PCWG: 1st Intelligence Sharing Initiative Definition Document (PCWG-Share-01)

Objective

The goals of the 1st PCWG Intelligence Sharing Initiative (hereafter PCWG-Share-01) are as follows:

- To objectively test candidate methods for predicting turbine performance in outer range climatic conditions (using real world turbine performance data).
- To define a set of generic (technology agnostic) best practice guidelines.
- To objectively quantify the uncertainties associated with the application of the best practice methods.
- To provide a framework for stakeholders to improve upon the generic guidelines using technology specific datasets.
- To publically disseminate all conclusions and recommendations to all relevant stakeholders.

The above objectives will achieve key elements of the PCWG 2015 Roadmap (see Appendix A for links to PCWG 2015 Roadmap).

Commercial Sensitivities

PCWG-Share-01 has been designed to neutralise any potential commercial sensitivities and avoid the need for explicit legal agreements between participants by adopting the following structure:

- **Inner Range Power Curves Extracted from the Dataset Itself:** the data analysis process has been designed such that the warranted power curve is never considered. Instead a power curve is extracted from a subset of the data (Inner-Range) which is then used to model the power output in the outer-range. For more details on the preparation of the Inner-Range power curve see Appendix B.

- **Intelligence Sharing, not Data Sharing:** the data analysis process has been designed such that the datasets do not need to be shared outside of the participant organisations. Instead of sharing the actual data, participants will share performance metrics which describe the accuracy of the trial methodologies. The metrics have been selected to prevent reverse engineering of the source datasets.

- **Aggregation Performed by an Academic PCWG Member:** the performance metrics from the individual participants will be aggregated by an academic institution (hereafter the Data Aggregator). No commercial organisation will received the individual participant results. The Data Aggregator will publically disseminate a pre-agreed set of aggregated performance metrics for the trial methodologies.

Consistent Data Analysis Process

PCWG-Share-01 will utilise the PCWG Open Source Analysis Tool (hereafter PCWG-AT) in order to ensure a consistent data analysis process. All trial methodologies will be implemented in PCWG-AT in advance of the start of the initiative. PCWG-AT will automatically calculate the metrics describing

the performance of the trial methodologies and prepare an appropriately normalised set of results in a format that can be readily shared with the Data Aggregator.

Information Flow

The primary data flow of PCWG-Share-01 is illustrated in Figure 1. The core elements of the process are as follows:

