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Internship

Power curve uncertainty analysis

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List of Abbreviations

B	the number of blades	$-$
C_P	the power coefficient	$-$
C_d	the drag coefficient	$-$
C_l	the lift coefficient	$-$
$F(V_i)$	Rayleigh cumulative probability distribution function for wind speed in bin i	$-$
F_N	the normal force	N
H	the height	m
H_{hub}	the hub height	m
H_{low}	the lower tip height	m
N	Number of bins	$-$
N_h	Number of hours in one year (8760)	h
N_i	number of 10min data sets in wind speed bin i	$-$
N_j	the number of wind speed ratios in wind direction bin j	$-$
P	the air pressure	hPa
P_{el}	the electric power	kW
P_i	Normalized, averaged power output in bin i	kW
$P_{n,i,j}$	Normalized power output of data set j in wind speed bin i	kW
P_{vapor}	the partial vapor pressure	Pa
Q	the differential torque	Nm
R	the specific gas constant for dry air	$J/kg/K$
RH	the relative humidity	$\%$
T	the temperature	$^\circ C$
T	the thrust	N
TI	the turbulence intensity	$-$
T_{kelvin}	the temperature	K
U	the wind speed	m/s
U_{rel}	the relative wind speed	m/s
V	the wind speed at hub height	m/s
V_{ave}	annual average wind speed at hub height	m/s
V_{cor}	the density corrected wind speed at hub height	m/s
V_i	Normalized, averaged wind speed in bin i	m/s
V_{low}	the wind speed at the lower tip	m/s

$V_{n,i,j}$	Normalized wind speed of data set j in wind speed bin i	m/s
V_{std}	the standard deviation in the wind speed	m/s
Ω	the angular velocity of the wind turbine rotor	rad/s
α	the wind shear	$-$
ρ	the air density	kg/m^2
ρ	the air density	kg/m^3
σ'	the solidity	$\frac{1}{rad}$
$\sigma_{P,i}$	the standard deviation of the normalized power data in bin i	kW
φ	the relative angle of attack	m/s
a	the induction factor	$-$
a'	the differential induction factor	$-$
c	the chord length	m
$c_{V,i}$	the sensitivity factor for the uncertainty in wind speed to uncertainty in electric power	$\frac{kW}{m/s}$
f_i	the average probability of wind speed in bin i	$-$
r	the radius	m
$s_{\alpha,j}$	the standard deviation of wind speed ratios in wind direction bin j	m/s
s_i	the category A uncertainty	kW
u_{AEP}	the combined standard uncertainty in the annual energy production	kWh
$u_{V,i}$	the uncertainty from wind speed in bin i	m/s
$u_{V1,i}$	the uncertainty of the anemometer calibration in bin i	m/s
$u_{V2,i}$	the uncertainty due to operational characteristics of the anemometer in bin i	m/s
$u_{V3,i}$	the uncertainty of flow distortion due to mounting effects in bin i	m/s
$u_{V4,i,j}$	the uncertainty from the site calibration in wind speed bin i and wind direction bin j	m/s
$u_{V4,i}$	the uncertainty of flow distortion due to the terrain in bin i	m/s
$u_{c,i}$	the combined uncertainty in electric power	kW
$u_{dV,i}$	the uncertainty in the data acquisition system for the wind speed in bin i	m/s
u_i	the category B uncertainty	kW

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AEP	annual energy production	Wh
MATLAB®	A programming environment for algorithm development, data analysis, visualization, and numerical computation.	
Method of bins	A data reduction procedure that groups test data for a certain parameter into wind speed intervals(bins) [IEC 2005]	
PCstat	MATLAB® program developed by Frank Goezinne and Leon Eilders that analyzes power curve measurement data, incorporating uncertainty evaluations and statistical rejection of outliers.	

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CHAPTER 1

Introduction

Contents

1.1 Part I: Power curve uncertainty analysis

The Suzlon [redacted] wind turbine in Snowtown (Australia) has been measured by the certifying body DEWI in August-September 2011. DEWI has delivered the data to Suzlon, together with a report [Bégué 2011]. This report not only shows the turbine performance but also the expected uncertainty of the performance.
Suzlon used the same data to establish the power curve, using a recent developed MATLAB® program named PCstat. The first part of this study focuses on the further development of PCstat to analyze the data from power curve measurements, focusing on incorporating uncertainty evaluations into Suzlon's own analysis tool. The results will be compared against the findings by DEWI [Bégué 2011].
The full description of the internship assignment can be found in Appendix A.

1.1.1 PCstat's layout

PCstat was initially designed by Frank Goezinne and has been modified by Leon Eilders to incorporate an uncertainty analysis. It requires two data sheets, firstly, the 10 minute averaged measurement data from a test site with a calibration sheet, secondly, the uncertainty values for each component. Both should be supplied in excel format. The complete structure of the MATLAB® program is shown in Figure 1.1.

1.2 Part II: Trend analysis

In the second part of this study, the basics of a trend analysis is explained as well as an example MATLAB® script.

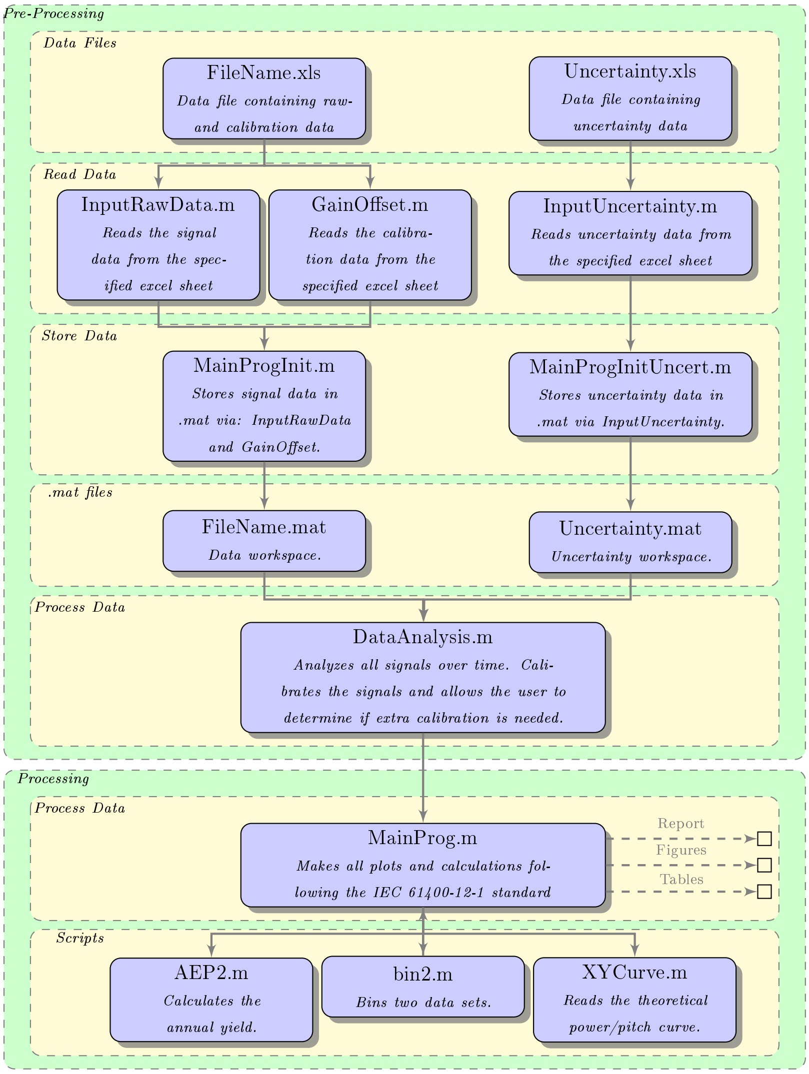

Figure 1.1: Flowchart of PCstat

1.3 Part III: Uncertainty progression Flex

The FLEX program calculates a theoretical power curve using both Blade Element Momentum (BEM) Theory and an experimentally obtained $\alpha/C_L, C_D$ table. The third part of this study focuses on propagating the measurement uncertainty in C_L and C_D through the BEM calculations.

