Real World Power Curves

13 January 2016

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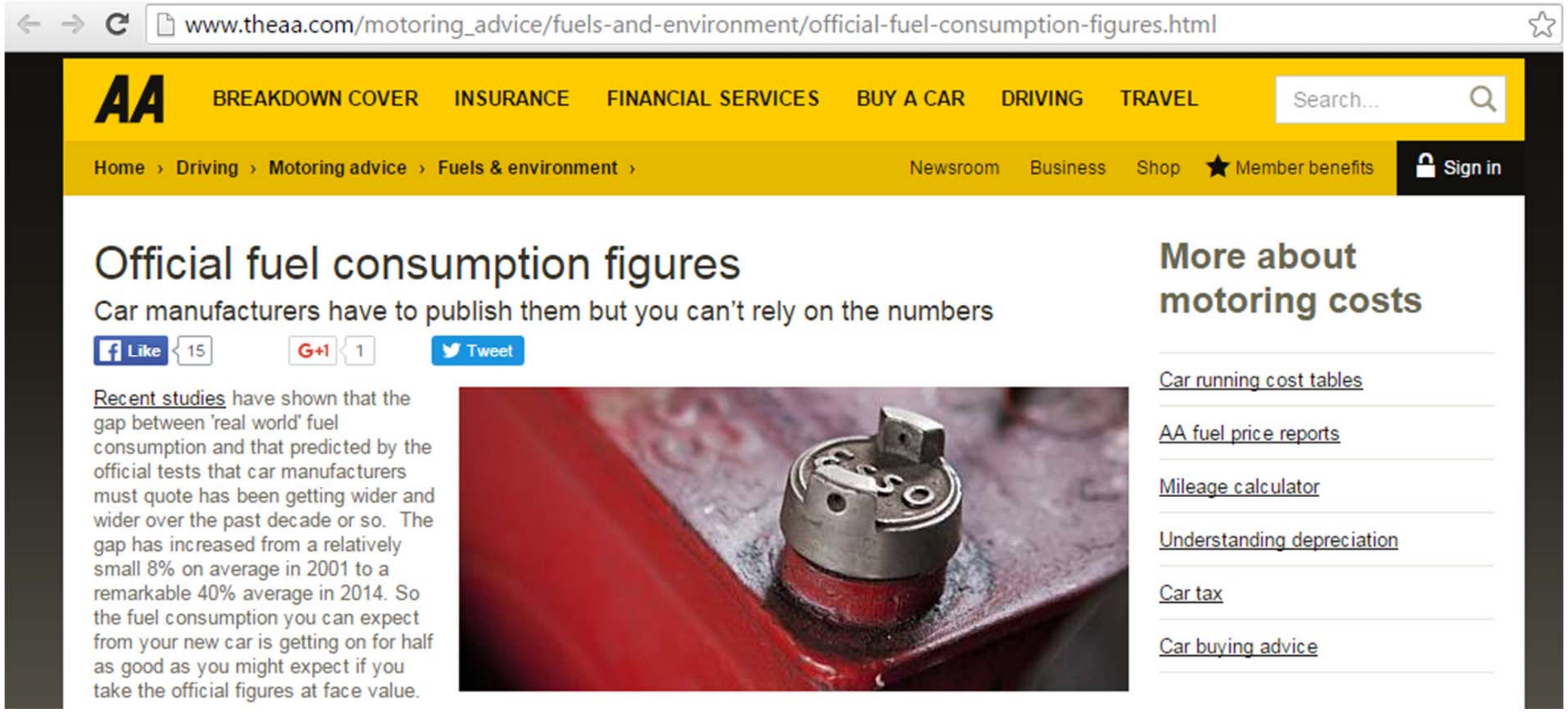
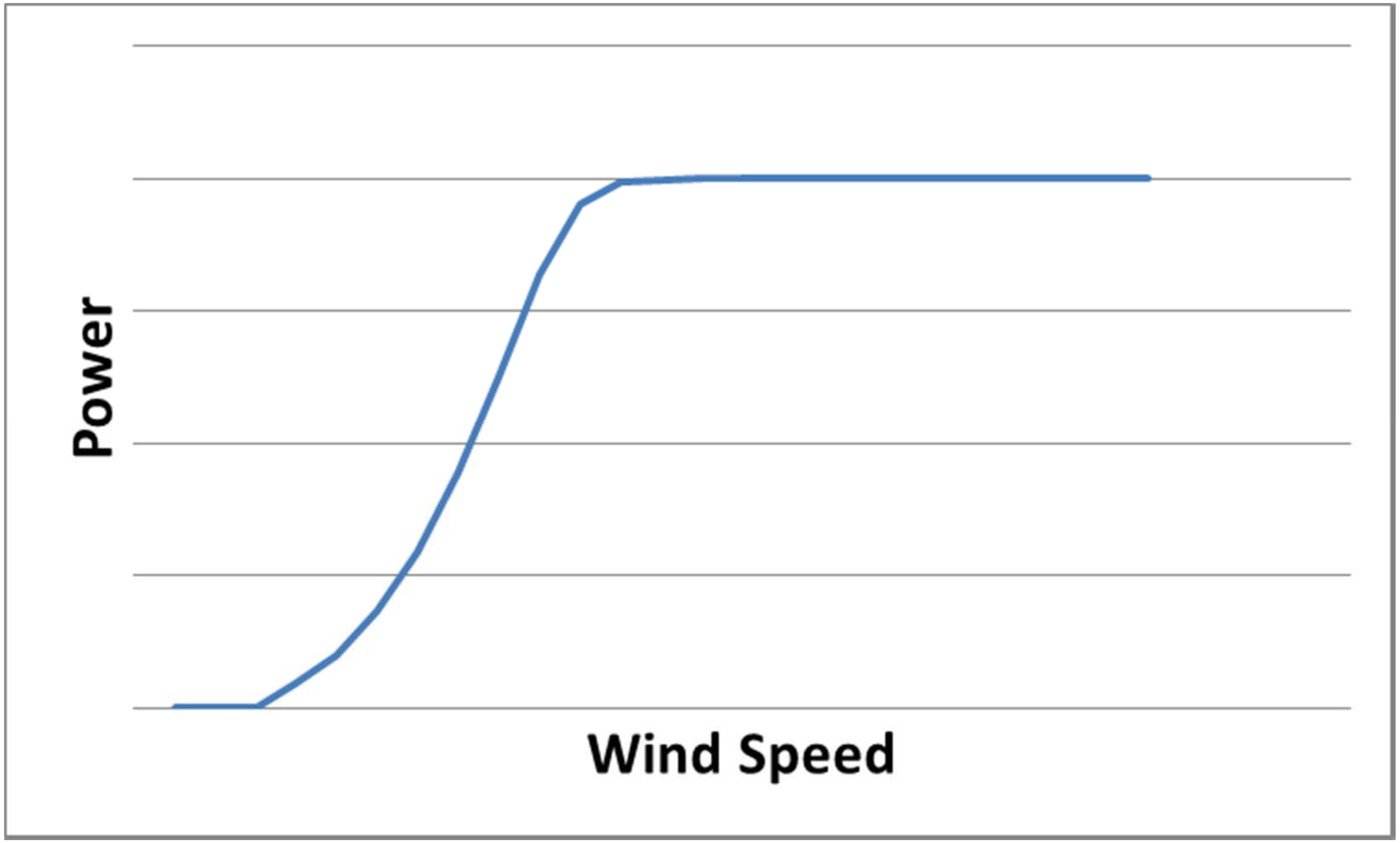
Real World MPG!



