DRAFT FOR COMMENT

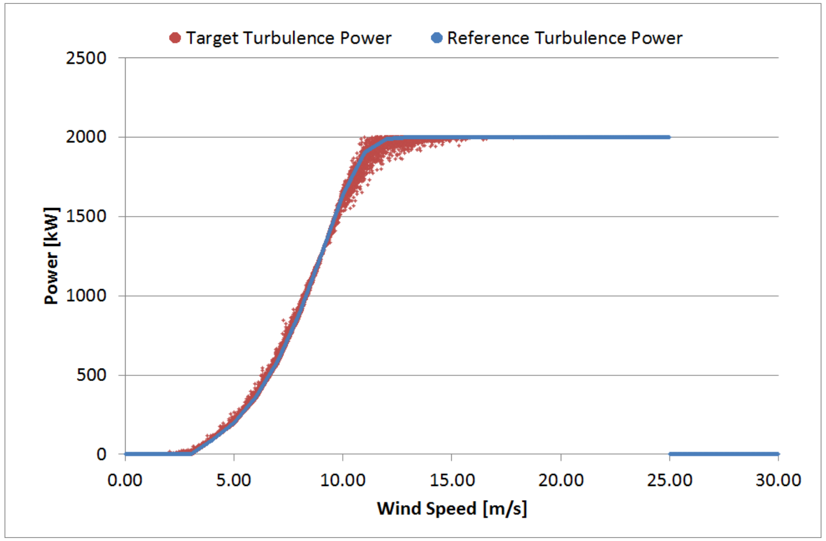
Turbulence Correction Method: Consensus Analysis Documentation

- This document attempts to explain the various steps involved in the Consensus Analysis implementation of the Turbulence Renormalisation Method (Turbulence Correction).

- The method is defined in Annex M (‘Normalisation of measured power curve data according to the turbulence intensity ‘) of the standard IEC 61400-12-1 (‘Power performance measurements of electricity producing wind turbines’), Draft CDV version 1.

- Note that the method can be applied in two contexts:
    - Power Performance
    - Resource Assessment

The Consensus Analysis demonstrates usage in the Resource Assessment context.



Basic Premise of Method: Power Performance Context

Starting Point — Observation of power at measured wind speed and Measured turbulence

End Point — Observation of adjusted power at wind speed and Reference turbulence

End Point = (Starting Point) + (Correction)

Correction = (End Point) − (Starting Point)

= (Power at Reference Turbulence) − (Power at Measured Turbulence)

≈ (Simulated Power at Ref Turb) − (Simulated Power at Measured Turb)

i.e. the simulated power at a given turbulence is trusted to define a correction (from one turbulence to another), but not trusted to defined the absolute value at given turbulence.

Basic Premise of Method: Resource Assessment Context

Starting Point ◆ Power curve interpolated power value at wind speed and Reference turbulence

End Point ◆ Prediction of power at wind speed and Site turbulence

End Point = (Starting Point) + (Correction)

Correction = (End Point) − (Starting Point)

= (Power at Site Turbulence) − (Power at Reference Turbulence)

≈ (Simulated Power at Site Turb) − (Simulated Power at Reference Turb)

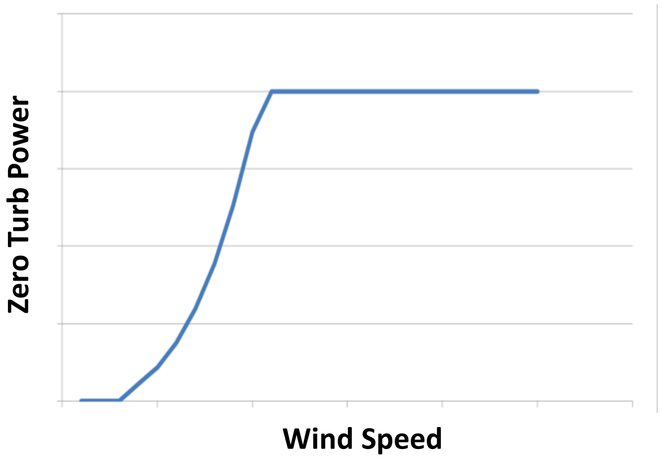
i.e. the simulated power at a given turbulence is trusted to define a correction (from one turbulence to another), but not trusted to defined the absolute value at given turbulence.

Power Curve Simulation Method

Concept: **a simulation method which can generate a power curve at any required turbulence.**

Note: as said previously the simulated power at a given turbulence is trusted to define a correction (from one turbulence to another), but not trusted to defined the absolute value at given turbulence.

Hypothesize: **that we can define a zero turbulence power curve which gives the 'instantaneous' power of a wind turbine.**



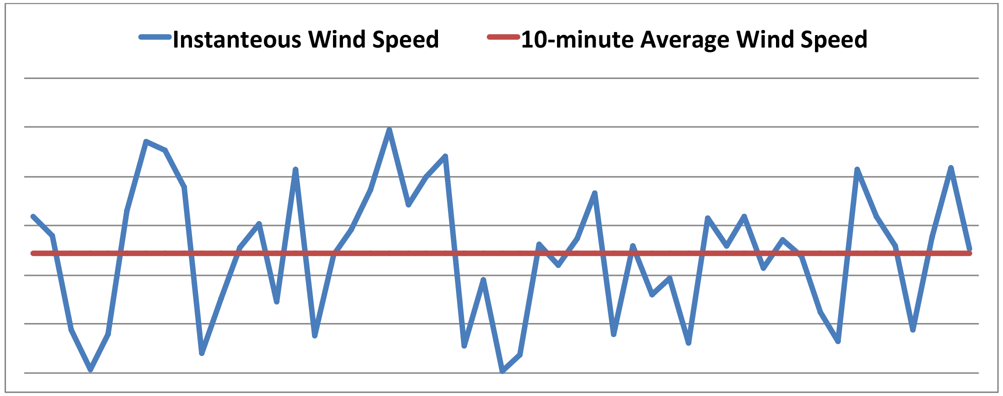


Illustration of instantaneous wind speed.
Turbulence Intensity = Std Dev / Mean (of instantaneous values)

Assume: **the power output perfectly follows the zero turbulence power curve for each instantaneous wind speed value.**