- A hypothesis/trial methodology is proposed.
- Each participant evaluates the performance of the trial methodology against their proprietary datasets using PCWG-AT.
- Each participant shares a standard set of metrics describing the performance of the trial methodology with the Data Aggregator.
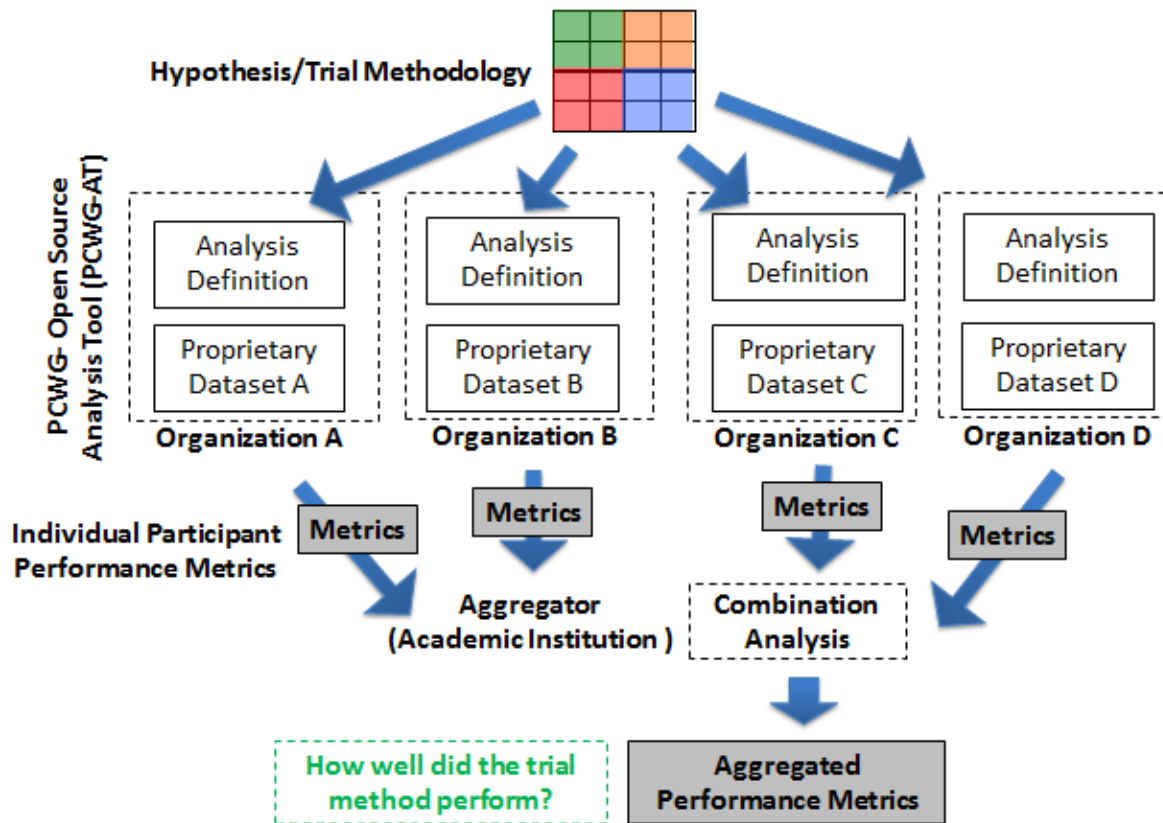- The data aggregator prepares an aggregated set of performance metrics which are publically disseminated.

Figure 1. Overview of primary data flow of PCWG-Share-01

Proposed Trial Methodologies

PCWG-Share-01 will examine the following methods for predicting wind turbine performance in outer range conditions:

1. **Rotor Equivalent Wind Speed (REWS)**: defined in the current draft of IEC 61400-12-1.
2. **Turbulence Correction/Normalisation**: defined in the current draft of IEC 61400-12-1.
3. **2D Power Deviation Matrix Method:** using a hypothesis matrix (wind speed and turbulence) agreed upfront by PCWG members (see Appendix E)
4. **The combination of Methods 1 & 2**

At the time of writing all of the above methods have been discussed in detail in the PCWG and open source Excel benchmark's (Consensus Analysis) have been prepared in all cases.

Other methods which have not yet been so thorough discussed by the PCWG will not be included in the initial phase (PCWG-Share-01) of the exercise. PCWG-Share-02 will seek to examine additional methods including:

1. **Production by Height:** Proposed by Dan Bernadette of AWS TruePower[1].
2. **REWS considering inflow angle (upflow)[2]**
3. **Empirical Turbulence Correction Method (see Appendix E)**
4. **Modified Turbulence Correction/Normalisation (see Appendix F)**
5. **3D Power Deviation Matrix Method:** using a hypothesis matrix (wind speed, shear/RotorTipRatio and turbulence) agreed upfront by PCWG members

As prerequisites for the above (and any other) candidate methods being included in PCWG-Share-02 they must first be discussed in sufficient detail by the PCWG and open source Excel benchmarks must be established.