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Part I

Power curve uncertainty analysis

CHAPTER 2

Theory

Contents

2.1 Method of bins

Throughout this study all binned values are calculated according to the 'Method of bins'. This method reduces the test data into intervals (bins) and gives the normalized and averaged value for all the data inside that bin. Normalizing is the process of isolating statistical error in repeated measurement data. The 'Method of bins' is shown for the wind speed and electric power in Equation 2.1 and Equation 2.2 resp..

$$V_i = \frac{1}{N_i} \sum_{j=1}^{N_i} V_{n,i,j} \tag{2.1}$$

$$P_i = \frac{1}{N_i} \sum_{j=1}^{N_i} P_{n,i,j} \tag{2.2}$$

Where:
V_i is the normalized and averaged wind speed in wind speed bin i $[m/s]$
$V_{n,i,j}$ is the normalized wind speed of data set j in wind speed bin i $[m/s]$
P_i is the normalized and averaged power output in wind speed bin i $[kW]$
$P_{n,i,j}$ is the normalized power output of data set j in wind speed bin i $[kW]$
N_i is the number of 10min data sets in wind speed bin i $[-]$

2.2 Annual Energy Production

The annual energy production (AEP) is the estimate of the total energy production of a wind turbine during a one-year period by applying the measured power curve to different reference wind speed frequency distributions at hub height, assuming 100% availability (Equation 2.3).[IEC 2005]

$$AEP = N_h \sum_{i=1}^{N} \left[\frac{(F(V_{i+1}) - F(V_i)) + (F(V_i) - F(V_{i-1}))}{2} \right] \left(\frac{\left(\frac{P_{i-1}+P_i}{2}\right) + \left(\frac{P_{i+1}+P_i}{2}\right)}{2} \right) \tag{2.3}$$

Where:
AEP is the annual energy production $[Wh]$
$F(V_i)$ is the Rayleigh cumulative probability distribution function for wind speed in bin i $[-]$ (Equation 2.4)
N_h is the number of hours in one year (8760) $[h]$
N is the number of bins $[-]$
V_i is the normalized and averaged wind speed in bin i $[m/s]$
P_i is the normalized and averaged power output in bin i $[kW]$

A Rayleigh distribution (Equation 2.4), which is identical to a Weibull distribution with a shape factor of 2, has been used as the reference wind speed frequency distribution.

$$F(V_i) = 1 - e^{\left(-\frac{\pi}{4}\left(\frac{V_i}{V_{ave}}\right)^2\right)} \tag{2.4}$$

Where:
$F(V_i)$ is the Rayleigh cumulative probability distribution function for wind speed in bin i $[-]$
V_{ave} is the annual average wind speed at hub height $[m/s]$
V_i is the normalized and averaged wind speed in bin i $[m/s]$

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2.3 Wind speed to standard air density

The measured wind speed has to be density corrected. The density can be calculated using the obtained pressure and temperature signal. As the pressure is measured at ground level it has to be corrected to hub height according to Equation 2.5.

$$P = P * e^{\frac{\left(\frac{-9.81*H}{287.05}\right)}{T+273.05}} \tag{2.5}$$

Where:
P is the air pressure $[hPa]$
H is the height $[m]$
T is the temperature $[°C]$

According to [IEC 2005] (page 20 formula 1) the air density may be determined from measured air temperature and air pressure according to Equation 2.6. If the humidity was high during the measurement period, the density can also be humidity corrected. Therefore the partial vapor pressure needs to be calculated (Equation 2.7) before a correction factor can be added to the density calculation (Equation 2.8).

$$\rho = \frac{P * 100}{R * T_{kelvin}} \tag{2.6}$$

$$P_{vapor} = T^3 * 0.0731 - T^2 * 0.2188 + T * 59.856 + 592.56 \tag{2.7}$$

$$\rho = \frac{P * 100}{R * T_{kelvin}} * \left(1 - 0.378 * \frac{RH}{100} * \frac{P_{vapor}}{P * 100}\right) \tag{2.8}$$

Where:
T_{kelvin} is the temperature $[K]$
ρ is the air density $[kg/m^2]$
R is the specific gas constant for dry air $[J/kg/K]$
P_{vapor} is the partial vapor pressure $[Pa]$
RH is the relative humidity $[\%]$

According to [IEC 2005] (page 21 formula 3) for a wind turbine with active power control, the normalization shall be applied to the wind speed according to Equation 2.9. (assuming a standard air density of $1.225 kg/m^3$)

$$V_{cor} = V * (\frac{\rho}{1.225})^{\frac{1}{3}} \tag{2.9}$$

Where:
V is the wind speed at hub height $[m/s]$
V_{cor} is the density corrected wind speed at hub height $[m/s]$

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The power coefficient, Turbulent intensity and wind shear are calculated according to Equation 2.10,Equation 2.11 and Equation 2.12 resp.

$$C_P = \frac{P_{el} * 1000}{V^3 * \frac{1}{2} * 1.225 * A} \tag{2.10}$$

$$TI = \frac{V_{std}}{V} \tag{2.11}$$

$$\alpha = \frac{log\left(\frac{V}{V_{low}}\right)}{log\left(\frac{H_{hub}}{H_{low}}\right)} \tag{2.12}$$

Where:
H_{hub} is the hub height $[m]$
H_{low} is the lower tip height $[m]$
V_{std} is the standard deviation in the wind speed $[m/s]$
V_{low} is the wind speed at the lower tip $[m/s]$
P_{el} is the electric power $[kW]$
C_P is the power coefficient $[-]$
TI is the turbulence intensity $[-]$
α is the wind shear $[-]$

2.4 Statistical data rejection

In this study data is rejected using the $Chauvenet's\ criterion$. Data points can be considered for rejection if the probability of obtaining their deviation from the mean value is less than $\frac{1}{2N}$ where N is the number of data points in the sample. [Coleman & Steele 1998] The maximum deviation away from the mean value is calculated using the normal inverse cumulative distribution function (Equation 2.13).

$$x = F^{-1}(p|\mu, \sigma) \tag{2.13}$$

Where:

$$p = F(x|\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{-(t-\mu)^2}{2\sigma^2}}\, dt \tag{2.14}$$

The integral of the cumulative distribution function (Equation 2.14) cannot be evaluated in closed form. The MATLAB® function *norminv*, which is part of the statistical toolbox, computes the confidence bounds for p using a normal approximation.[The MathWorks, Inc] When this toolbox is not available, the inverse cumulative distribution function can also be computed by a function in the Python toolbox scipy called scipy.stats.norm.ppf.[The Scipy community]