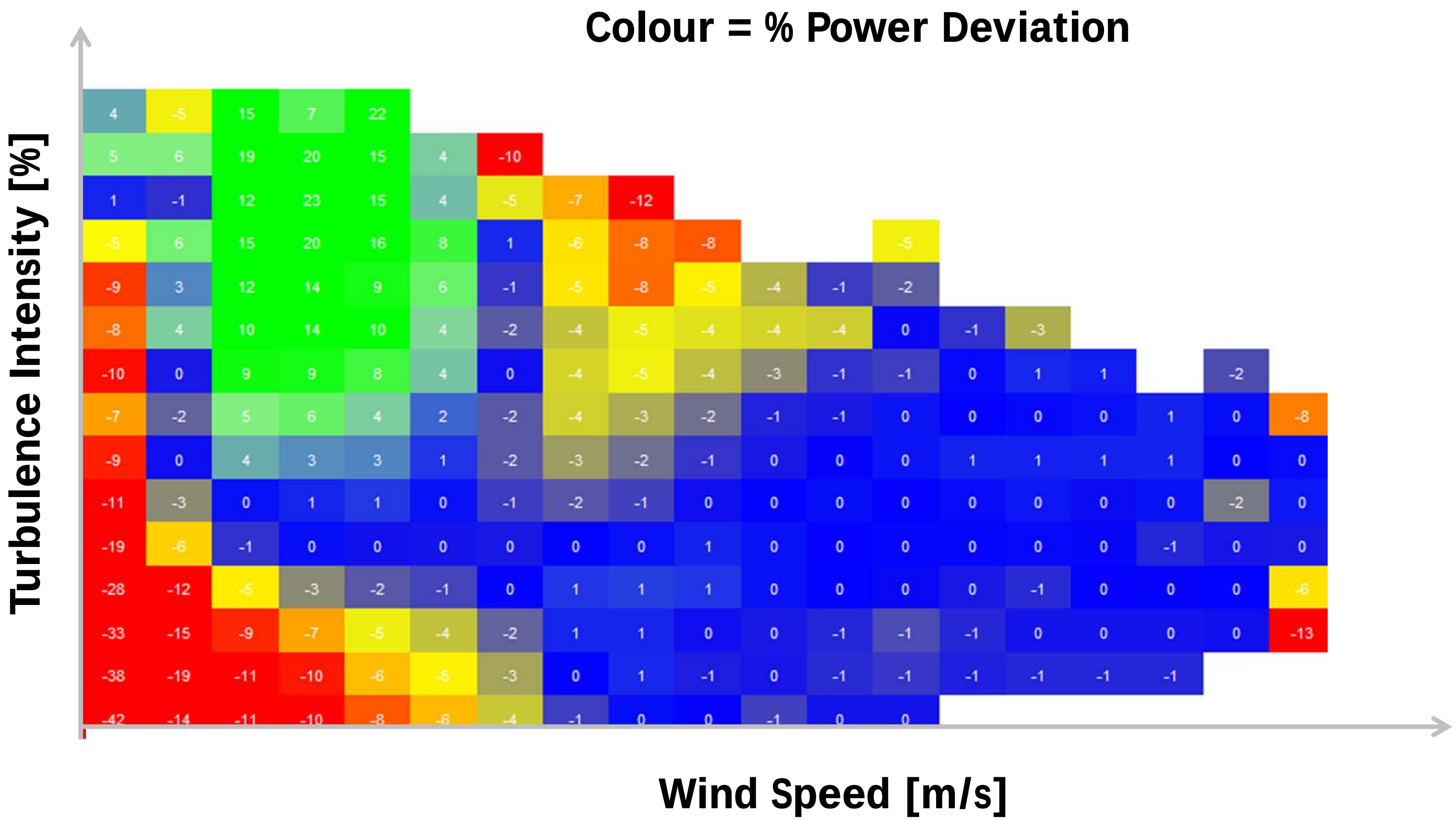
***WWW.THEAA.COM**: Recent studies have shown that the gap between 'real world' fuel consumption and that predicted by the official tests that car manufacturers must quote has been getting wider and wider over the past decade or so. The gap has increased from a relatively small 8% on average in 2001 to a remarkable 40% average in 2014. So the fuel consumption you can expect from your new car is getting on for half as good as you might expect if you take the official figures at face value*

An Idealised View of Turbine Performance

- In an ideal world the power output of a wind turbine is dependent on hub height wind speed and air density



Real World Power Performance



Power Deviation Matrix (derived from met mast power performance data)

What the investors say…

Our view is that ***energy yield is the single biggest risk of investing in onshore wind projects without an operational track record****, significantly greater than all construction risks which tend to be managed through contractually allocating away from the investor.*

Unnamed Renewables Investment Manager

Impact of Investment Risk on Project Economics

- Investors quantify risk using a discount rate (also called a hurdle rate). The discount rate expresses an expectation of return for a given level of risk.

Net present value (NPV) can be interpreted as the money left over after an investor's expectation if return has been satisfied.

$$NPV = -Capex + \sum_{i}^{Life} \frac{Revenue - Opex}{(1+d)^{i}}$$

- Examine impact of cost reduction and discount rate on NPV (**illustrative numbers only**)

Define cost reduction factor r

$$NPV = -(1-r) \times Capex + \sum_{i}^{Life} \frac{Revenue - (1-r) \times Opex}{(1+d)^{i}}$$

Discount Rate

Cost

	8.0%	8.5%	9.0%	9.5%	10.0%
10%	60%	40%	21%	3%	-13%
5%	101%	80%	60%	42%	25%
0%	142%	121%	100%	81%	63%
-5%	184%	161%	140%	120%	101%
-10%	225%	201%	179%	158%	139%

Increasing Cost

Increasing Risk

Reducing of investment risk and reducing of costs has similar impact on project economics

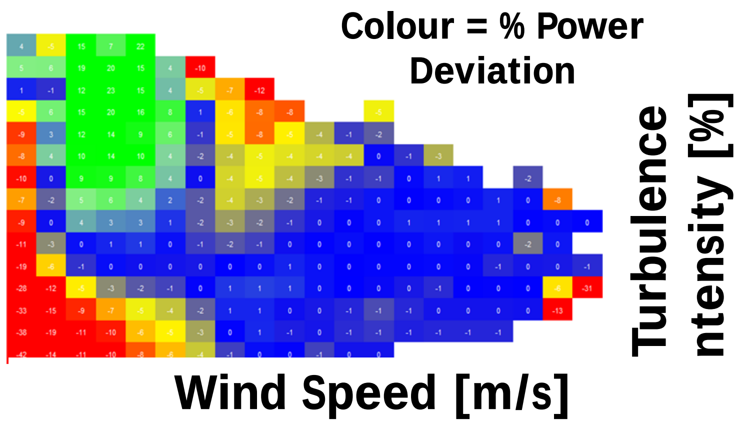
The Power Curve Working Group:

- The PCWG aims to further refine the accuracy turbine performance modelling (and therefore wind farm resource assessments) in order to **improve investor confidence.**

- The PCWG has over 200 members across 80 organisations. Email pcwg@res-ltd.com to join.