Performance Metrics

PCWG-Share-01 has been designed such that the actual datasets need not be shared outside of the participant organisations. Instead of sharing the actual data, participants will share performance metrics which describe the accuracy of the trial methodologies. The metrics have been selected to prevent reverse engineering of the source datasets. In order to define the performance metrics the following quantities are used:

- $P_{Baseline}(t)$: The baseline modelled power calculated from the inner-range power curve, hub height wind speed and hub height density for a given time period.
- $P_{Candidate}(t)$: The modelled power using the candidate methodology for a given time period.
- $P_{Actual}(t)$: The actual power production for a given time period.
- P_{Rated}: The rated power of the turbine.
- $\varepsilon_{Baseline}(t)$: $(P_{Baseline}(t) - P_{Actual}(t))$ (baseline error for a given time period)
- $\varepsilon_{Candidate}(t)$: $(P_{Candidate}(t) - P_{Actual}(t))$ (candidate error for a given time period)

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[1] Presented at AWEA Resource Assessment 2014 (Orlando), "Production by Height, A new way to estimate energy production from a wind turbine", Daniel W. Bernadett, Chief Engineer, AWS Truepower

[2] As proposed by Iñaki Lezaun Mas (Gamesa) at the PCWG meeting on the 1st April 2014 (see www.pcwg.org).

The following metrics have been proposed:

- **Normalised Mean Error (NME)**: $\sum\varepsilon_{Baseline}/\sum P_{Actual}$
- **Normalised Mean Absolute Error (NMAE)**: $\sum|\varepsilon_{Baseline}|/\sum|P_{Actual}|$

The above metrics (and associated data counts) will be calculated as follows:

- A single value for all data
- By wind speed bin
- By time of day bin
- By direction (in order to identify erroneous data)
- By range; Inner Range vs Outer Range.
- A 'Four cell' matrix describing performance under the following conditions:
  - Low Wind Speed and Low Turbulence
  - Low Wind Speed and High Turbulence
  - High Wind Speed and Low Turbulence
  - High Wind Speed and High Turbulence
- By calendar month

Quality Metrics

In order to confirm that the quality of the submitted results an image of a two-dimensional scatter plot of normalised wind speed vs. normalised power overlaid on the normalised inner range power curve will be included in the results. This plot will allow to data aggregator to identify submissions which have included erroneous data e.g. waked directional sectors. Note that these normalised scatter plots will **<u>not</u>** be included in the results disseminated by the Data Aggregator.

Minimum Data Counts

In order to generate an inner range power curve a dataset must contain sufficient data in the Inner Range. Specifically it is required that the following bin populations are achieved:

Bin Ranges	Bin Width	Minimum Data Count
From V_A to Cut-In		6
From Cut-In to V_B	1m/s	10
From V_B to V_C		6

where:
- V_A is defined as the wind speed 1m/s below Cut-In
- *V_B is defined as 1.2 times the speed at which 85% of the rated power is achieved.*
- *V_C is defined as 1.5 times the speed at which 85% of the rated power is achieved.*

Furthermore in order to calculate the performance metrics at least 10 data points are required for each bin (e.g. by direction, time of day etc.). It should be noted that the above criteria have been selected to be broadly consistent with IEC 61400-12-1, though somewhat relaxed in order to help achieve the specific aims of PCWG-Share-01.

Inner Range Definition

It is acknowledged that the requirement to populate sufficient data in the Inner Range necessitates some flexibility in the PCWG-Share-01 Inner Range definition. Participants should choose a suitable Inner Range[3] Definition per dataset from the following choices:

- Inner Range A:
    - Shear: 0.05 to 0.25
    - Turbulence 8% to 12%
- Inner Range B:
    - Shear: 0.05 to 0.25
    - Turbulence 5% to 9%
- Inner Range C:
    - Shear: 0.10 to 0.30
    - Turbulence 10% to 14%

If possible participants should apply Inner Range A in order to maximise the number of participants using the same Inner Range definition. If sufficient data capture cannot be achieved with Inner Range A participants should fall-back to either Inner Range B or Inner Range C.

Composite Datasets

Composite submissions (i.e. submissions derived from multiple datasets) are permissible, although the following should be adhered to:

- Composite submissions must be formed from the same turbine model (and model variant), with the same hub height (and diameter), operating in the same operational mode.
- The site classification must be the same for all component sites and must be non-complex terrain.
- The components sites must be from the same country.
- The component submissions must use the same Inner Range Definition.