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2.5 Uncertainty

Uncertainty in the power curve measurement can be divided into two categories A and B. An uncertainty expressed as an uncertainty limit should be properly converted into a standard uncertainty. A standard uncertainty is equal to one standard deviation (eg. $1 * \sigma$). If a rectangular probability distribution is assumed: Equation 2.15, or if a triangular probability distribution is assumed: Equation 2.16. All uncertainty components as stated in [IEC 2005] are shown in Table 2.1

$$\sigma = \frac{U}{\sqrt{3}} \tag{2.15}$$

$$\sigma = \frac{U}{\sqrt{6}} \tag{2.16}$$

Where:
U is the uncertainty limit
σ is the standard uncertainty

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Table 2.1: List of categories B and A uncertainties (from [IEC 2005])

Category B: Instruments		Note	Standard	Uncertainty	Sensitivity
Power output				$u_{P,i}$	$c_{P,i} = 1$
Current transformers	*	a	IEC 60044-1	$u_{P1,i}$	
Voltage transformers	*	a	IEC 60044-2	$u_{P2,i}$	
Power transducer	*	a	IEC 60688	$u_{P3,i}$	
Power measurement device	*	c		$u_{P4,i}$	
Data acquisition system	*			$u_{P5,i}$	
Wind speed				$u_{V,i}$	$c_{V,i} = \left\lvert \frac{P_i - P_{i-1}}{V_i - V_{i-1}} \right\rvert$
Anemometer	*	b		$u_{V1,i}$	
Operational characteristics	*	cd		$u_{V2,i}$	
Mounting effects	*	c		$u_{V3,i}$	
Flow distortion due to terrain	*	bc		$u_{V4,i}$	
Data acquisition system	*			$u_{P5,i}$	
Air density					
Temperature				$u_{T,i}$	$c_{T,i} = \frac{P_i}{288{,}15K}$
Temperature sensor	*	a		$u_{T1,i}$	
Radiation shielding	*	cd		$u_{T2,i}$	
Mounting effects	*			$u_{T3,i}$	
Data acquisition system	*			$u_{T4,i}$	
Air pressure			ISO 2533	$u_{B,i}$	$c_{B,i} = \frac{P_i}{1013hPa}$
Pressure sensor	*	a		$u_{B1,i}$	
Mounting effects	*	cd		$u_{B2,i}$	
Data acquisition system	*			$u_{B3,i}$	
Method				$u_{m,i}$	$c_{T,i}$ and $c_{B,i}$
Air density correction		cd		$u_{m1,i}$	
Category A: Statistical					
Electric power		e		$s_{P,i}$	$c_{P,i} = 1$
Climatic variations		e		s_w	—

* parameter required for the uncertainty analysis

NOTE Identification of uncertainties:
a=reference to standard;
b=calibration;
c=other ‘objective’ method;
d=‘guestimate’;
e=statistics.

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2.5.1 Category A uncertainty

Category A uncertainties are statistical uncertainties as the variability in electric power (Equation 2.18) and the uncertainties in climatic variations.

$$\sigma_{P,i} = \sqrt{\frac{1}{N_i - 1}\sum_{j=1}^{N_i}(P_i - Pn,i,j)^2} \tag{2.17}$$

Where:
$\sigma_{P,i}$ is the standard deviation of the normalized power data in bin i $[kW]$
N_i is the number of 10 min data sets in bin i $[-]$
P_i is the normalized and averaged power output in bin i $[kW]$
$P_{n,i,j}$ is the normalized power output of data set j in bin i $[kW]$

$$s_{P,i} = \frac{\sigma_{P,i}}{\sqrt{N_i}} \tag{2.18}$$

Where:
$s_{P,i}$ is the category A standard uncertainty of power in bin i $[kW]$

2.5.2 Category B uncertainty

Category B uncertainties are assumed to be related to the instruments, the data acquisition system, and the terrain surrounding the power performance test site. [IEC 2005]

Components expressed as a standard uncertainty, can be added as shown for the uncertainty in wind speed in Equation 2.19 .

$$u_{V,i} = \sqrt{u_{V1,i}^2 + u_{V2,i}^2 + u_{V3,i}^2 + u_{V4,i}^2 + u_{dV,i}^2} \tag{2.19}$$

Where:
$u_{V,i}$ is the uncertainty from wind speed in bin i $[m/s]$
$u_{V1,i}$ is the uncertainty of the anemometer calibration in bin i $[m/s]$
$u_{V2,i}$ is the uncertainty due to operational characteristics of the anemometer in bin i $[m/s]$
$u_{V3,i}$ is the uncertainty of flow distortion due to mounting effects in bin i $[m/s]$
$u_{V4,i}$ is the uncertainty of flow distortion due to the terrain in bin i $[m/s]$
$u_{dV,i}$ is the uncertainty in the data acquisition system for the wind speed in bin i $[m/s]$

When a site calibration has been undertaken, the uncertainty from the site calibration shall be included as the uncertainty of the flow distortion due to the terrain $u_{V4,i}$.(Equation 2.20)

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$$u_{V4,i} = \frac{\sum_{j} u_{V4,i,j} N_{i,j}}{\sum_{j} N_{i,j}} \tag{2.20}$$

Where:
$u_{V4,i,j}$ is the uncertainty from the site calibration in wind speed bin i and wind direction bin j $[m/s]$(Equation 2.21)

$$u_{V4,i,j} = \sqrt{2u_{V1,i}^2 + 2u_{dV,i}^2 + \frac{s_{\alpha,j}^2 V_i^2}{N_j}} \tag{2.21}$$

Where:
$s_{\alpha,j}$ is the standard deviation of wind speed ratios in wind direction bin j $[m/s]$
N_j is the number of wind speed ratios in wind direction bin j $[-]$

To combine the category A and B uncertainties, the uncertainty components are multiplied by their sensitivity factors (Equation 2.23). For the uncertainty in wind speed the sensitivity factor is the slope of the power curve (Equation 2.22 and Table 2.1).

$$c_{V,i} = \left| \frac{P_i - P_{i-1}}{V_i - V_{i-1}} \right| \tag{2.22}$$

$$u_{c,i} = \sqrt{s_i^2 + u_i^2} = \sqrt{s_i^2 + uP,i^2 + c_{V,i}^2 * u_{V,i}^2 + c_{T,i}^2 * u_{T,i}^2 + c_{B,i}^2 * u_{B,i}^2} \tag{2.23}$$

With all the uncertainty components calculated, the uncertainty in the annual energy production can be calculated according to Equation 2.24.

$$u_{AEP} = N_h * \sqrt{\sum_{i=1}^{N} f_i^2 * s_i^2 + \left(\sum_{i=1}^{N} f_i * u_i \right)^2} \tag{2.24}$$

Where:
u_{AEP}, the combined standard uncertainty of AEP $[kWh]$
s_i is the category A uncertainty $[kW]$
u_i is the category B uncertainty $[kW]$
f_i is the average probability of wind speed in bin i $[-]$(Equation 2.25)

$$f_i = \left(\frac{(F(V_{i+1}) - F(V_i)) + (F(V_i) - F(V_{i-1}))}{2} \right) \tag{2.25}$$

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Where:
$F(V_i)$ is the Rayleigh cumulative probability distribution function for wind speed in bin i $[-]$(Equation 2.4)

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Chapter 3

Matlab® program: PCstat

Contents

This chapter will explain the workings of PCstat. The complete layout is shown in Figure 1.1. Examples of produced figures and tables will be given for the data from Snowtown II, Australia.