Note: **we will explain later how to calculate the zero turbulence power curve.**

Power Curve Simulation Method

Starting Point:

- A zero turbulence power curve
- Values of wind speed and turbulence intensity

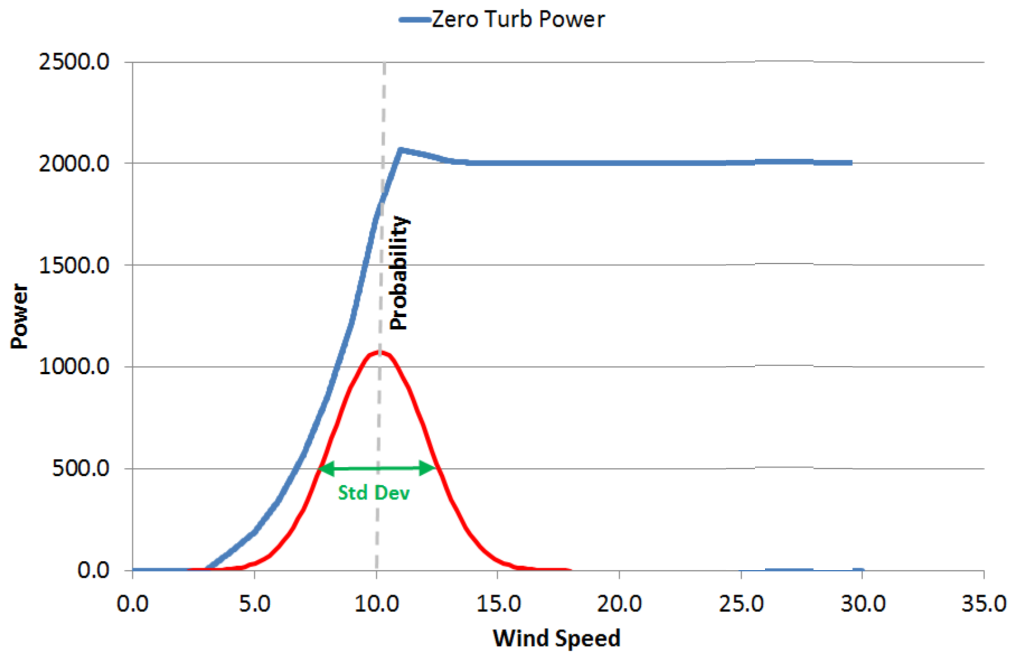
End Point:

- Simulated power at a given power curve and turbulence intensity

Don't worry we haven't explained how to derive the zero turbulence power curve yet (we'll do this later)

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)



Zero Turbulence Power

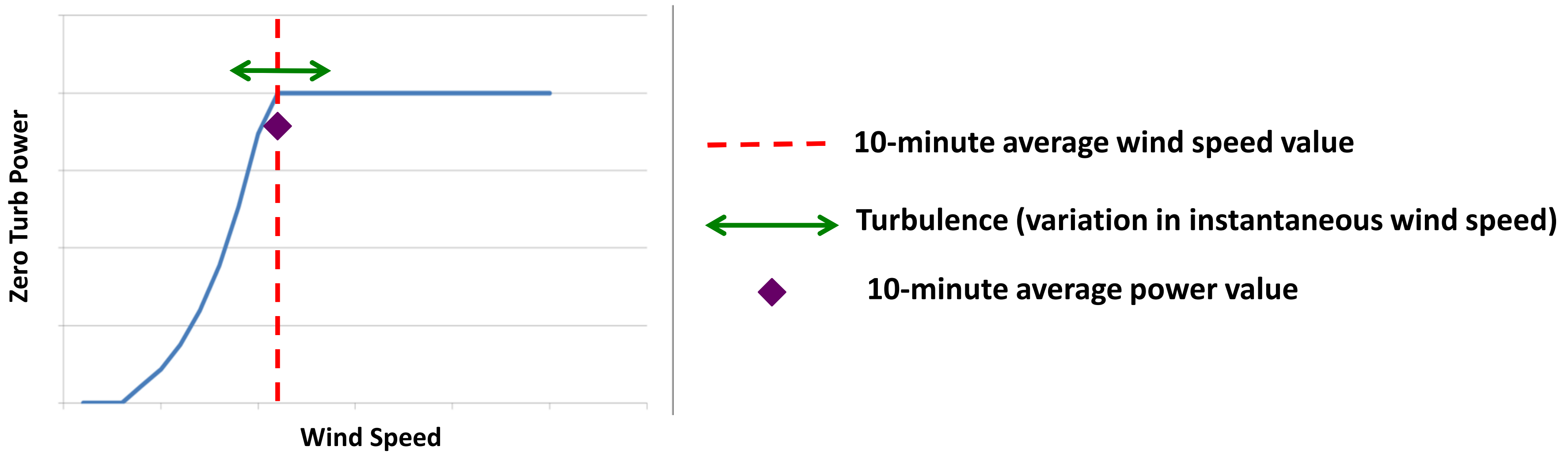
Normal Distribution (for 10minute period)

- Interpolate the zero turbulence power curve at every wind speed in the probability distribution (0 to 100m/s in 0.1m/s steps)
- Take the sum product of the interpolated probability distribution and the interpolated zero turb power values:

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

Behaviour of Zero Turbulence Power Curve at the Power Curve Knee

At the power curve knee turbulence causes the 10-minute average power to fall below the zero turbulence (instantaneous) power (knee degradation)

