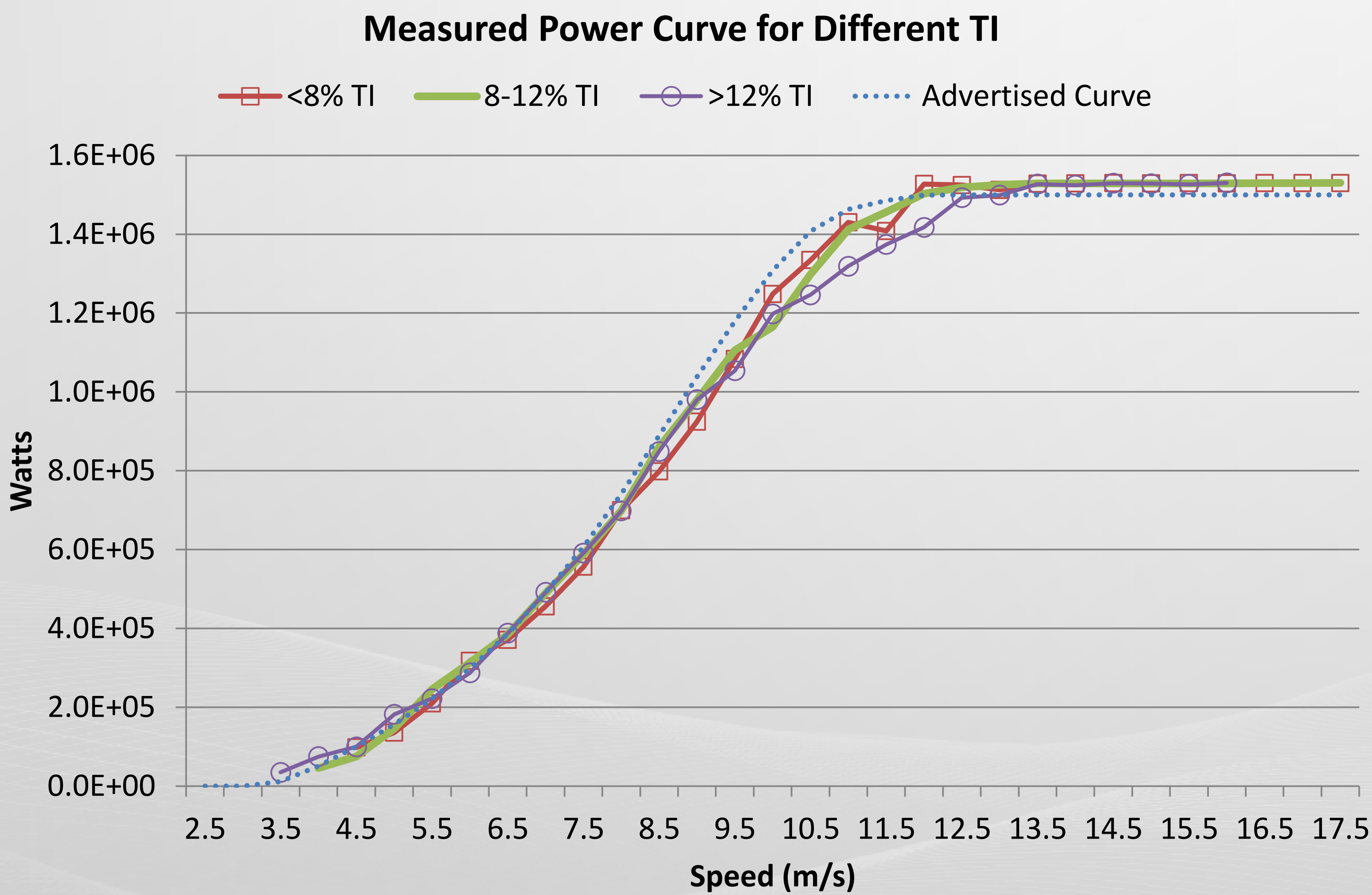
Turbulence