3.1 Pre-Processing

Before the main program can process the data, the data has to be pre-processed to make sure it is in the right format and well calibrated.

3.1.1 Data Files

The data files are two Excel files. One containing the 10 minute averaged measurement data from a test site, calibration data and theoretical power curve data. The other contains the standard uncertainties for each component specified in Table 2.1. There are certain constraints to the format of these Excel files, for the 10 minute averaged measurement data:

- Data set starts at cell A1
- First row contains sensor names
- First column contains the data-time stamp
- Cells outside the dataset should really be empty

for the uncertainty data:

- Data set starts at cell A1
- First row contains uncertainty names
- Cells outside the dataset should really be empty

3.1.2 Read Data

The data is read by 'InputRawData.m", 'GainOffset' and 'InputUncertainty.m'.

3.1.3 Store Data

"MainProgInit.m' and 'MainProgInitUncert.m' call the scripts mentioned in subsection 3.1.2. The data is then stored in '.mat' files. 'MainProgInit.m' only needs to run one time as 'DataAnalysis.m' and 'MainProg.m' will only look for the produced '.mat' files.

3.1.4 Process Data

With the data stored in '.mat' format for MATLAB® to use, 'DataAnalysis.m' is used to analyze the data. First the file needs to be edited to match the used variables to the signal names used in the original Excel file as well as turbine specific data like: Cut-in, Cut-out, Hub-height and Diameter.

The next step is to run the first part of the script. Here the raw data is calibrated using the gain and offset specified in the excel sheet (Equation 3.1). The total timespan is calculated and all signals are plotted against time. An example is given in Figure 3.1 showing the wind speed signal versus time.

$$X_{calibrated} = X_{raw} * X_{Gain} + X_{Offset} \tag{3.1}$$

Where:
$X_{calibrated}$ is the calibrated dataset
X_{raw} is the raw dataset
X_{Gain} is the calibration gain
X_{Offset} is the calibration offset

All time figures should be analyzed. Abrupt changes in the signal are often a sign that the recorded signal changed. This should be investigated and when needed extra calibration should take place. Also the maximum values should be looked at closely, when these are different from normal values there might be a difference in units. For instance the power could be in W instead of kW, this should be corrected as the main program will expect kW as the unit for power.

An example of a signal change is shown in Figure 3.2. The signal changed from a 0 - 3600 degree range to a 0 - 360 degree range. The gain factor used for calibration should be 1 instead of 0.1 for the data after Time=450. Also the offset is not corrected for, angles above 360 degrees should be corrected so that they start at 0 degree again (Equation 3.2). The correctly calibrated wind direction signals are shown in Figure 3.3.

$$W_{cor} = W - 360 \qquad for : W > 360 \tag{3.2}$$

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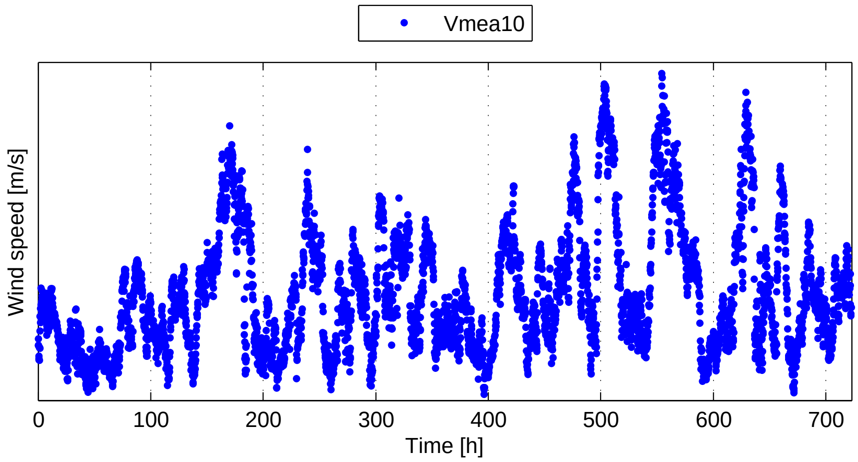

Figure 3.1: Wind speed versus Time

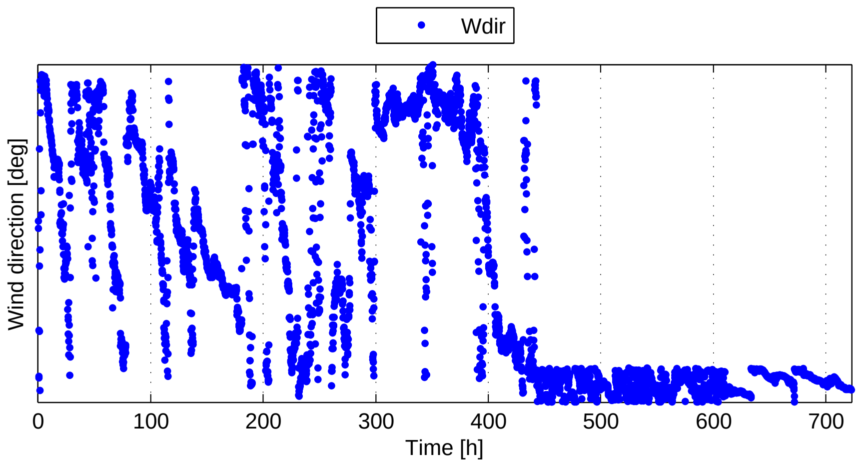

Figure 3.2: Wind speed versus Time

When the calibration is satisfactory the last part of the analysis can be run. The density is calculated and the wind speed is calculated (see section 2.3). When this part of the script passes without error 'MainProg.m' can be edited and run.

3.2 Processing

The steps needed to calibrate the data are now known and can be copied to 'MainProg.m' together with the 'Generic variable' definitions and site specifications. The filter settings need to be adapted to match the site characteristics (eg. Measurement sectors). With the pre-processing done the actual processing can be started.

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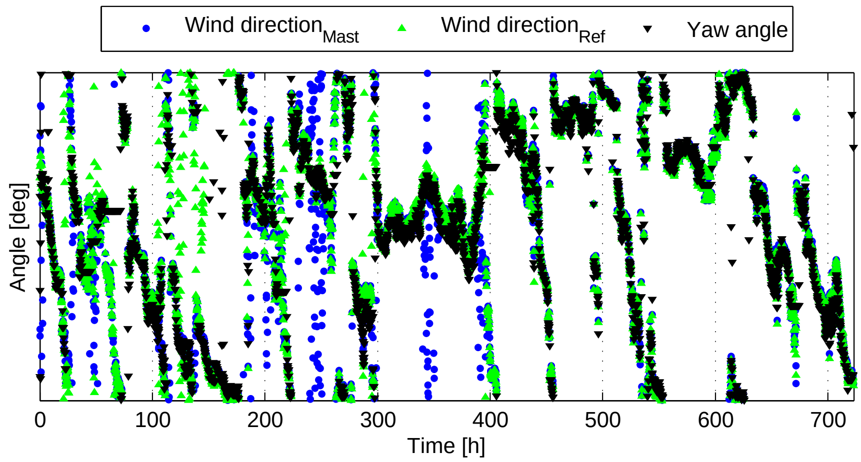

Figure 3.3: Wind direction, reference wind direction and yaw angle versus Time

The pressure is corrected to the hub height (Equation 2.5) and density is calculated using Equation 2.6 or with humidity correction Equation 2.8.(Figure 3.4)