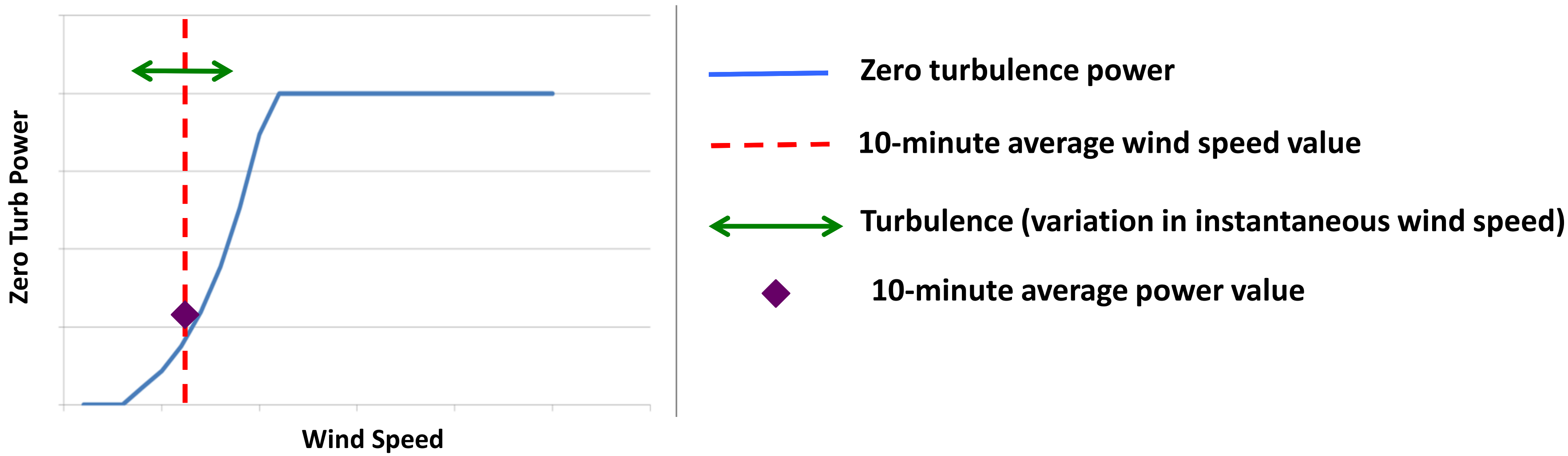


- **In the above illustration the 10-minute average value is exactly at the rated wind speed of the zero turbulence curve.**
- **Therefore half of the ten minute period is at rated power and half below rated power.**
- **Hence the ten-minute average power is less than the rated power.**

Note: mathematically speaking we can say this behaviour is because the second derivative of the power curve at the knee (with respect to wind speed) is negative.

Behaviour of Zero Turbulence Power Curve at the Power Curve Ankle

At the power curve ankle turbulence causes the 10-minute average power to be above the zero turbulence (instantaneous) power.

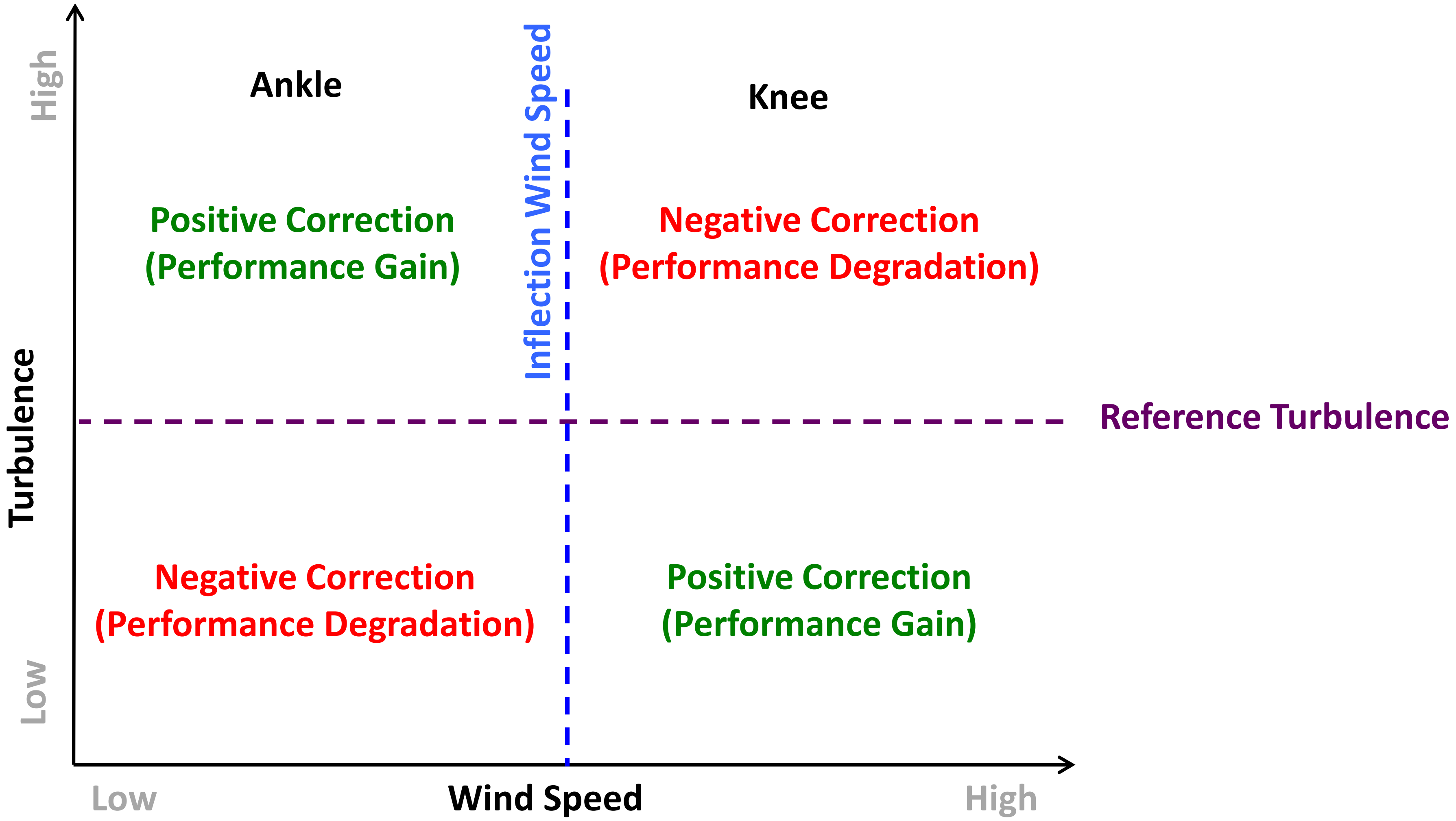


The above effect is essentially the inverse of the knee behaviour.