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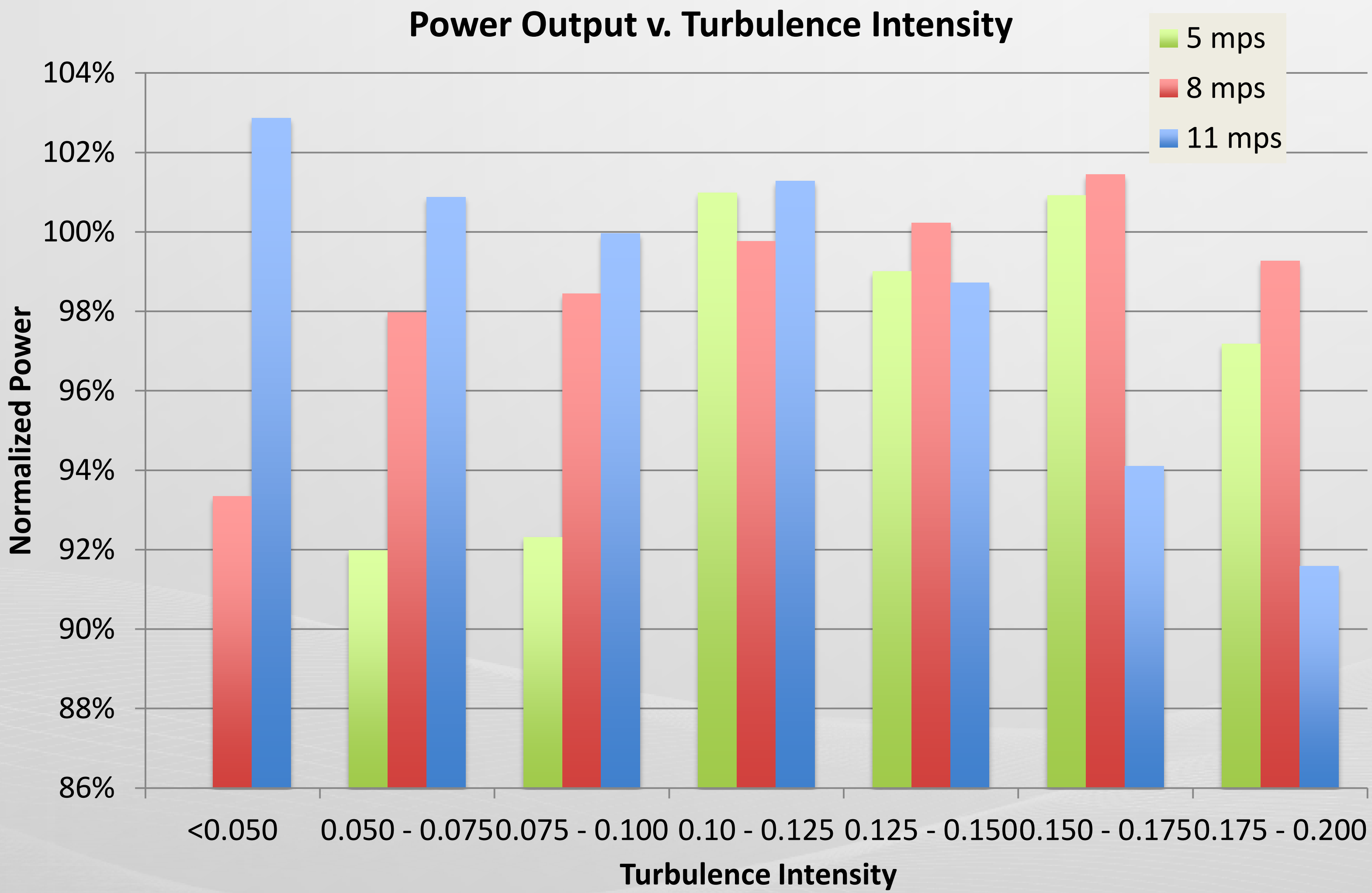
Turbulence