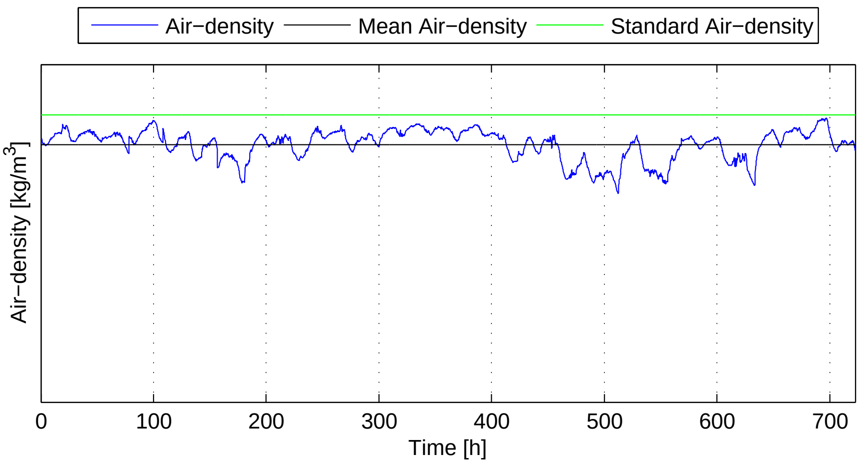

Figure 3.4: Air density, Averaged air density and Standard air density versus Time

The wind speed is density corrected using Equation 2.9 and the Power Coefficient, Turbulent Intensity and Wind Shear are calculated according to Equation 2.10, Equation 2.11 and Equation 2.12 resp. Next the data is filtered where all data outside the specified filter is rejected. It was found that after the normal filters are applied, some outliers might still be present. Therefore the user is presented a choice to apply a statistical filter that will reject outliers. First the program looks for outliers in the difference between the wind speed measured at the meteorological

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mast and the nacelle (Figure 3.5). The second outlier-rejection is based on the power curve. A section of the curve is analyzed and outliers in this section are rejected. This way data point that are clearly wrong (eg. high electric power output at low wind speeds (high C_p)) can be rejected on a scientific basis (section 2.4).

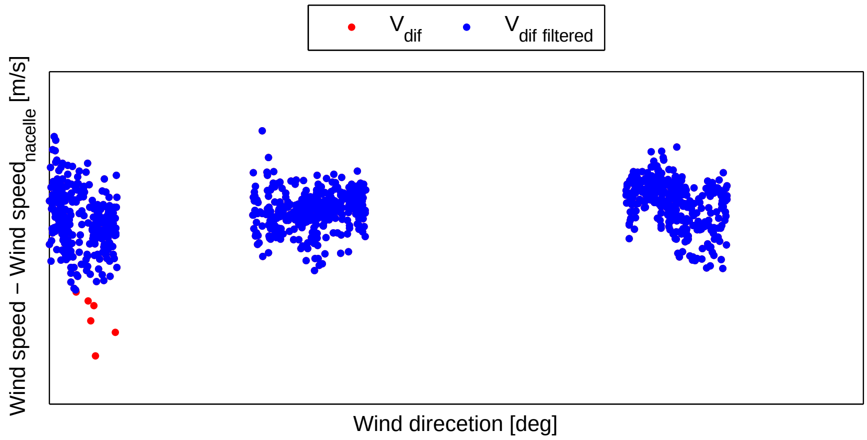

Figure 3.5: Comparison of power curve before and after data rejection

'MainProg.m' will now start the data evaluation as stated in IEC 61400-12-1 [IEC 2005] starting with the power curve plots. Some data will be presented in bins. The bins are calculated using the 'Method of bins' explained in section 2.1.

The uncertainty is calculated as shown in section 2.5. When a site calibration is performed, the fixed value (3% - 4%) for the uncertainty in wind speed due to terrain $u_{V4,i}$ is changed to the uncertainty in site calibration and is calculated acording to Equation 2.20.

The power curve is incomplete when during the measurement period wind speeds up to cut-out are not reached. To evaluate the AEP it is therefore needed to extrapolate the power curve. This is done by filling the empty bins below the lowest recorded wind speed with 0kW electric power output and the empty bins above the highest recorded wind speed with the power output of that wind speed bin(Figure 3.6). This is then compared to the theoretical power curve (Figure 3.7).

The AEP is then calculated as explained in section 2.2 and compared with the theoretical AEP (Figure 3.8). The extrapolated AEP can, if available, also be compared with results from third parties.(Figure 3.9)

Once the program is finished it will ask the user if it should generate a report. If the user chooses to do so, the program will generate a PDF file stating the applied filters and report the results of the power curve measurements as prescribed in [IEC 2005]. An example of such a report is given in Appendix B. This report is generated by MATLAB® via a LaTeXtemplate.

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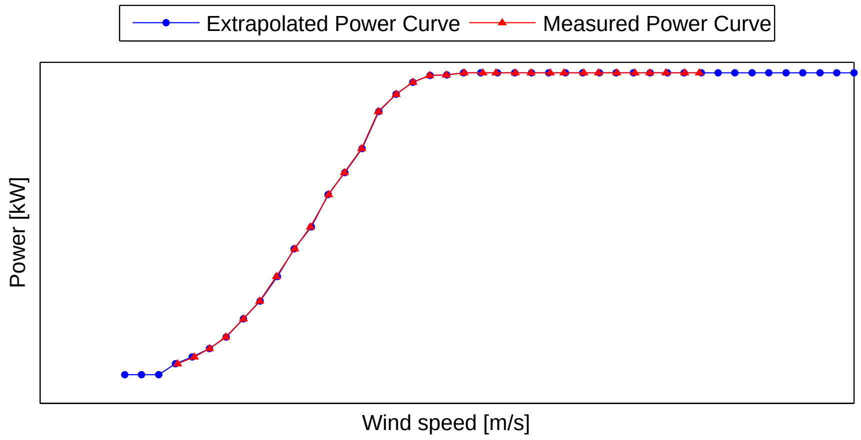

Figure 3.6: Extrapolated power curve and Measured power curve versus wind speed

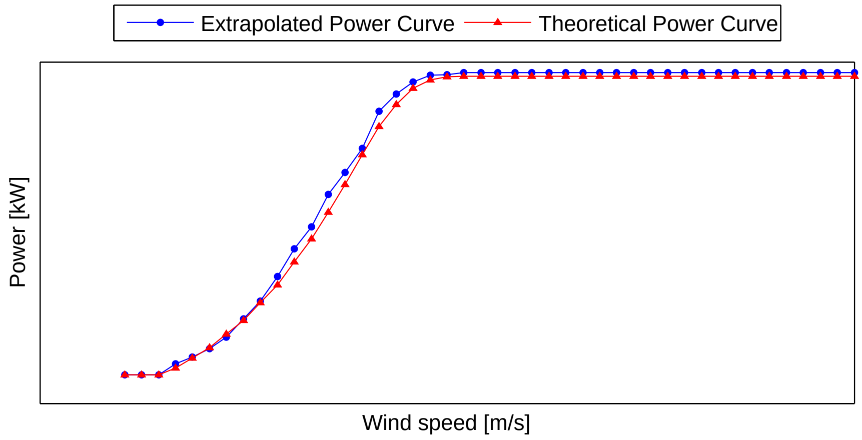

Figure 3.7: Extrapolated power curve and Theoretical power curve versus wind speed