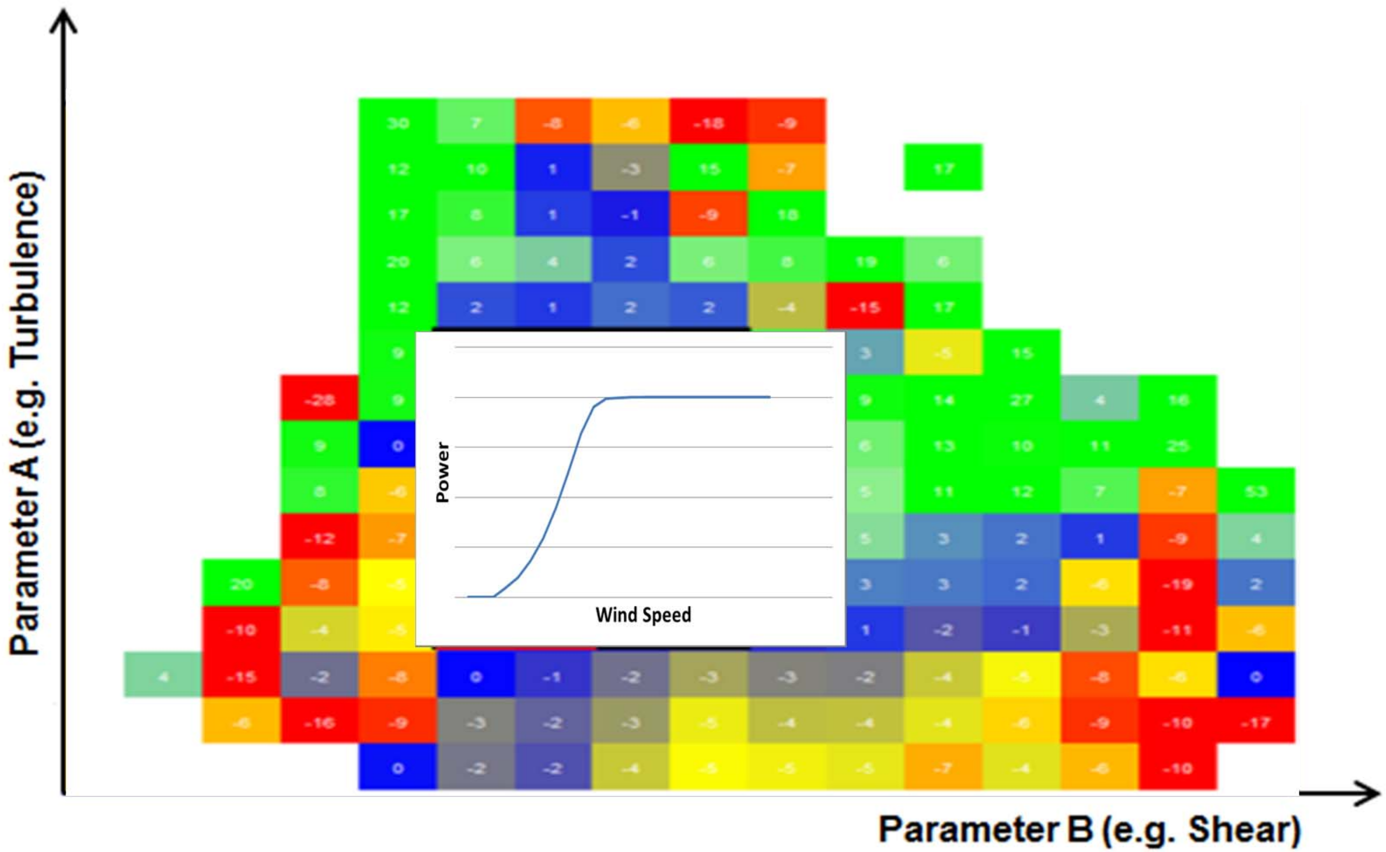
- Openness is a key PCWG principle, all historic proceedings are available online at www.pcwg.org

- The PCWG is **focused on accurately predicting wind turbine performance in ‘non-standard’ (outer range) atmospheric conditions** e.g. low/high shear/veer, low/high turbulence, inflow etc.



PCWG Key Concept: Inner/Outer Range

In Dec 2013 the PCWG published a document on the **Inner/Outer Range Proposal** (see www.pcwg.org).



Inner/Outer Range proposal is a **concept developed to assist technical and contractual discussions** relating to turbine performance in real world conditions.

Key Concepts: Types of Correction

Corrections should be applied for ‘real world’ conditions which are different to those for which a power curve is representative. These corrections fall into two categories:

Available Energy

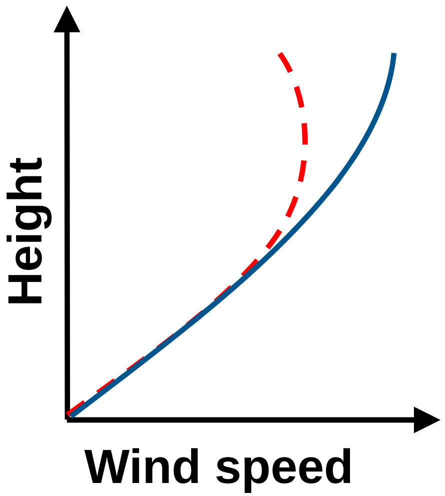
Type A: Adjustments made to reflect changes in the energy available for conversion across the rotor in a ten minute period due to ‘non-standard conditions’.

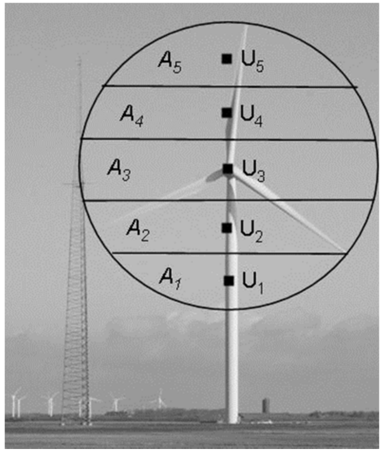
Type B: Adjustments made to reflect changes in the conversion efficiency due to ‘non-standard conditions’.

Turbine Behaviour

- **Rotor equivalent wind speed (REWS):** Define wind speed which reflects the energy content of the full rotor (not just hub wind speed).

$$V = \sqrt[3]{\frac{1}{A}\int_{H-R}^{H+R}\left(v(z)\cos(\varphi(z))\right)^{3}\,dA}$$





Example Type A Correction: Turbulence Correction

Inputs:

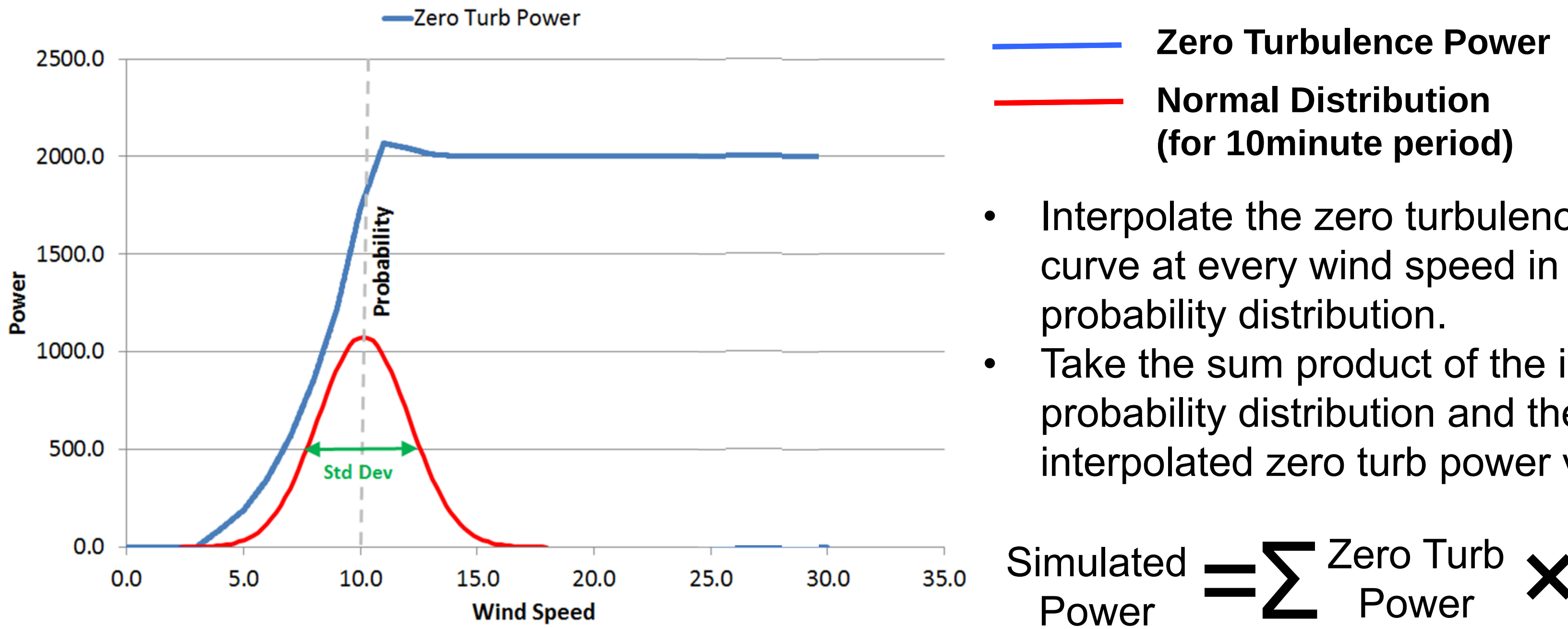
- **A 'zero turbulence' power curve (derived from reference turbulence power curve)**
- **Values of wind speed and turbulence intensity**