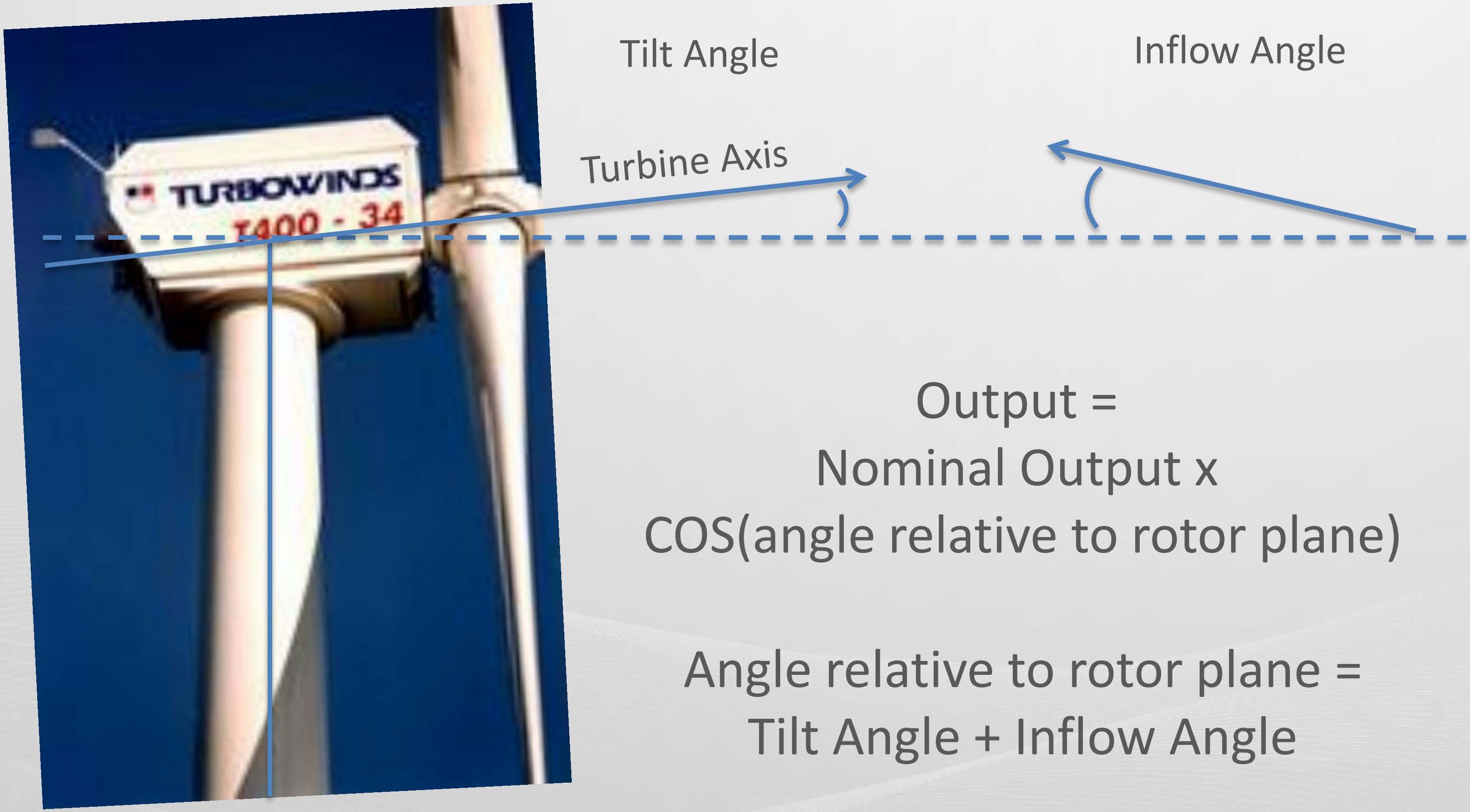


Power Output v. Turbulence Intensity
5 mps
8 mps
11 mps
104%
102%
100%
98%
96%
94%
92%
90%
88%
86%
Normalized Power
<0.050
0.050 - 0.075
0.075 - 0.100
0.10 - 0.125
0.125 - 0.150
0.150 - 0.175
0.175 - 0.200
Turbulence Intensity

Inflow Angle

- Power curve tests assume level ground
- But in complex terrain and under certain weather conditions, significant vertical speeds can occur
- Placement of turbines along ridgelines can create a persistent bias