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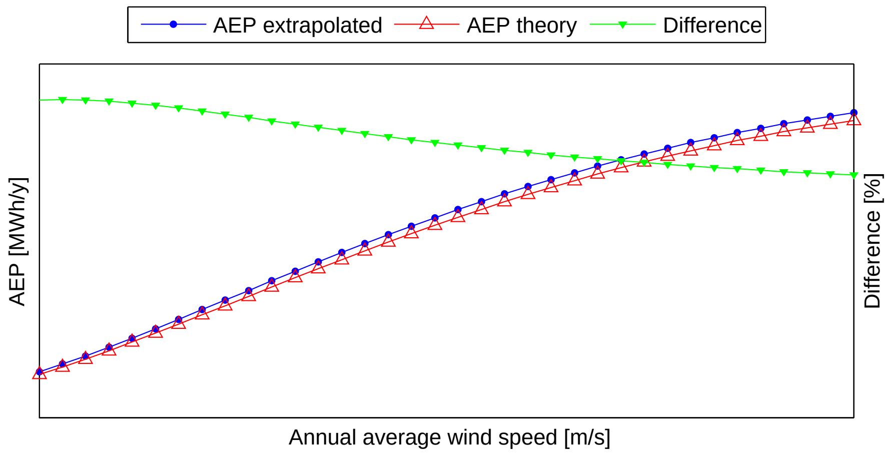

Figure 3.8: Calculated annual energy production for the extrapolated and theoretical power curve

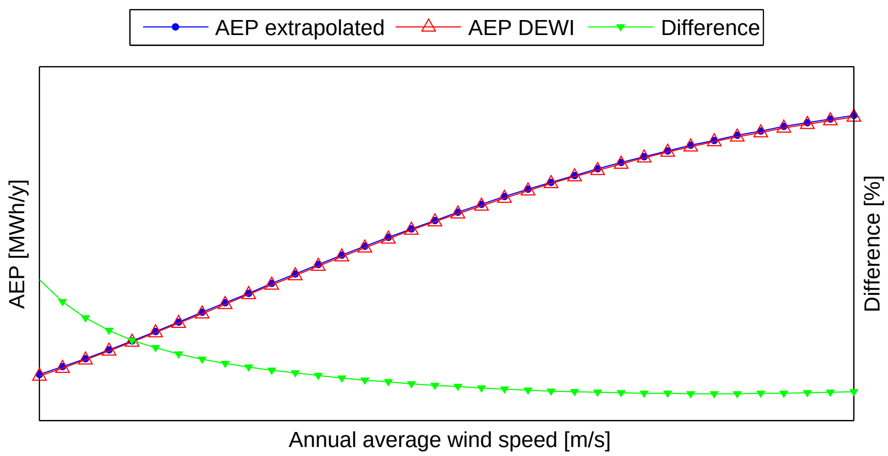

Figure 3.9: Calculated annual energy production for the extrapolated and DEWI power curve

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Part II

Trend Analysis

CHAPTER 4

Basic Trend Analysis

The objective is to check how the power performance of a wind turbine for a given wind speed range varies over time. All data is therefore filtered for a given wind speed range (for example 0.5 - 1.5 m/s so 1m/s). The selected data can be plotted (Time vs Power production). This shows the trend over time for a given wind speed range. To make the trend more obvious and easy to read a second order polynomial is fitted through all the data points. The green line in Figure 4.1 is the polynomial fit. The black line is a moving average. All polynomials can be compared to get a more complete picture of the power performance trend Figure 4.2. A MATLAB® template can be found in Appendix C.

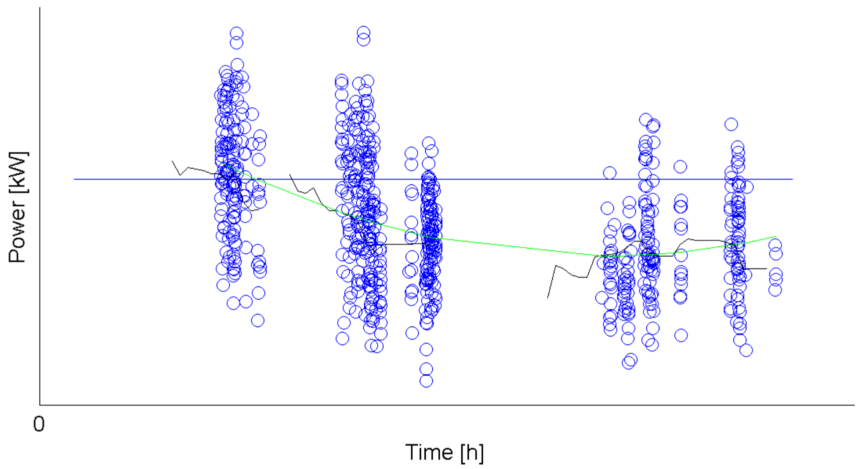

Figure 4.1: Trend analysis: Period 24h, Segment 168h

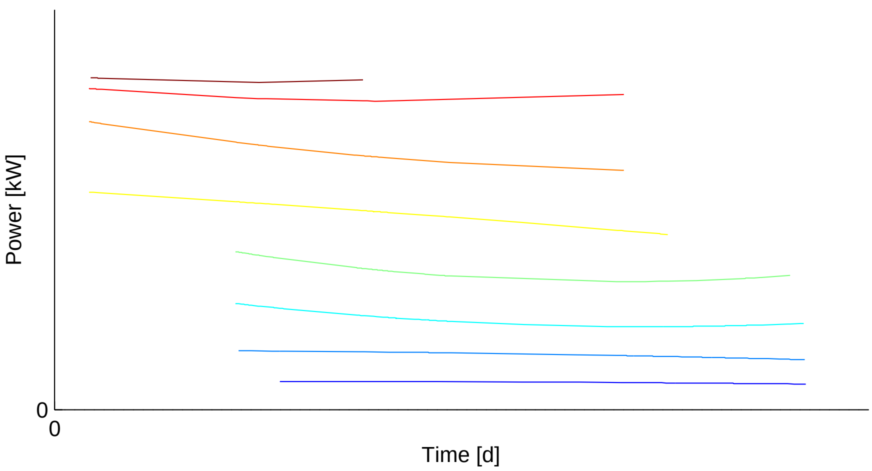

Figure 4.2: Trend analysis

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Part III

Uncertainty progression Flex

Chapter 5

Uncertainty progression Flex

The FLEX program calculates a theoretical power curve using both Blade Element Momentum (BEM) Theory and an experimentally obtained $\alpha/C_L, \alpha/C_D$ table. The measurement uncertainty in C_L and C_D through the BEM calculations. This part of the study forms a theoretical basis to estimate the propagated uncertainty of the theoretical power curve produced by FLEX.