Output:

- **A correction factor to adjust from the reference turbulence to any turbulence.**

In place of using instantaneous wind speed values we assume that the variation of wind speed within the ten minute period is described by a normal distribution as follows:

- **Mean = 10-minute Wind Speed Mean**
- **Std Dev = (10-minute Wind Speed Mean) * (10-minute Turbulence Intensity)**



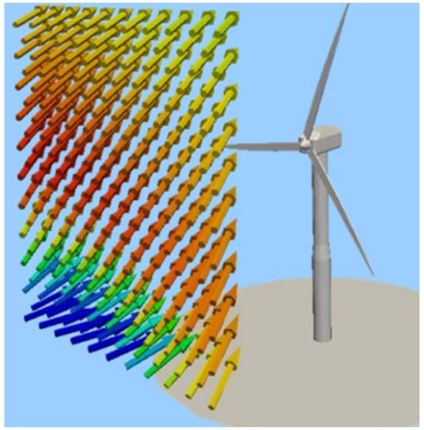
- Interpolate the zero turbulence power curve at every wind speed in the probability distribution.
- Take the sum product of the interpolated probability distribution and the interpolated zero turb power values:

$$\text{Simulated Power} = \sum \text{Zero Turb Power} \times \text{Probability}$$

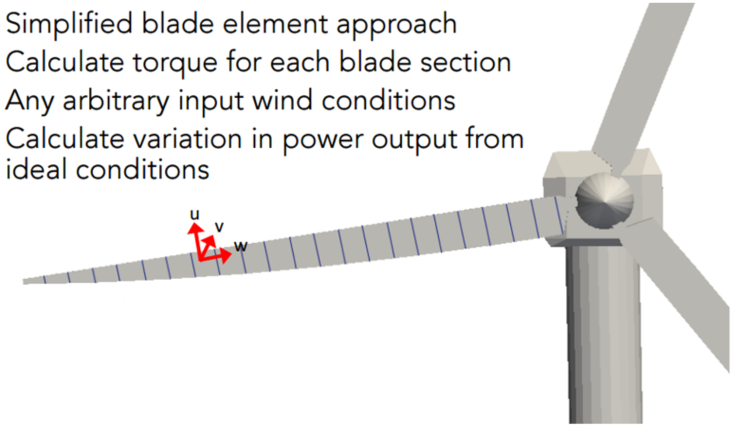
Example Type B Correction: Aeroelastic Models

Type B Example: use of aerodynamic and aero-elastic models to predict reduction in turbine efficient due to ‘outer range’ conditions

- Turbine Performance Prediction, A Head, Prevailing, EWEA Paris 2015

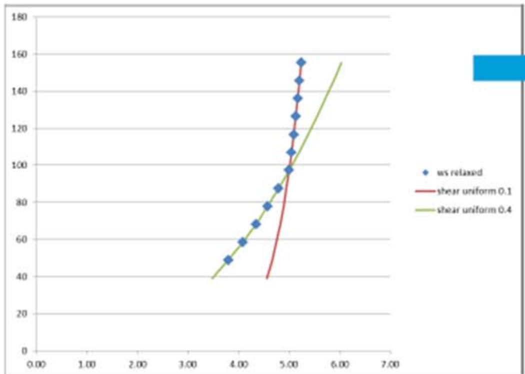


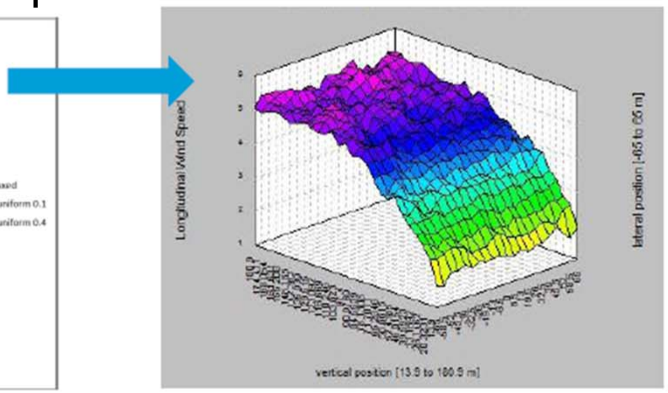
- Simplified blade element approach
- Calculate torque for each blade section
- Any arbitrary input wind conditions
- Calculate variation in power output from ideal conditions



- Modelling type B effects in the 4th Quadrant using BLADED, R Whiting, DNV GL, PCWG Dec 2014

Bladed Aero-elastic Simulations of performance in non-standard conditions.