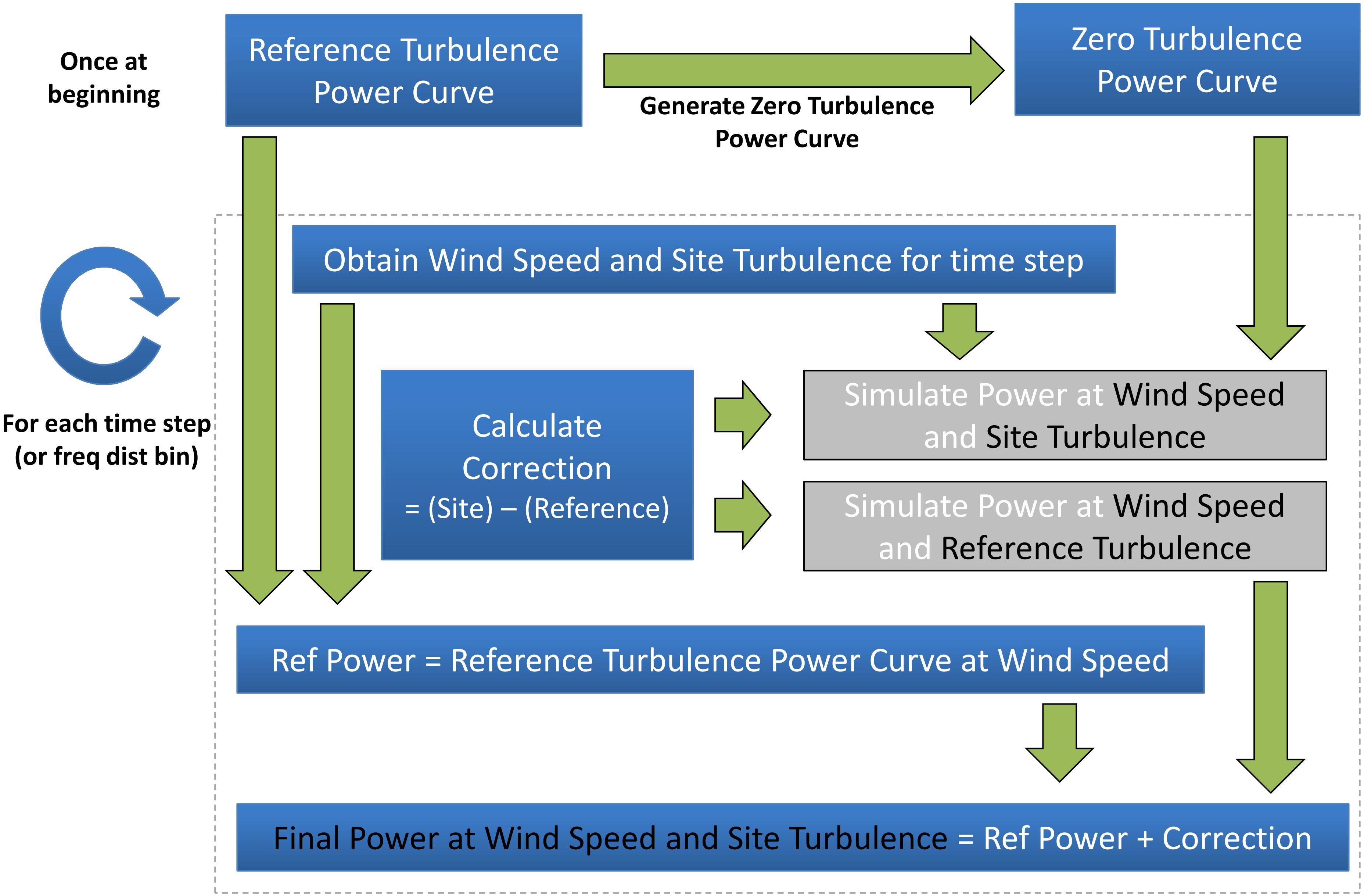
Note: mathematically speaking we can say this behaviour is because the second derivative of the power curve at the ankle (with respect to wind speed) is positive.

Overview of Impact of Applying Turbulence Correction (Resource Assessment Context)

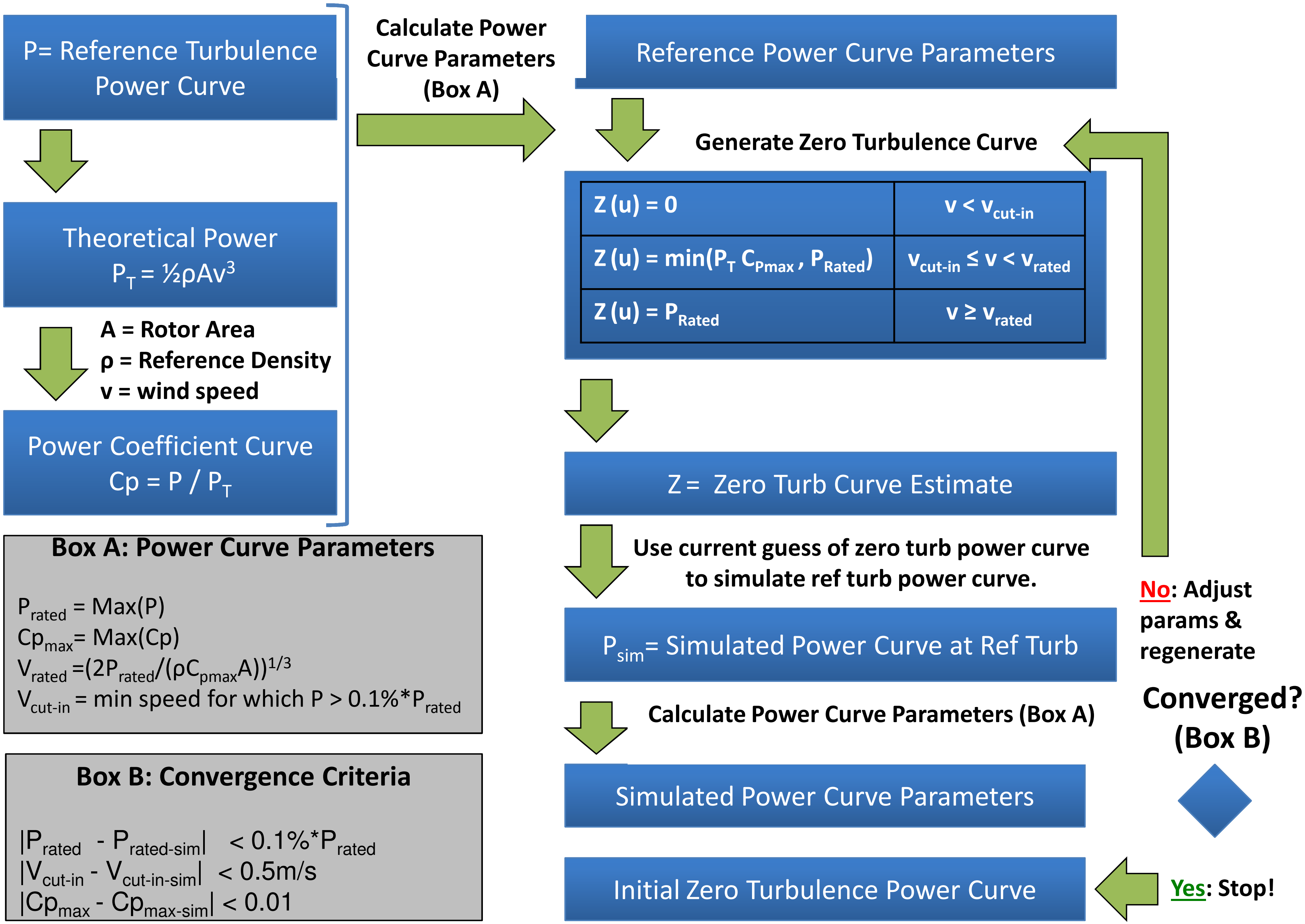
Correction = (Simulated Power at Site Turb) − (Simulated Power at Reference Turb)