5.1 Momentum Theory

From [Manwell *et al.* 2009]:

$$dT = 4a(1-a)\rho U^2 \pi r \; dr \tag{5.1}$$

$$dQ = 4a'(1-a)\rho U \Omega \pi r^3 \; dr \tag{5.2}$$

Where:
T is the thrust $[N]$
ρ is the air density $[kg/m^3]$
U is the wind speed $[m/s]$
a is the induction factor $[-]$
a' is the differential induction factor $[-]$
r is the radius $[m]$
Q is the differential torque $[Nm]$
Ω is the angular velocity of the wind turbine rotor $[rad/s]$

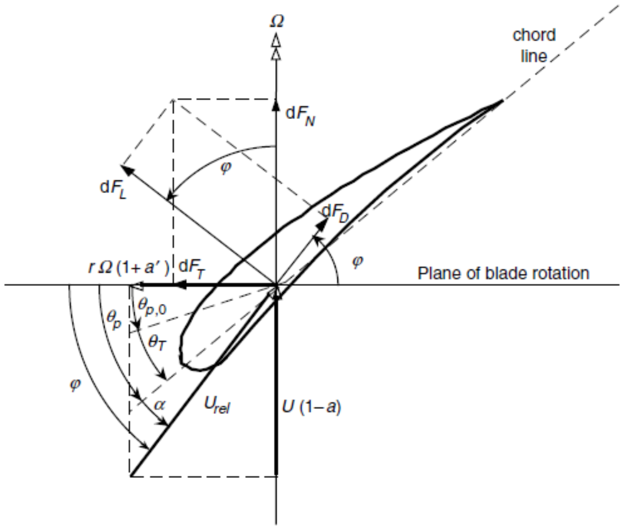

Figure 5.1: Blade geometry for analysis of a horizontal axis wind turbine. [Manwell *et al.* 2009]

5.2 Blade Element Theory

$$dF_N = \frac{1}{2} B \rho U_{rel}^2 \left(C_l \cos(\varphi) + C_d \sin(\varphi) \right) c \; dr \tag{5.3}$$

$$dQ = \frac{1}{2} B \rho U_{rel}^2 \left(C_l \sin(\varphi) - C_d \cos(\varphi) \right) cr \; dr \tag{5.4}$$

Where:
F_N is the normal force $[N]$
B is the number of blades $[-]$
ρ is the air density $[kg/m^3]$
U_{rel} is the relative wind speed $[m/s]$
C_l is the lift coefficient $[-]$
C_d is the drag coefficient $[-]$
φ is the relative angle of attack $[m/s]$
r is the radius $[m]$
Q is the differential torque $[Nm]$
c is the chord length $[m]$

U_{rel} can be expressed as:

$$U_{rel} = \frac{U(1-a)}{\sin(\varphi)} \tag{5.5}$$

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And the solidity is defined as:

$$\sigma' = \frac{Bc}{2\pi r} \tag{5.6}$$

Where:
σ' is the solidity $[\frac{1}{rad}]$

Rewriting Equation 5.3 and Equation 5.4 using Equation 5.5 and Equation 5.6 gives:

$$dF_N = \sigma' \pi \rho \frac{U^2(1-a)^2}{\sin^2(\varphi)} \left(C_l \cos(\varphi) + C_d \sin(\varphi)\right) r \; dr \tag{5.7}$$

$$dQ = \sigma' \pi \rho \frac{U^2(1-a)^2}{\sin^2(\varphi)} \left(C_l \sin(\varphi) - C_d \cos(\varphi)\right) r^2 \; dr \tag{5.8}$$

5.3 Blade Element Momentum Theory

The thrust equations from momentum and blade element theory are equated (Equation 5.1 and Equation 5.7).

$$dT = dF_N \tag{5.9}$$

$$4a(1-a)\rho U^2 \pi r \; dr = \sigma' \pi \rho \frac{U^2(1-a)^2}{\sin^2(\varphi)} \left(C_l \cos(\varphi) + C_d \sin(\varphi)\right) r \; dr \tag{5.10}$$

$$4a\cancel{(1-a)}\cancel{\rho}\cancel{U^2}\cancel{\pi r \; dr} = \sigma' \cancel{\pi}\cancel{\rho} \frac{\cancel{U^2}(1-a)^{\cancel{2}}}{\sin^2(\varphi)} \left(C_l \cos(\varphi) + C_d \sin(\varphi)\right) \cancel{r \; dr} \tag{5.11}$$

$$\frac{a}{(1-a)} = \frac{\sigma'}{4\sin^2(\varphi)} \left(C_l \cos(\varphi) + C_d \sin(\varphi)\right) \tag{5.12}$$

With:

$$\csc(\varphi) = \frac{1}{\sin(\varphi)} \tag{5.13}$$

$$\cot(\varphi) = \frac{1}{\tan(\varphi)} = \frac{\cos(\varphi)}{\sin(\varphi)} \tag{5.14}$$

This can be rewritten to:

$$a = \frac{\sigma' \csc(\varphi) \left(C_l \cot(\varphi) + C_d\right)}{\left(\sigma' \csc(\varphi) \left(C_l \cot(\varphi) + C_d\right) + 4\right)} \tag{5.15}$$

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The torque equations from momentum and blade element theory are equated (Equation 5.2 and Equation 5.8).

$$dQ = dQ \tag{5.16}$$

$$4a'(1-a)\rho U \pi r^3 \Omega dr = \sigma' \pi \rho \frac{U^2(1-a)^2}{\sin^2(\varphi)} \left(C_l \sin(\varphi) - C_d \cos(\varphi)\right) r^2 \ dr \tag{5.17}$$

$$4a'\cancel{(1-a)}\cancel{\rho U}\pi r^{\cancel{3}}\Omega \ \cancel{dr} = \sigma' \cancel{\pi\rho} \frac{U^{\cancel{2}}(1-a)^{\cancel{2}}}{\sin^2(\varphi)} \left(C_l \sin(\varphi) - C_d \cos(\varphi)\right) \cancel{r^2 \ dr} \tag{5.18}$$

$$\frac{a'}{(1-a)} = \frac{U\sigma'}{4r\Omega \sin^2(\varphi)} \left(C_l \sin(\varphi) - C_d \cos(\varphi)\right) \tag{5.19}$$

The local speed ratio is the ratio of the rotor speed at some intermediate radius to the wind speed:[Manwell *et al.* 2009]

$$\lambda_r = \frac{\Omega r}{U} \tag{5.20}$$

$$\frac{a'}{(1-a)} = \frac{\sigma'}{4\lambda_r \sin^2(\varphi)} \left(C_l \sin(\varphi) - C_d \cos(\varphi)\right) \tag{5.21}$$

Via iteration the values of a and a' are determined by FLEX. Once a has been obtained for each section, the overall power can be calculated. The total power from the rotor is:

$$P = \int_{r_h}^{R} dP = \int_{r_h}^{R} \Omega dQ = \int_{r_h}^{R} \Omega \sigma' \pi \rho \frac{U^2(1-a)^2}{\sin^2(\varphi)} \left(C_l \sin(\varphi) - C_d \cos(\varphi)\right) r^2 \ dr \tag{5.22}$$

The power for each section (annulus) can be calculated by discretization of Equation 5.22. The end of each section is given in the FLEX output and defined as r_i where $r_0 = 0$.(Figure 5.2)
The width of each section is defined as:

$$\Delta r_i = r_i - r_{i-1} \tag{5.23}$$

The center position of each section is defined as:

$$\bar{r}_i = r_{i-1} + \frac{\Delta r_i}{2} \tag{5.24}$$

$$P_{tot} = \sum_{i=1}^{N} \frac{1}{2} \Omega B c_i \rho U^2 (1-a_i)^2 \frac{\left(C_{l,i} \sin(\varphi_i) - C_{d,i} \cos(\varphi_i)\right)}{\sin^2(\varphi_i)} \bar{r}_i \Delta r_i \tag{5.25}$$

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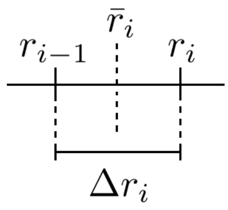