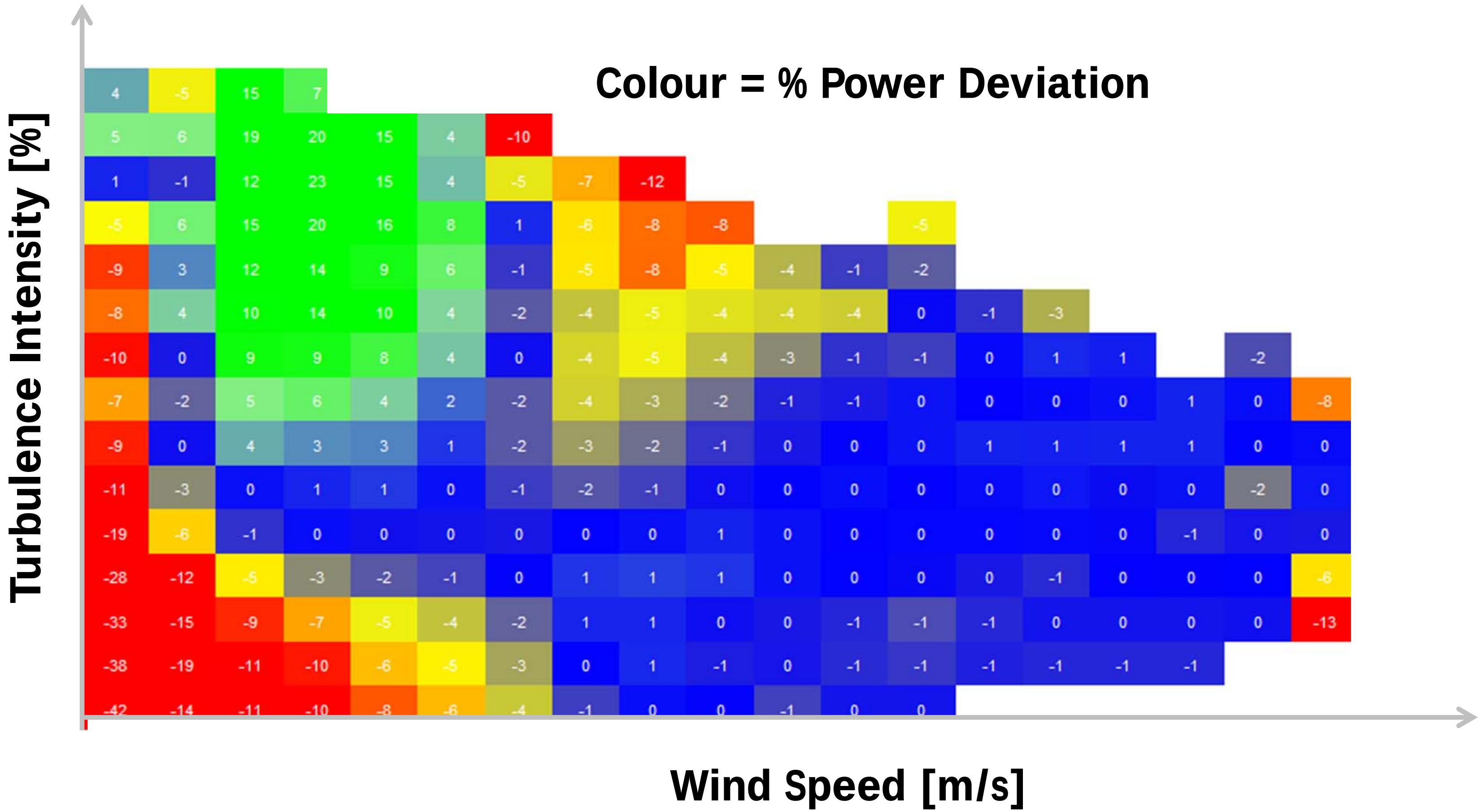




Example Empirical Correction (Type A and Type B Combined)

Power Deviation Matrix Method:

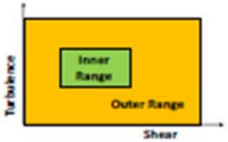
- **Use historic data to create a look-up table of turbine performance (proxy variable)**
- **For each modelled time period 'look-up' correction (deviation) value.**



Power Curve Working Group 2015 Roadmap

Background: Reasons For Action

- **Real world wind conditions** are composed of both inner range and outer range wind conditions:
  - **Inner range conditions** refers to moderate shear and moderate turbulence.
  - **Outer range conditions** refers to high turbulence, low turbulence, high shear, low shear etc.



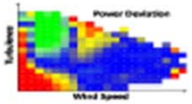
- **Outer range conditions are relatively frequent** and therefore the calculation of turbine power output in outer range conditions is an important consideration in wind energy resource assessment.
- There are **no industry consensus methods** for predicting wind turbine power output in outer range conditions for the purposes of resource assessment.
- **Power performance tests and associated warranties** are **normally limited to** a relatively narrow range of idealised conditions i.e. **inner range conditions.**

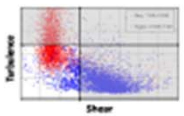
Current Wind Industry State

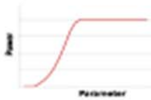
- There are no industry consensus methods for predicting wind turbine power output in outer range conditions for the purposes of resource assessment.
- Power performance tests and associated warranties are normally limited to a relatively narrow range of idealised conditions i.e. inner range conditions.
- The lack of a validated industry consensus methods for predicting power output in outer range conditions (for resource assessment applications) increases the risk perceived by wind energy investors.
- The failure to consider outer range conditions in power performance tests increases the risk perceived by wind energy investors.

Target Wind Industry State

- Well document and validated consensus methods for predicting wind turbine power output in outer range conditions for the purposes of resource assessment.
- Open source benchmarks (e.g. Excel examples) available for all validated consensus methods.
- Open source tools (which comply with benchmarks) available for all validated consensus methods.
- Power performance tests routinely make some consideration of outer range conditions.
- Harmonised communication of power curve information so that corrections for outer range conditions can be unambiguously applied.
- Consensus methods embedded in real world resource assessment industry practice. Reduced resource assessment risk perceived by wind energy investors.
- Reduced power performance risk perceived by wind energy investors.







Reasons for gap between current and target

- REWS and turbulence renormalisation methods are helpful, but do not fully solve the problem.
- There are no industry standard tools for applying existing methods for modelling power output in outer range conditions.
- Several empirical (proxy) methods are available which tie observed turbine performance to key (frequently measured) parameters such as turbulence intensity and lower rotor shear exponent. However, there is a lack of industry consensus regarding which proxy methods are best.
- No objective criteria for evaluating performance of correction methods.
- Minimal data/intelligence sharing between key stakeholders.
- Current power curve documentation can make the application of corrections for outer range conditions difficult e.g. it can be hard to tell if a power curve is defined for hub wind speed, rotor equivalent wind speed or both.
- Currently there is currently no consensus method to extrapolate conclusions at the test turbine to all turbines e.g. extrapolation of shear and turbulence to all turbine locations
- Confusion over contractual and resource assessment contexts inhibits progress on is of turbine performance in non-standard conditions.