Turbulence Turbulence Correction Flow Chart (Resource Assessment Context)



Initial Zero Turbulence Power Curve Generation Flow Chart



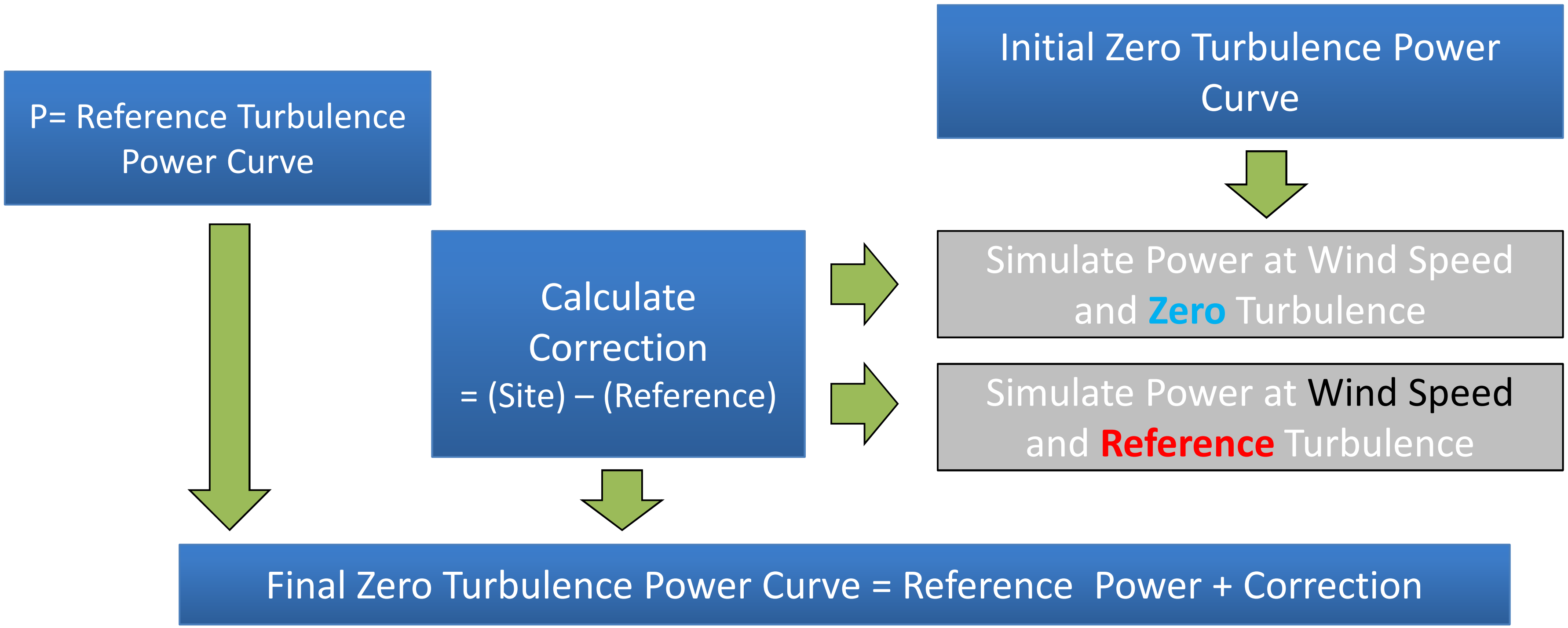
Final Zero Turbulence Power Curve Generation Flow Chart

The initial zero turbulence curve is refined using one final step. Using the Initial Zero turbulence Curve we derive a correction to change the reference turbulence curve to a new zero turbulence curve. To make this sound a little less confusing we can write this out as follows:

Correction = (End Point) − (Starting Point)

= (Simulated Power at Zero Turb) − (Simulated Power at Reference Turb)