Participants are free to submit the component datasets of a composite submission individually (in addition to as a composite), but this must be flagged to the Data Aggregator.

Data Required to Complete Rotor Equivalent Wind Speed (REWS)

Participants should only attempt to calculate REWS if they have sufficient data to do so. In order to calculate REWS a minimum of three measurement heights is required, with at least one height above the hub height and one height below hub height.

Direction Sectors

Data sectors will only be included in PCWG-Share-01 if there are determined to be obstacle and wake free according to Annex A of IEC 61400-12-1 (2006). A sector width of 10 degrees should be

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[3] Readers are advised to note that the Inner/Outer Range PCWG proposal is a conceptual decomposition of the full range of real world atmospheric conditions and does not imply specific boundaries of the Inner and Outer ranges. In the commercial execution of the Inner/Outer Range concept the boundaries of the Inner and Outer Ranges should be agreed by the relevant stakeholders. Specific ranges for the Inner Range are presented here solely for the purposes of PCWG-Share-01 The PCWG Inner/outer range proposal is described in detail in http://www.pcwg.org/proposals/PCWG-Inner-Outer-Range-Proposal-Dec-2013.pdf.

applied. The output by direction performance metrics should be inspected to identify erroneous direction data and if necessary the sectors redefined.

Participants are encouraged to be cautious when including Remote Sensing data to ensure that the full measurement profile is wake free e.g. it is possible for a mast hub height wind speed to be wake free, but a co-located SoDAR/LiDAR to have height(s) that are waked.

Mast and Remote Sensing Data

Both mast and Remote Sensing (LiDAR/SoDAR) data may be used for PCWG-Share-01. The following dataset permutations are applicable:

1) Mast only.
2) LiDAR/SoDAR only.
3) Mast (hub data) with co-located LiDAR/SoDAR (profile data)

Item 3) above is considered to be the ideal configuration for the purposes of PCWG-Share-01. For the avoidance of doubt it should be noted that nacelle mounted LiDARs datasets can be submitted.

Low Temperature

Participants should filter out data below two degrees Celsius in order to eliminate possible periods of anemometer Icing.

Averaging Period

Participants should only use data with a 10-minute averaging period.

Reference Numbers

The PCWG-AT will automatically create a reference number associated with a given submission and/or dataset. This will allow for the participant to has traceability or their submission and reduce the risk of duplicate submissions. Where relevant the reference numbers will be a 'checksum' based on the contents of input files.

Meta-Data

Participants will be asked to include the following meta-data with their submission:

Item	Description	Required?
Data Type	• Mast • LiDAR (Ground Mounted) • SoDAR (Ground Mounted) • Mast & LiDAR (Ground Mounted) • Mast & SoDAR (Ground Mounted) • Spinner • Nacelle Mounted LiDAR	Required
REWS Definition	• Number of Heights • Veer Included	Required
Inner Range Definition	• Inner Range A • Inner Range B • Inner Range C	Required
Outline Site Classification	• Flat • Complex • Offshore	Required
Outline Forestry Classification	• Forested • Non-forested	Required
IEC Site Classification	• As described by Annex B of IEC 61400-12-1 (2006).	If available
Geography	• Latitude (to no decimal places) e.g. 53° • Continent • Country • Elevation above sea level (rounded to nearest 100m).	If available
Consistency of measurements with IEC 61400-12-1 (2006)	• Yes • No • Unknown	Required
Anemometry Type	• Sonic • Cups • Spinner	Required
Anemometry Heating	• Heated • Unheated	If available
Turbulence Measurements	• LiDAR • SoDAR • Cups • Sonic • Spinner	Required
Power Measurement	• Transducer • SCADA • Unknown	If available
Turbine Geometry	• Diameter (rounded to nearest 10m) • Hub Height (rounded to nearest 10m). • Specific Power (rated power divided by swept area)	Required
Turbine Control Type	• Pitch • Stall • Active Stall	If available
Vintage	• Year of Test • Year of first commercial operation of turbine.	If available
Time Zone	• Local • UTC	Required

Timeline

The timeline for the proposed initiative is outline in Appendix D.