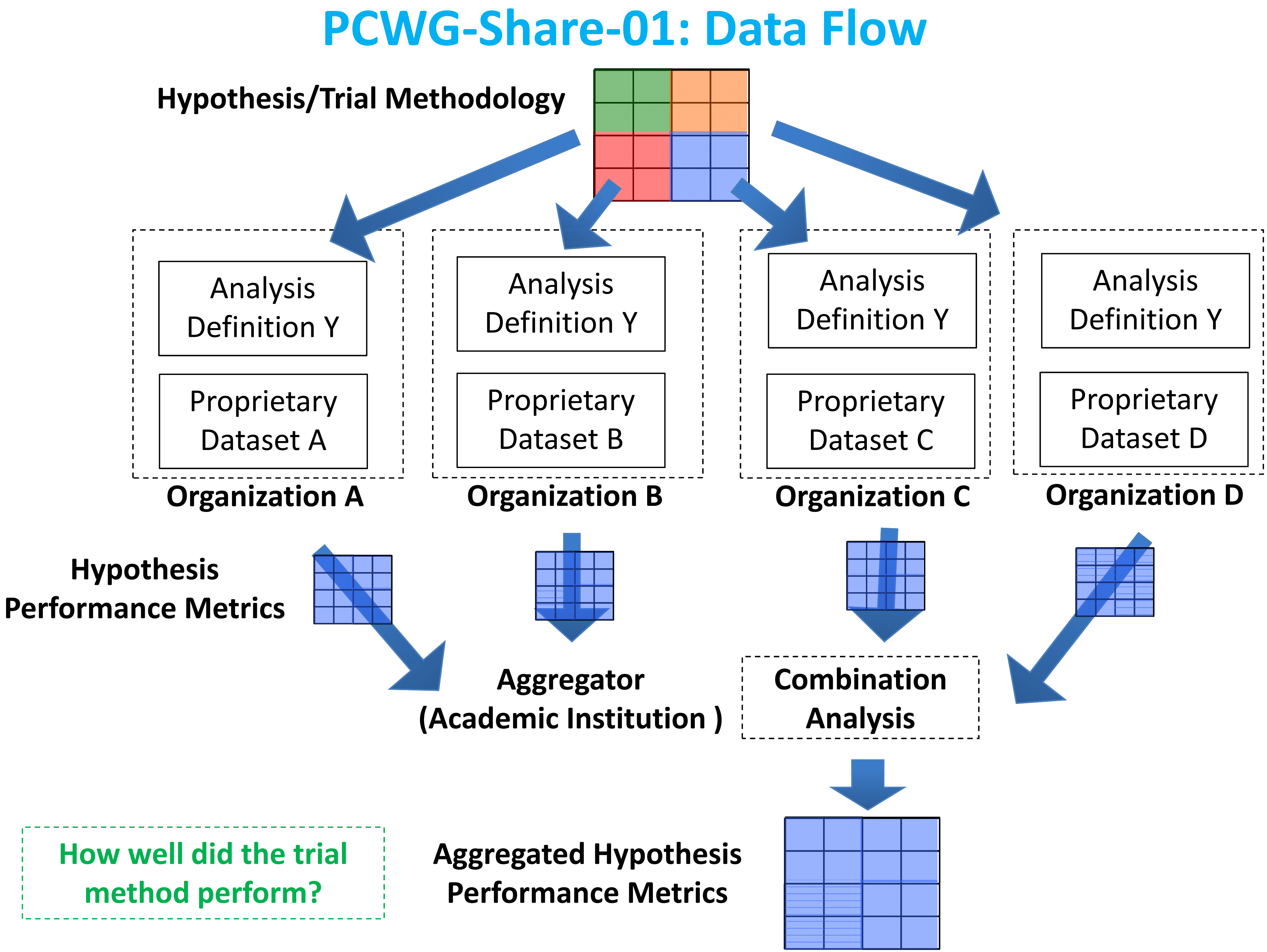
PCWG 2015 Key Actions

- **PCWG-Share-01: Intelligence Sharing Initiative (testing of correction methods)**
- **Harmonisation of stakeholder communication.**

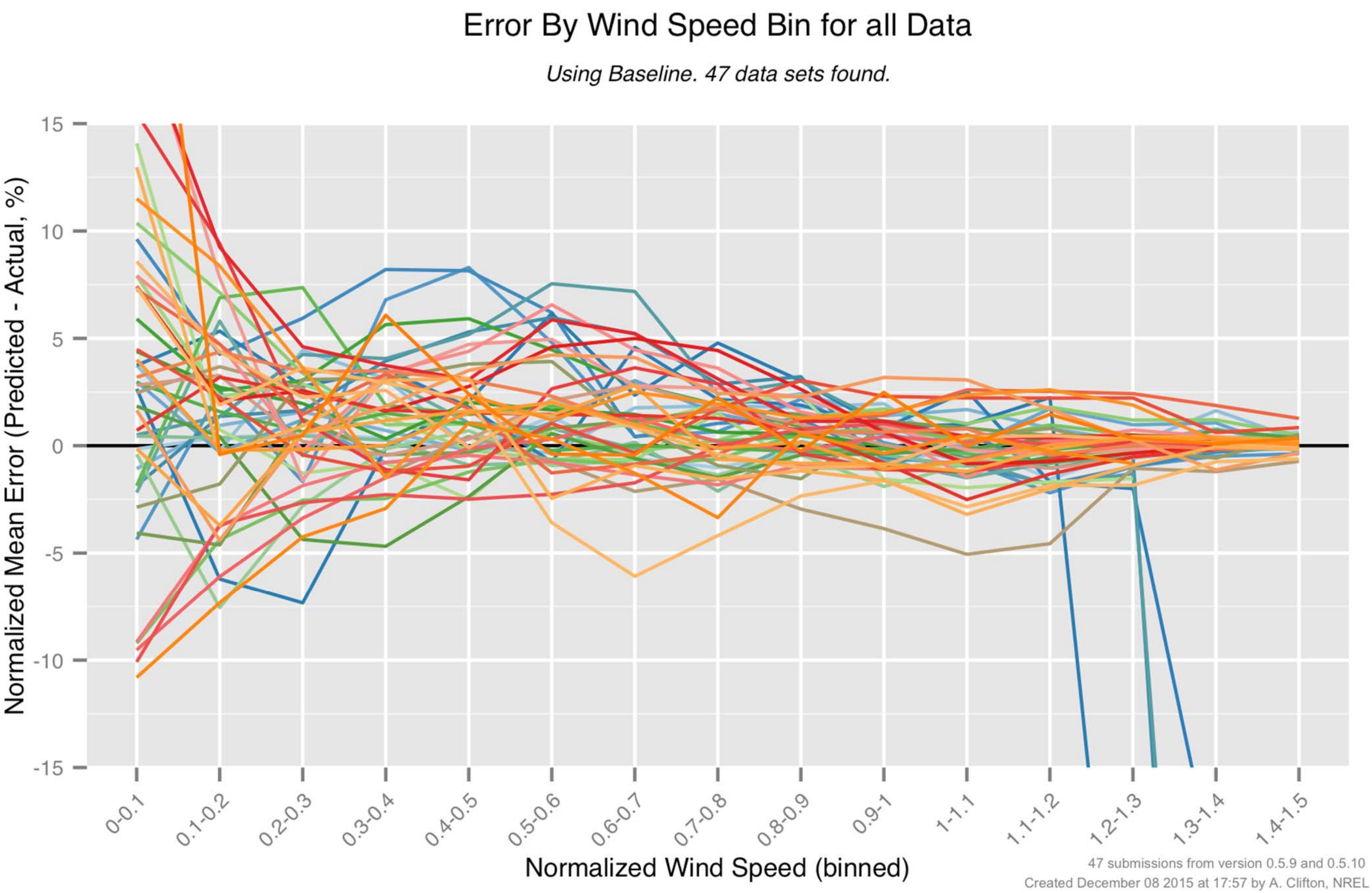
Observations

- No clear consensus method for determining long term representativeness of measured shear, turbulence etc.
- No existing consensus method for modelling turbine performance in non-standard conditions in wake conditions.
- No metric for describing both the energy context and 'bending' of a shear profile.