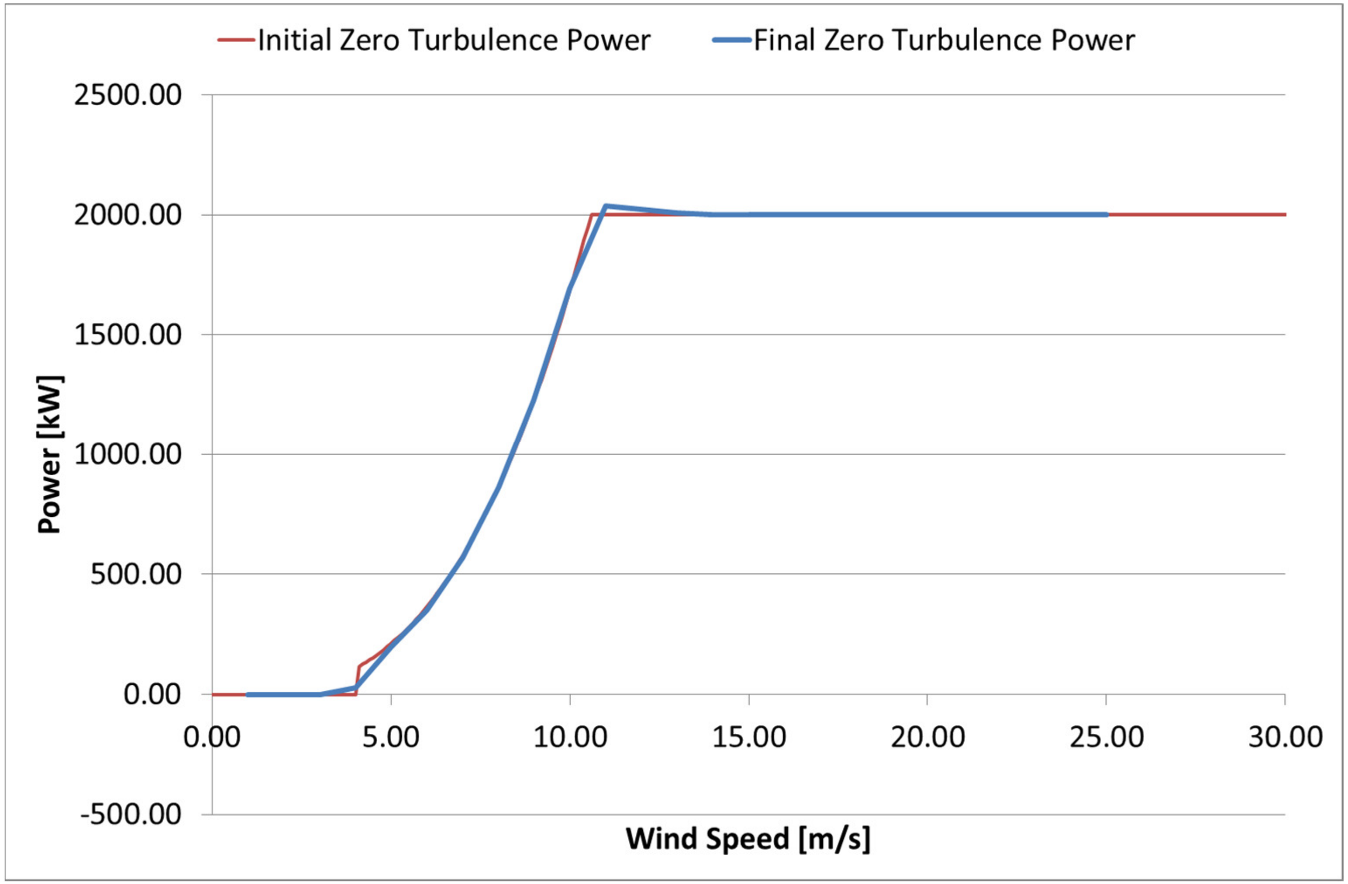
Which gives the following flow chart



Consequences of Final Calculation of Zero Turbulence Power Curve

- **Once consequence of the final calculation step of the zero turbulence power curve is that the final curve can exceed rated power. Although this is a non-physical result, it does tend improve the accuracy of the final application.**

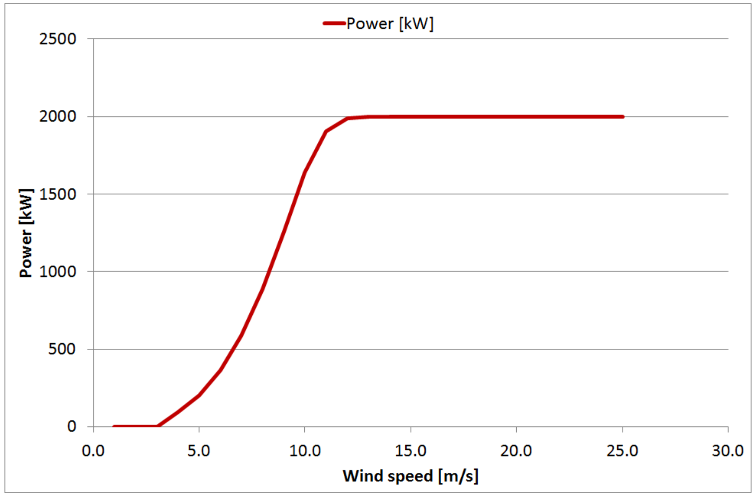
- **The final zero turbulence curve should therefore be thought of as the *"Zero Turbulence Curve which gives the best correction to the reference curve"* as opposed to being a true reflection of the instantaneous behaviour of the power curve.**

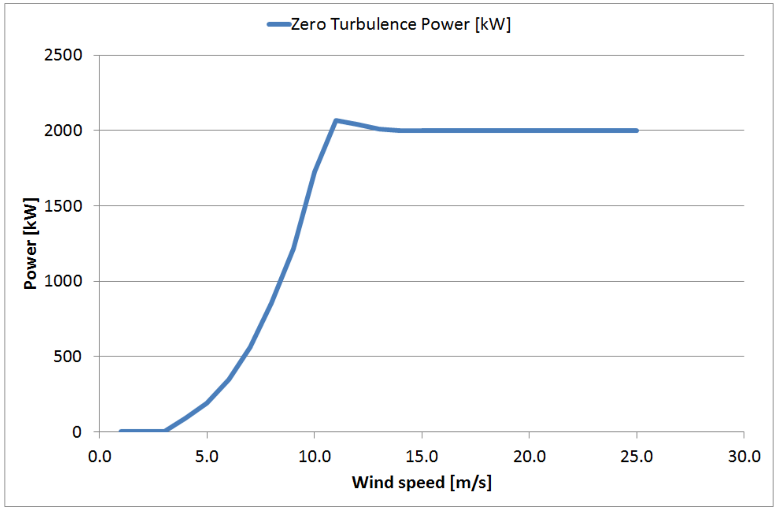


Turbulence Turbulence Correction Illustration (Resource Assessment Context)