Aggregation of Results

The data aggregator will prepare aggregated versions of the dataset performance metrics for each candidate correction method:

- Aggregated Normalised Mean Error: $1/D \times \sum NME$
- Aggregated Normalised Mean Absolute Error: $1/D \times \sum NMAE$

where D is the number of datasets. In addition the data aggregator will prepare aggregated versions of the binned metrics:

- Aggregated NME and NMAE by wind speed bin
- Aggregated NME and NMAE by time of day bin
- Aggregated NME and NMAE by range; Inner Range vs Outer Range.
- 'Four Cell' matrix of aggregated NME and NMAE.

The data aggregator will also prepare a list of key observations in order to highlight areas to be addressed in a potential 2016 PCWG Roadmap and broader research community.

Results Submission

Results should be exported from the PCWG-AT into the standard anonymous Excel format using the dedicated PCWG-Share-01 export function within the tool. One the Excel report has been exported from the tool participations should manually add the relevant meta-data fields (for each input dataset) in the spaces provided in the 'Meta Data' worksheet. Finally participations should review the contents of their anonymous report and once happy submit their results to the Data Aggregator (NREL) by emailing their document to pcwg@nrel.gov.

By emailing their results to pcwg@nrel.gov participants will be giving their organisation's consent for the results to be analysed (and disseminated) for the purposes of the PCWG Intelligence Sharing Initiative (PCWG-Share-01) in line with the contents of this content.

Participants will be contacted by the data aggregator if issues are found with the submission.

The deadline for results submission for PCWG-Share-01 is the 23rd of November 2015.

Appendix A: Relationship to PCWG 2015 Road Map

The actions defined within the PCWG 2015 roadmaps are shown below. The actions which will be completed during the course of PCWG-Share-01 are highlighted in **green**.

PCWG 2015 Actions:

- **Define trial methods and validate them (including new and novel methods) e.g. REWS, RAWS, site/conditions specific power curves, turbulence renormalisation, power deviation matrix, production by height, modified turbulence renormalisation method.**
- **Implement PCWG data/intelligence sharing initiate to provide a platform for developing and validating trial correction methods. As part of sharing initiative develop objective criteria/framework for testing corrections for non-standard conditions.**
- **Develop open source benchmarks (e.g. Excel examples) for applying trial methods so that methods are well understood. Where appropriate perform round robin exercises to develop consensus understanding e.g. Power Curve Deviation Matrix and REWS with Inflow Round Robins**
- **Develop open source python tools so that trial methods can be applied to many datasets efficiently:**
    - **Power Curve Deviation Matrix Implemented**
    - **Rotor Equivalent Wind Speed Considering Inflow Implemented**
- Promote application of Inner/Outer range concept for power performance tests by sharing experiences.
- Develop a document to harmonise the communication of power curve information. Document should express requirements for site specific power curves and/or power deviation matrices from a developer/consultant (required outputs) and manufacturer (required inputs) perspective. Document should difference between the resource assessment and contractual contexts.
- Develop methods for applying corrections for non-standard conditions across a wind farm in order to reduce 'by turbine errors' and facilitate the design of better wind farms.

In turn these actions should bring about the elements of the target state highlighted in **blue**:

PCWG 2015 Target 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.