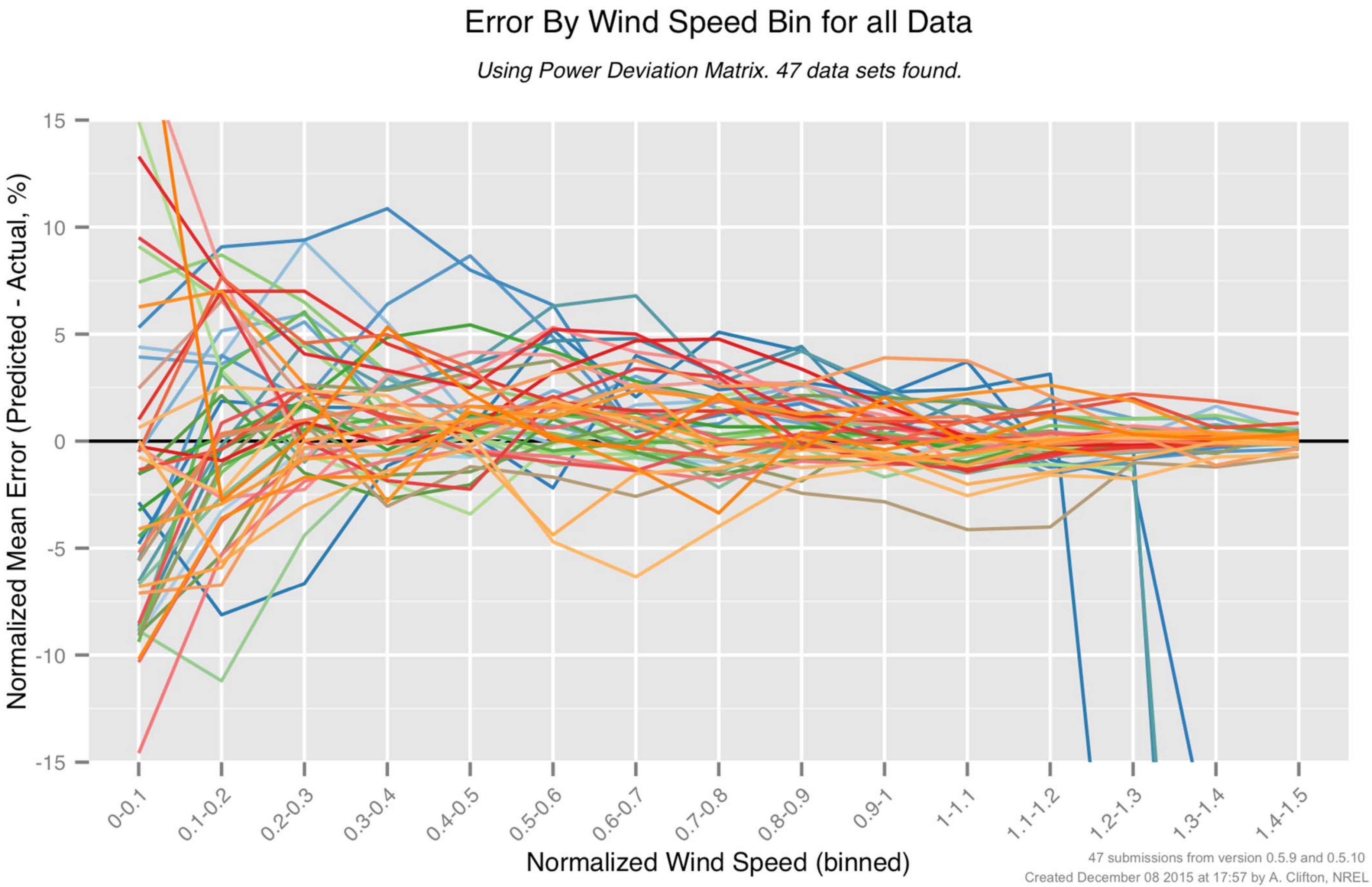
Download PCWG 2015 'A3' Roadmap from www.pcwg.org


PCWG-Share-01: Data Flow
Hypothesis/Trial Methodology
Analysis Definition Y
Proprietary Dataset A
Organization A
Analysis Definition Y
Proprietary Dataset B
Organization B
Analysis Definition Y
Proprietary Dataset C
Organization C
Analysis Definition Y
Proprietary Dataset D
Organization D
Hypothesis Performance Metrics
Aggregator (Academic Institution)
Combination Analysis
How well did the trial method perform?
Aggregated Hypothesis Performance Metrics

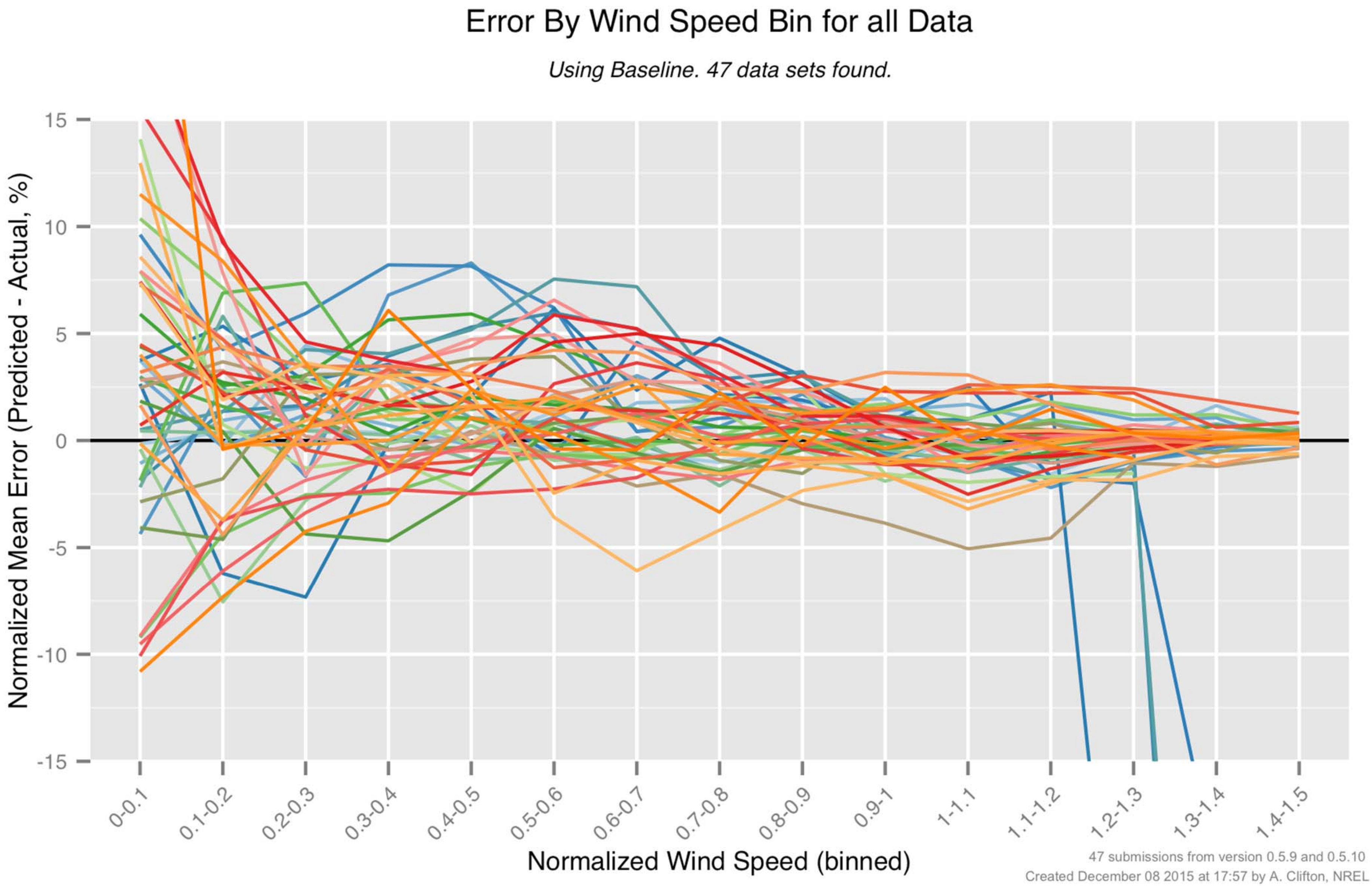
PCWG-Share-01: Baseline Errors by Wind Speed (0.5.9/10)