Step 1. Reference Turbulence Power Curve → Zero Turbulence Power Curve

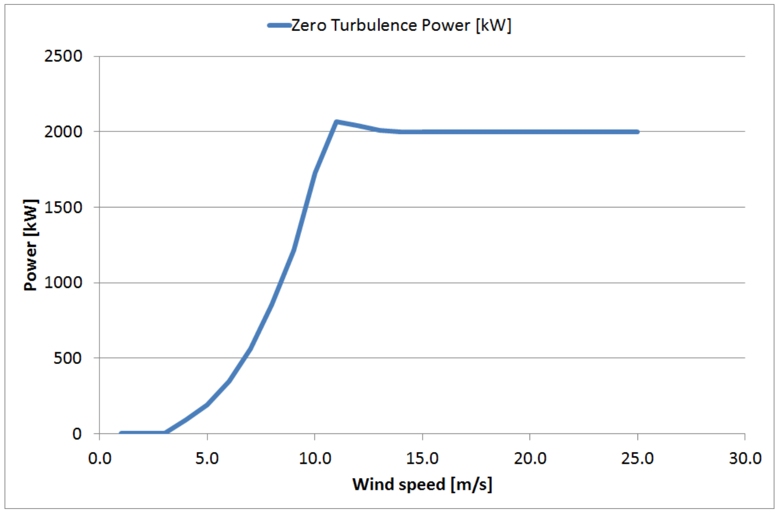
IEC 61400-12-1 Annex M.3

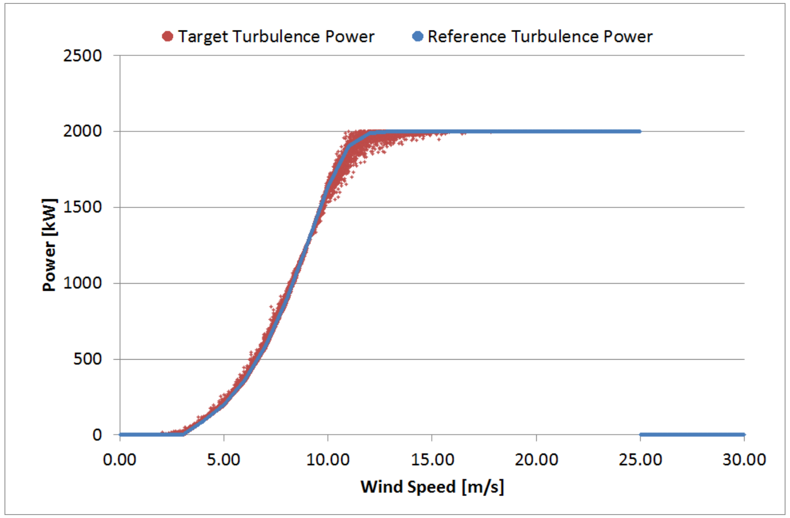




Step 2. Zero Turbulence Power Curve + Ref Power Curve → Target Turbulence Power Curve

IEC 61400-12-1 Annex M.2





Consensus Analysis Document Overview

Dropbox ▸ PowerCurveWorkingGroup ▸ Consensus Analysis ▸

- Dataset 1
- Dataset 2
- Dataset 3
- Consensus Power Look Up Generation.xlsx
- Consensus Zero Turbulence Power Curve Generation.xlsx

Step 1: The calculation of the power curve look up tables and the zero turbulence power curve is dataset independent.

Step 2: The calculation of the power curve at the target turbulence intensity is dataset dependent

Dropbox ▸ PowerCurveWorkingGroup ▸ Consensus Analysis ▸ Dataset 1

- Dataset 1 - Consensus Frequency Distribution Methods.xlsx
- Dataset 1 - Consensus Rotor Equivalent Wind Speed and Turbulence Renormalisation.xlsx
- Dataset 1 - Consensus Rotor Equivalent Wind Speed.xls
- Dataset 1 - Consensus Turbulence Renormalisation.xlsx

Dropbox ▸ PowerCurveWorkingGroup ▸ Consensus Analysis ▸ Dataset 2

- Dataset 2 - Consensus Turbulence Renormalisation.xlsx
- Dataset 2 - Consensus Rotor Equivalent Wind Speed.xls
- Dataset 2 - Consensus Rotor Equivalent Wind Speed and Turbulence Renormalisation.xlsx

Dropbox ▸ PowerCurveWorkingGroup ▸ Consensus Analysis ▸ Dataset 3

- Dataset 3 - Consensus Rotor Equivalent Wind Speed and Turbulence Renormalisation.xlsx
- Dataset 3 - Consensus Rotor Equivalent Wind Speed.xls
- Dataset 3 - Consensus Turbulence Renormalisation.xlsx

<u>Consensus Analysis Use of Excel Array Formulas</u>

- In order to make a pure excel implementation of the zero turbulence power curve possible **Excel Array Formulas** have been used.

- The array formulas are found in columns N and O of the 'Input Time Series' sheet (highlighted in blue) of 'Dataset X - Consensus Turbulence Renormalisation.xlsx'

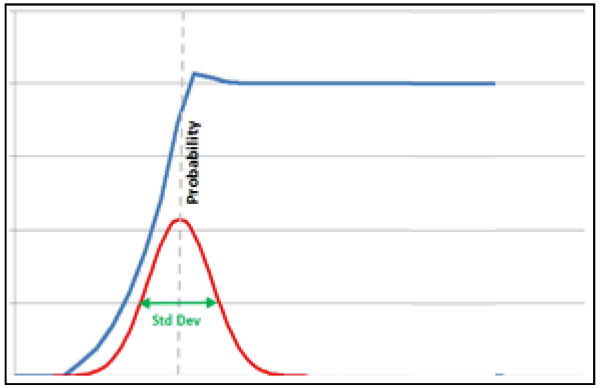
- Please note the following regarding array formulas:

  - Array formulas allow for very distilled operations e.g. element-wise multiplication of two columns and sum the result can be executed as 'sum(A:A*C:C)'.