For the full PCWG 2015 Roadmap please visit www.pcwg.org

Appendix B: Preparation of the Inner-Range Power Curve

PCWG-Share-01 has been designed to sidestep commercial sensitives associated with using warranted power curves. The data analysis process is thus structured such that the warranted power curve is never considered. Instead a power curve is extracted from a subset of the data (inner-range) which is then used to model the power output in the outer-range (see Figure B1). In this way PCWG-Share-01 will examine the deviation in performance in the Outer-Range relative to that in the Inner-Range, but remain completely agnostic about the absolute performance in the Inner-Range.
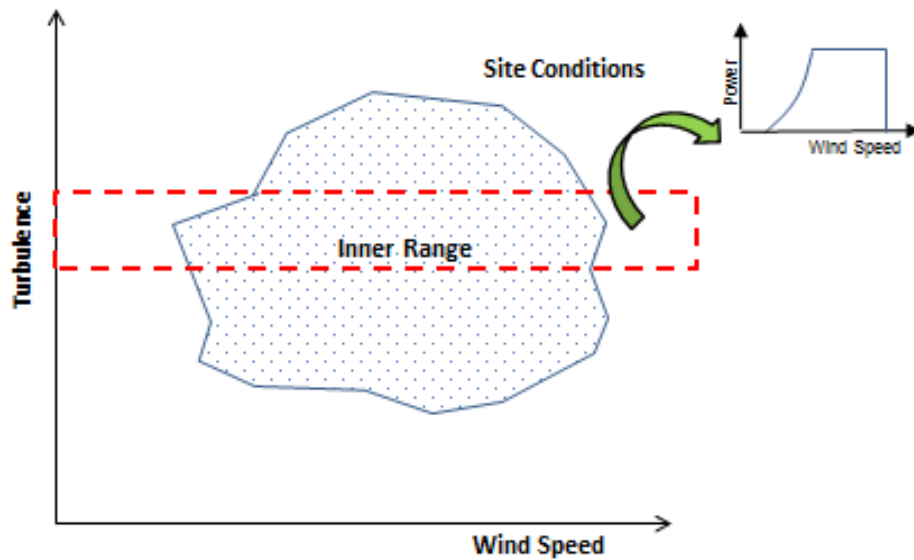

Figure B1. Illustration of the data analysis process used to extract an inner-range power curve from a participant dataset.

Appendix C: Draft Hypothesis Power Deviation Matrix

The **draft** hypothesis power deviation matrix for use in PCWG-Share-01 is shown below. The Power Deviation Matrix will be finalised prior to the commencement of PCWG-Share-01.

Power Deviation Matrix

Turbulence Intensity [%]	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
29%	10%	20%	25%	23%	15%	11%	6%	0%	-3%	-6%	-7%	-6%	-2%	0%	0%	0%	0%	0%	0%	0%	0%
27%	10%	20%	25%	20%	14%	10%	5%	0%	-3%	-5%	-6%	-5%	-2%	0%	0%	0%	0%	0%	0%	0%	0%
25%	10%	20%	24%	18%	12%	9%	5%	0%	-2%	-5%	-5%	-5%	-2%	0%	0%	0%	0%	0%	0%	0%	0%
23%	10%	18%	21%	16%	10%	8%	4%	0%	-2%	-4%	-5%	-4%	-1%	0%	0%	0%	0%	0%	0%	0%	0%
21%	10%	15%	18%	13%	9%	7%	3%	0%	-2%	-3%	-4%	-3%	-1%	0%	0%	0%	0%	0%	0%	0%	0%
19%	8%	11%	14%	11%	7%	5%	3%	0%	-1%	-3%	-3%	-3%	-1%	0%	0%	0%	0%	0%	0%	0%	0%
17%	4%	8%	11%	8%	6%	4%	2%	0%	-1%	-2%	-2%	-2%	-1%	0%	0%	0%	0%	0%	0%	0%	0%
15%	0%	4%	8%	6%	4%	3%	2%	0%	-1%	-2%	-2%	-2%	-1%	0%	0%	0%	0%	0%	0%	0%	0%
13%	-4%	0%	5%	4%	2%	2%	1%	0%	0%	-1%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
11%	-8%	-3%	2%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
9%	-12%	-7%	-2%	-1%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
7%	-16%	-10%	-5%	-4%	-2%	-2%	-1%	0%	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
5%	-20%	-14%	-8%	-6%	-4%	-3%	-2%	0%	1%	2%	2%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%
3%	-24%	-18%	-11%	-8%	-6%	-4%	-2%	0%	1%	2%	2%	2%	1%	0%	0%	0%	0%	0%	0%	0%	0%
1%	-28%	-21%	-14%	-11%	-7%	-5%	-3%	0%	1%	3%	3%	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%

Normalised Wind Speed [m/s]

Where the normalised wind speed (s) if defined as

$$s = \frac{u - u_{cut-in}}{u - u_{rated}}$$

and the values u_{cut-in} and u_{rated} are those calculated during the generation of the initial zero turbulence power curve.