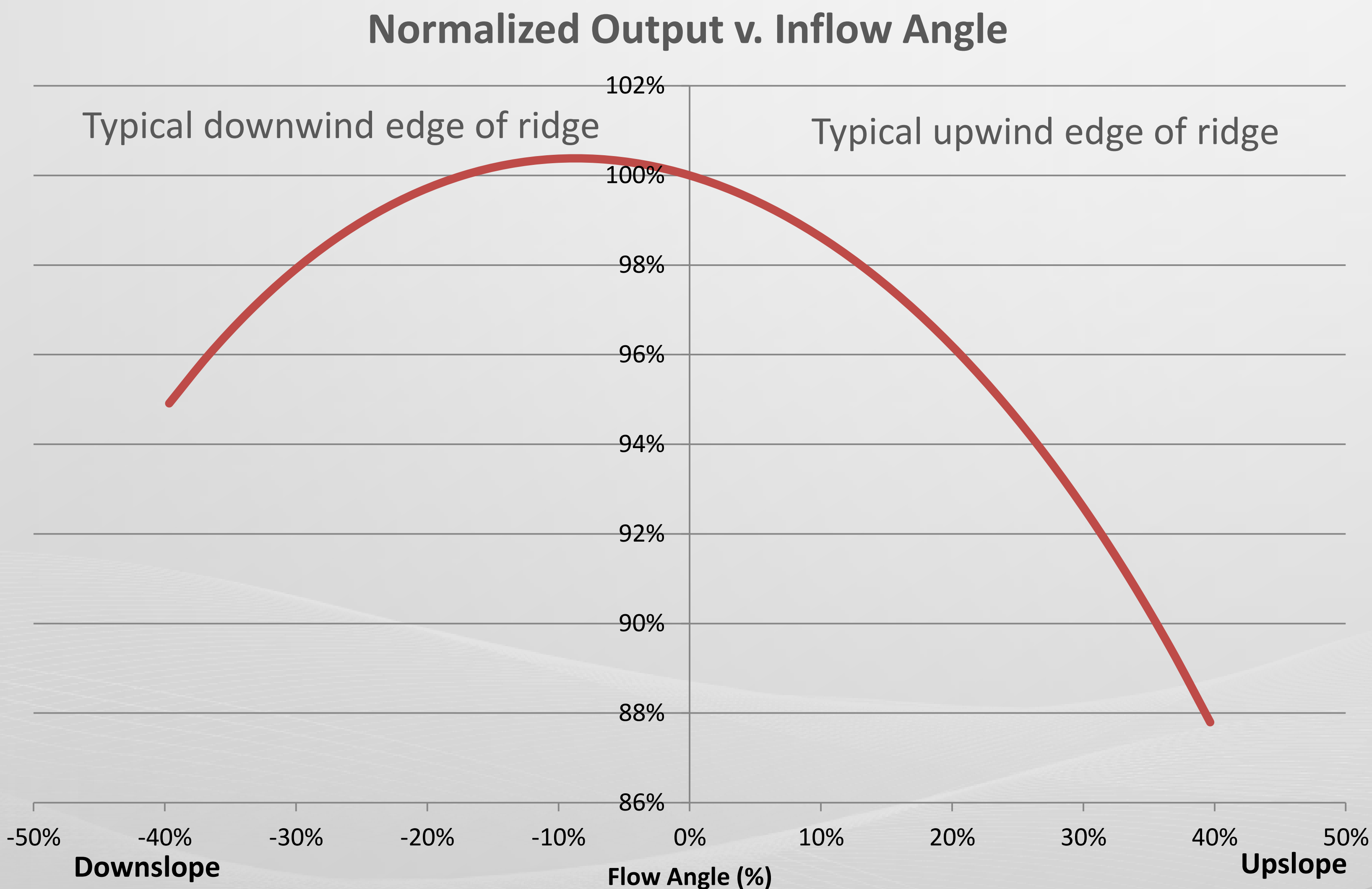
Inflow Angle



Output =
Nominal Output x
COS(angle relative to rotor plane)

Angle relative to rotor plane =
Tilt Angle + Inflow Angle

Effect of Inflow Angle on Power Output



Observations and Conclusions

- Turbine underperformance is a big part of general plant underperformance
- Turbines typically fall 1%-3% short of advertised power curves under IEC-compliant conditions
  - Gap will be incorporated into energy yield estimates to align with experience – OEMs are "chasing their tail"
  - Better to be able to rely on turbine-supplied power curves
- Deviations of shear, turbulence, inflow angle from normal conditions can cause additional power deficits
  - Time-varying, not just average, conditions are important
  - Where there is a question, use appropriate tools (lidar, advanced wind flow modeling) to gauge problem
  - Forget OEM warranted "site power curves": Use appropriate methods for energy production estimates