  - Array formulas can be identified by their curly brackets e.g. {=sum(A:A*C:C)}.- In order for excel to execute an array formula you must press control+shift+return (instead of just return for non-array formulas)."

- For some simple examples on using Excel Array Formulas please see: http://www.mrexcel.com/articles/CSE-array-formulas-excel.php

Consensus Analysis Use of Excel Array Formulas



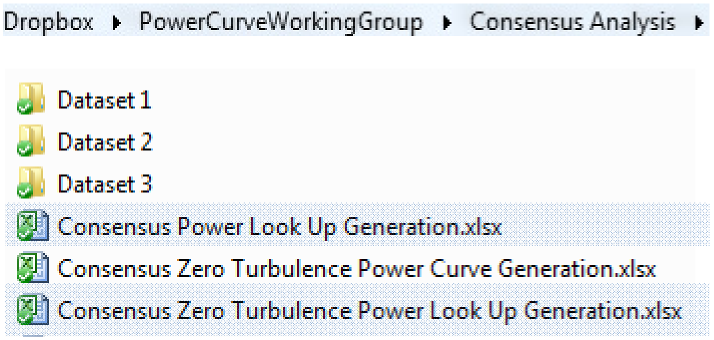
Excel Array formulae used to integrated probability distribution.

{=SUM(NORM.DIST($Q$3:$Q$1003,$F3,$N3,FALSE)*WindSpeedStep*$R$3:$R$1003)}

E	F	G	H	I	K	L	N	O	Q	R
					Array formulas: see description for info					
Time Stamp	Hub Wind Speed [m/s]	Turbulence [%]	Reference Turbulence Power	Site Speficic Turbulence Power [kW]	Simulated Reference	Simulated Site	Reference Std Dev	Site Std Dev	Wind Speed	Zero Turbulence Power
07/10/2011 12:50	15.50	13.55%	2000	1997	2001.4	1998.9	1.6	2.1	0.0	0.0
07/10/2011 13:00	15.70	12.23%	2000	1999	2001.2	2000.7	1.6	1.9	0.1	0.0
07/10/2011 13:10	16.66	12.06%	2000	2000	2000.5	2000.6	1.7	2.0	0.2	0.0
07/10/2011 13:20	15.20	15.79%	2000	1989	2001.8	1990.7	1.5	2.4	0.3	0.0
07/10/2011 13:30	15.43	13.67%	2000	1997	2001.5	1998.5	1.5	2.1	0.4	0.0
07/10/2011 13:40	14.41	14.92%	2000	1985	2002.9	1988.1	1.4	2.2	0.5	0.0
07/10/2011 13:50	15.11	14.03%	2000	1995	2001.9	1996.7	1.5	2.1	0.6	0.0
07/10/2011 14:00	14.98	14.15%	2000	1994	2002.1	1995.8	1.5	2.1	0.7	0.0
07/10/2011 14:10	15.61	14.99%	2000	1995	2001.3	1995.8	1.6	2.3	0.8	0.0
07/10/2011 14:30	15.00	13.80%	2000	1995	2002.1	1997.0	1.5	2.1	0.9	0.0
07/10/2011 14:40	14.40	13.06%	2000	1994	2003.0	1996.7	1.4	1.9	1.0	0.0
07/10/2011 14:50	13.88	12.75%	2000	1991	2003.5	1994.3	1.4	1.8	1.1	0.0
07/10/2011 15:00	13.01	12.68%	1999	1979	2000.5	1980.9	1.3	1.7	1.2	0.0
07/10/2011 15:10	12.77	11.67%	1996	1983	1997.5	1983.9	1.3	1.5	1.3	0.0
07/10/2011 15:20	13.34	12.59%	1999	1985	2002.6	1988.5	1.3	1.7	1.4	0.0
07/10/2011 15:30	12.93	15.93%	1998	1941	1999.6	1942.7	1.3	2.1	1.5	0.0
07/10/2011 15:40	12.14	13.34%	1990	1945	1979.8	1934.8	1.2	1.6	1.6	0.0
07/10/2011 15:50	12.65	15.42%	1995	1936	1995.4	1935.9	1.3	2.0	1.7	0.0
07/10/2011 16:00	13.02	11.98%	1999	1986	2000.6	1987.2	1.3	1.6	1.8	0.0
07/10/2011 16:10	12.95	10.73%	1998	1994	1999.9	1995.2	1.3	1.4	1.9	0.0
07/10/2011 16:20	12.45	12.93%	1993	1960	1990.8	1958.1	1.2	1.6	2.0	0.0
07/10/2011 16:30	12.01	12.16%	1988	1958	1973.5	1943.4	1.2	1.5	2.1	0.0
07/10/2011 16:40	11.75	12.34%	1967	1930	1956.9	1920.1	1.2	1.5	2.2	0.0
07/10/2011 16:50	11.43	10.94%	1940	1924	1927.7	1911.6	1.1	1.3	2.3	0.0
07/10/2011 17:00	10.59	11.14%	1795	1775	1787.5	1768.2	1.1	1.2	2.4	0.0

ory | Description | Input Time Series | Power Look Up | Zero Turbulence Curve | Reference vs Site Specific

Consensus Analysis Use of Reference Power Curve Look Up Table



Step 2 involves many individual interpolations of power curves. In order to excessive calculations times in Excel a reference power curve look-up table is first generated.

N.B. Although convenient the use of the look-up tables is not core to either the rotor equivalent wind speed or turbulence renormalisation methodologies i.e. it is perfectly acceptable not to use a look-up table and directly interpolate the reference power curve.

Consensus Analysis Power Curve Look Up

- Used to simplify and speed up excel calculations
- Defined using linear interpolation of the input power curve with a wind speed interval of 0.01m/s.
- The interval of 0.01m/s means that the table index is given by Round(WindSpeed* 100, 0)
- An Excel defined name is used to reference the look up table called PowerArray
- The look up is applied using Excel formula Index(PowerArray, Round(WindSpeed* 100, 0))