Appendix D: Timeline
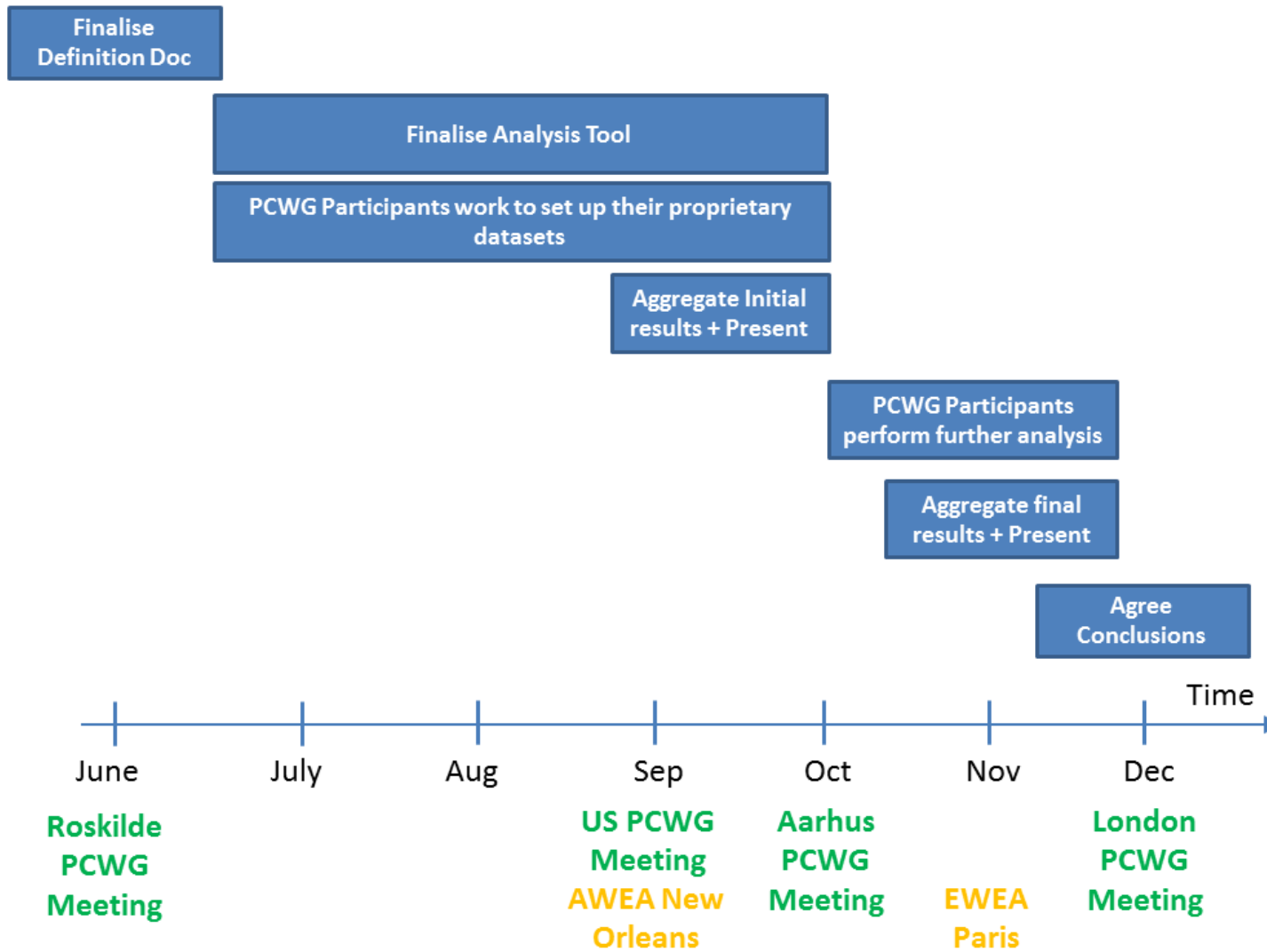
Appendix E: Empirical Turbulence Correction Method