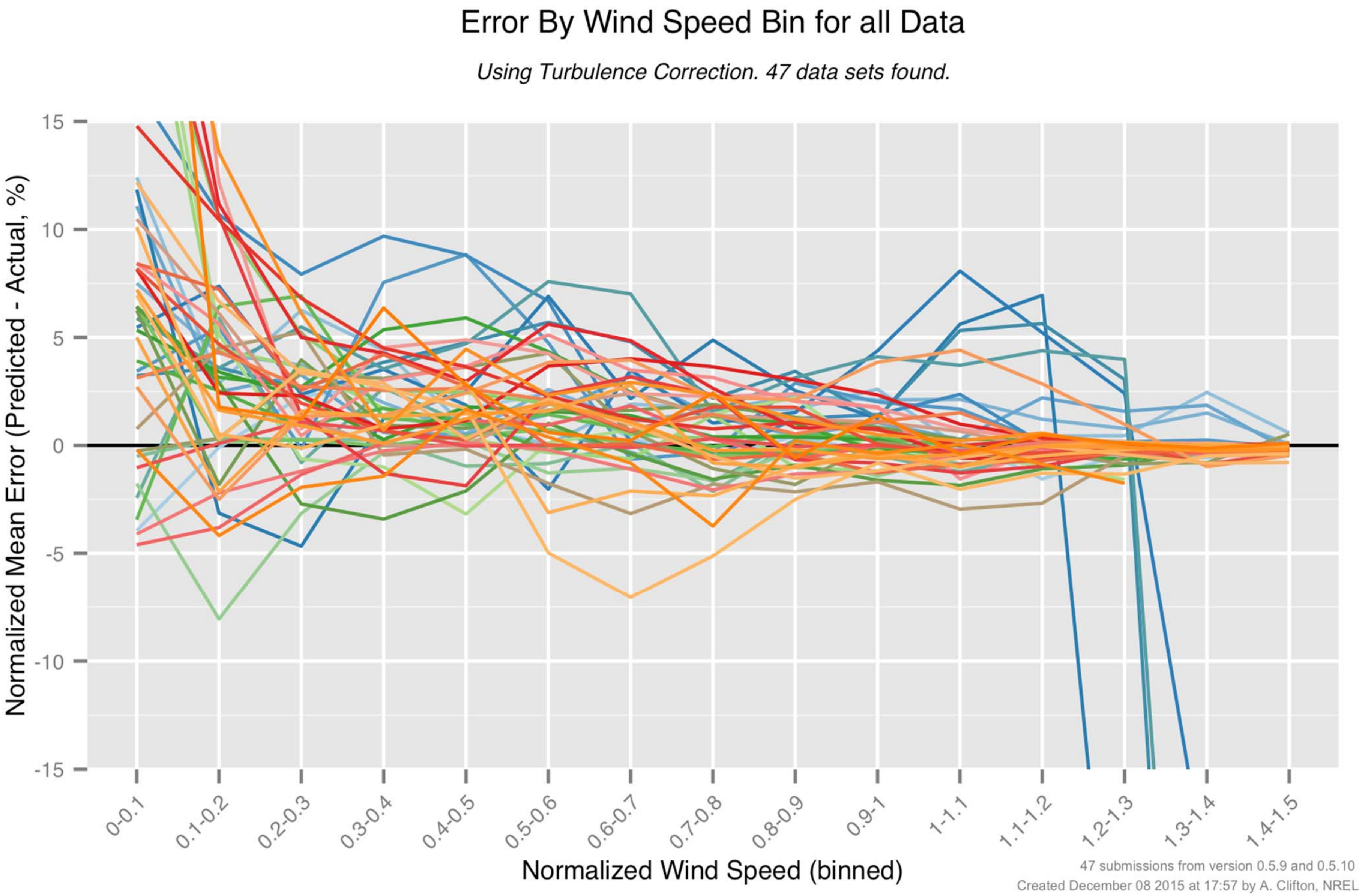
PCWG-Share-01: PDM Errors by Wind Speed (0.5.9/10)



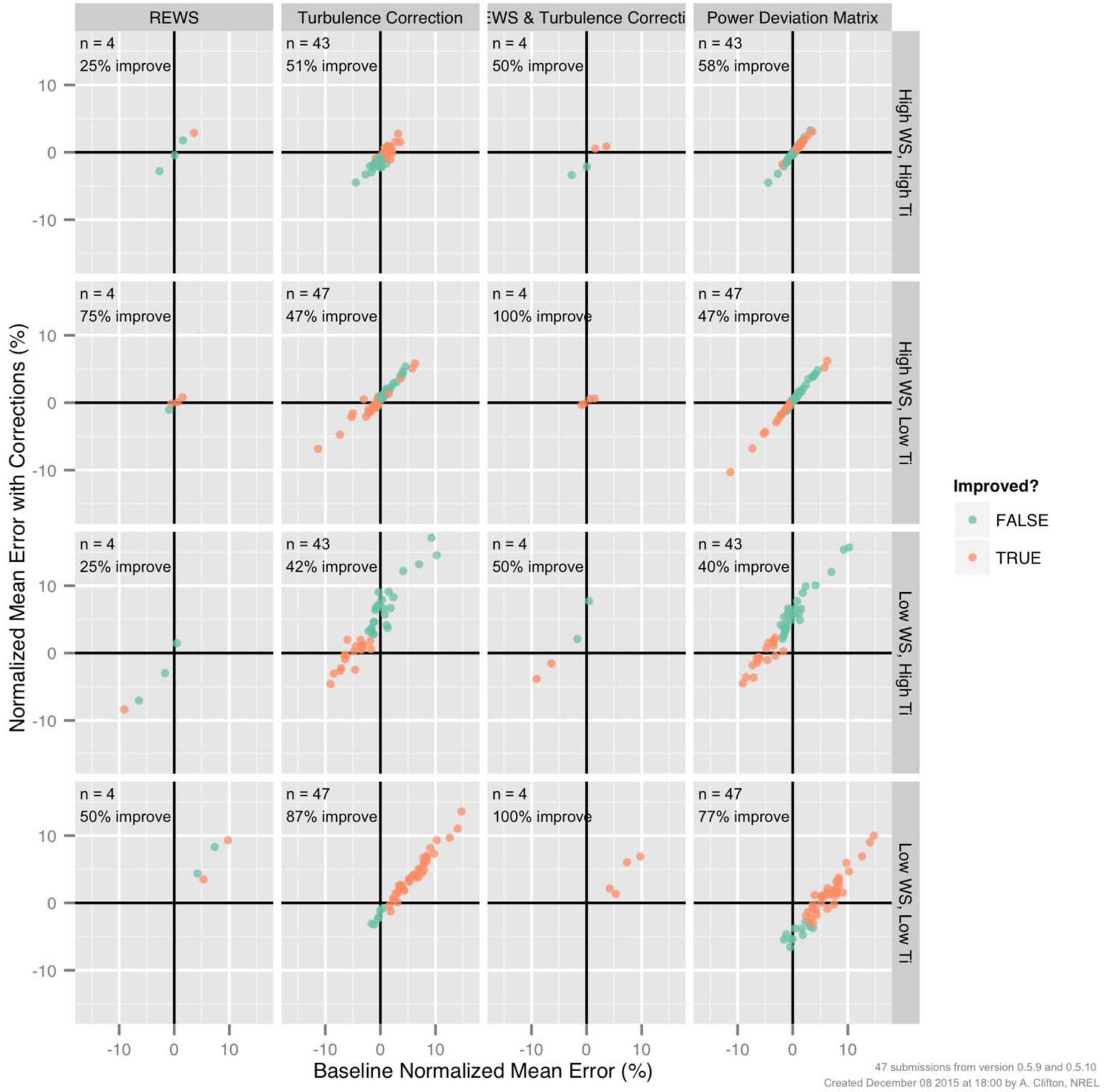
PCWG-Share-01: Baseline Errors by Wind Speed (0.5.9/10)



PCWG-Share-01: Turbulence Correction Errors by Wind Speed (0.5.9/10)



PCWG-Share-01: Improvements by Method ('Four Cell Matrix')



Summary & Conclusions

- 'Real World' Wind Conditions can be decomposed into Inner Range (Ideal) Conditions and Outer Range Conditions.
- Turbine performance in Outer Range conditions deviates from that in Inner Range Conditions.
- Corrections for Outer Range performance can be decomposed into Type A (available energy) and Type B (conversion efficiency).
- Correction methods for both Type A and Type B effects exist and the PCWG is working to test and develop these methods in order to improve industry consensus/alignment.
- Improving out understanding (and prediction) of real world turbine performance will reduce investor risk will in turn reduce the cost of wind energy (reduced the cost of capital).
- There remain key gaps in our understanding of Real World Power Performance (more work needed).

Any Questions?