The proposed correction attempts to describe the residual correction necessary after the Rotor Equivalent wind speed (REWS) and Turbulence Correction (Renormalisation) methods have been applied. The methodology involves the following quantities

- $x' = x_{saddle} - x$
- $t' = (t_{reference} - t) / t_{reference}$

where:

- x = windspeed
- x_{saddle} = turbine saddle (inflection) wind speed i.e. somewhere between cut-in and rated.
- t = site turbulence
- $t_{reference}$ = power curve reference turbulence (for wind speed x)

The loss is then calculated as follows:

```
IF x' >0 and t' >0
        loss = A*x' + B
ELSE
        loss = 0
```

where:

- $A = -2\% * \tanh(2t')$
- $B = -3\% * (e^{3/2t'} - 1)$

Appendix F: Modified Turbulence Correction

The fundamental premise of the Turbulence Correction defined in the current draft of IEC61400-12-1 is that a correction can defined as follows[4]:

$$P_{Target\_TI} = P_{Ref\_TI} + \delta P$$

$$\delta P = S_{Target\_TI} - S_{Ref\_TI}$$

where:

- P is the power
- S is the simulated power

The simulated power is calculated using a 'zero turbulence power curve'. Using the functional notation (whereby square brackets denote an input function) we can express the turbulence correction as:

$$\delta P = S_{Target\_TI}[Z] - S_{Ref\_TI}[Z]$$

An initial guess is made of the zero turbulence power curve ($Z_{Initial}$) based upon the C_{PMax}, cut-in wind speed and rated power of the reference turbulence power curve. The final zero turbulence power curve is then calculated by deriving a correction to take the reference turbulence power curve to the target turbulence using the initial zero turbulence power curve

$$Z_{Final} = P_{Ref\_TI} +(S_{Target\_TI}[Z_{Initial}] - S_{Ref\_TI}[Z_{Initial}])$$

Validation of the Turbulence Correction has both demonstrated its effectiveness (in many situations) and identified some shortcomings (in certain situations). One key observation is the tendency for overcorrection of the knee of the power curve in high turbulence. The proposed modified method attempts to adjust the performance by introducing a 'relaxation factor':

$$\delta P = (1+a) \times (S_{Target\_TI}[Z] - S_{Ref\_TI}[Z])$$

where a is a step function of both turbulence intensity and wind speed

a	TI	Wind Speed	Range
0	Inner		
a_1	$TI < TI_{Lower}$	$U > U_{Saddle}$	Outer (High Turbulence, High Speed)
a_2	$TI > TI_{Upper}$	$U > U_{Saddle}$	Outer (Low Turbulence, High Speed)
a_3	$TI > TI_{Upper}$	$U < U_{Saddle}$	Outer (High Turbulence, Low Speed)
a_4	$TI < TI_{Lower}$	$U < U_{Saddle}$	Outer (Low Turbulence, Low Speed)

To derive the constants a_1-a_4 a zero turbulence power curve is first calculated using the normal method (assuming a=0). This model (with a=0) is then used to calculate turbine performance for several subdivisions of the outer range (see above table). The constants are then adjusted to minimise the residual:

$$r =\int | (P_{Outer} - P_{Inner}) - (S_{Outer} - S_{Inner})|du$$

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[4] For more details and worked examples of this method please visit www.pcwg.org