Figure 5.2: Graphic interpretation of a bin

5.4 Uncertainty Progression

A method for the summation of uncertainties is explained in [Anderson & Cnossen 2011], [Coleman & Steele 1998] and previously in subsection 2.5.2. The power produced per section is given by Equation 5.26.

$$P_i = \frac{1}{2}\Omega B c_i \rho U^2 (1-a_i)^2 \frac{(C_{l,i}\sin(\varphi_i) - C_{d,i}\cos(\varphi_i))}{\sin^2(\varphi_i)} \bar{r}_i \Delta r_i \tag{5.26}$$

Equation 5.26 is solved via iteration of a. See also section 5.5. In each iteration step a value for a is chosen. From Figure 5.1 we can derive Equation 5.27. Choosing a value for a can therefore be interpreted as choosing a value for φ for a fixed wind speed and rotational speed. There is no uncertainty in a chosen value of φ. The uncertainty in a (Equation 5.15), can therefore be calculated by propagating the uncertainty in C_L and C_D. (Equation 5.28)

$$tan(\varphi) = \frac{U(1-a)}{r\Omega} \tag{5.27}$$

$$U_{a,i}^2 = \left(\left(\frac{\partial a_i}{\partial C_{l,i}} \right)^2 * U_{C_l,i}^2 + \left(\frac{\partial a_i}{\partial C_{d,i}} \right)^2 * U_{C_{d,i}}^2 \right) \tag{5.28}$$

The uncertainty in P (Equation 5.26), can therefore be calculated by propagating the uncertainty in C_L ,C_D and a. For each section (annulus) the propagated uncertainty in power can be calculated. (Equation 5.29) A simple case is worked out in Appendix D.

$$U_{P,i}^2 = \left(\left(\frac{\partial P_i}{\partial C_{l,i}} \right)^2 * U_{C_l,i}^2 + \left(\frac{\partial P_i}{\partial C_{d,i}} \right)^2 * U_{C_d,i}^2 + \left(\frac{\partial P_i}{\partial a_i} \right)^2 * U_{a,i}^2 \right) \tag{5.29}$$

Where:

$$\frac{\partial a_i}{\partial C_{l,i}} = \frac{4\sigma_i' \csc(\varphi_i)\cot(\varphi_i)}{\left(\sigma_i' \csc(\varphi_i)\left(C_{l,i}\cot(\varphi_i) + C_{d,i}\right) + 4\right)^2} \tag{5.30}$$

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$$\frac{\partial a_i}{\partial C_{d,i}} = \frac{4\sigma_i' \csc(\varphi_i)}{\left(\sigma_i' \csc(\varphi_i)\left(C_{l,i}\cot(\varphi_i) + C_{d,i}\right) + 4\right)^2} \tag{5.31}$$

$$\frac{\partial P_i}{\partial C_{l,i}} = \frac{\Omega B \rho c_i U^2 (1-a_i)^2}{2} \frac{1}{\sin(\varphi_i)} \bar{r}_i \Delta r_i \tag{5.32}$$

$$\frac{\partial P_i}{\partial C_{d,i}} = -\frac{\Omega B \rho c_i U^2 (1-a_i)^2}{2} \frac{\cos(\varphi_i)}{\sin^2(\varphi_i)} \bar{r}_i \Delta r_i \tag{5.33}$$

$$\frac{\partial P_i}{\partial a_i} = -\frac{\Omega B \rho c_i U^2 (1-a_i)\left(C_{l,i}\sin(\varphi_i) - C_{d,i}\cos(\varphi_i)\right)}{\sin^2(\varphi_i)} \bar{r}_i \Delta r_i \tag{5.34}$$

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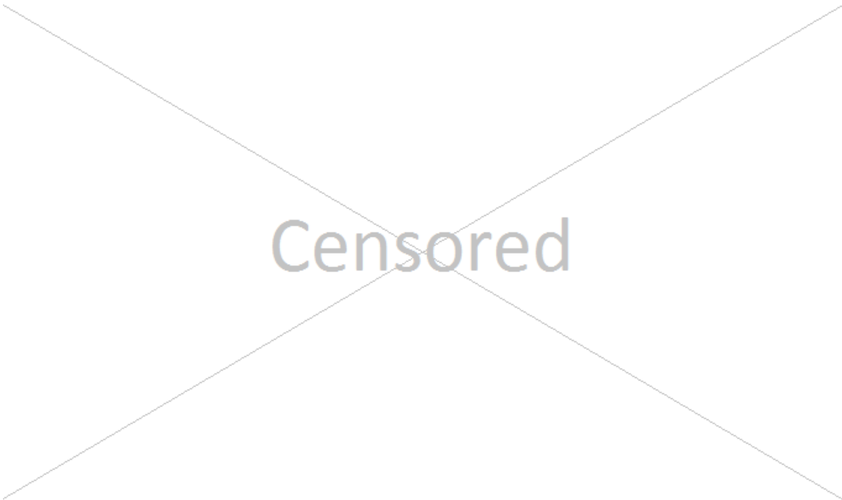

Figure 5.3: Uncertainty and absolute Power difference for a 1% C_L change

5.5 MATLAB®

A MATLAB® script was written that solves the BEM theory (section 5.3) via iteration of a. For a given radius and fixed rotational speed the $\frac{c_i}{r_i}$ is calculated and the $\alpha/C_L, \alpha/C_D$ tables are interpolated for α and $\frac{c_i}{r_i}$. It takes approximately 7 iterations to estimate a within a $\frac{1}{10000}$ difference in a.

The absolute difference in P_i for a 1% increase in C_L has been calculated by MATLAB® . The uncertainty has been propagated as well for an assumed standard uncertainty in C_L of 1%. The results are shown in Figure 5.3.

The power curve calculated by the MATLAB® script was found to be equal to the power curve produced by FLEX. Calculating the propagated uncertainty in the power curve however proved to be more complicated. The uncertainties shown in Figure 5.3 for each annulus are correlated. Therefore they cannot simply be summed by taking the root of the sum of squares. Unfortunately there was no time to calculate the correlation factor.

To get a feel for the magnitude of this error, an absolute change in C_L was calculated to see the absolute change in AEP. When C_L changed 1%, the AEP changed [redacted]%. This was also done for an absolute change in C_D. An absolute change of 2% in C_D turned out to have an absolute change of [redacted]% in the AEP. Combined this would result in a [redacted]% error in AEP.

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Chapter 6

Conclusion

6.1 Part I: Power curve uncertainty analysis

The Matlab® tool PCstat, that incorporates uncertainty evaluations in the power curve measurement analysis has been completed. It analyzes power curve measurement data and presents its results in an auto generated report following the IEC standard. PCstat comes with a manual that explains in detail the workings of the code.

It has become clear that the main uncertainty in the power curve is due to the uncertainty in wind speed measurement. One recommendation of this report is therefore to change the way wind speed is measured. There are several other ways to measure wind speed other than a cup anemometer. One is measurement of wind speed via a laser mounted on the nacelle itself which will always measure the wind speed in front of the turbine. A second recommendation is to always perform a site calibration. A second influential uncertainty component is the uncertainty of the flow distortion due to terrain. Performing a site calibration lowers this part of the uncertainty considerably and gives a more accurate power curve measurement.

6.2 Part II: Trend analysis

A trend analysis script has been build. This gives insight in the behavior of the turbine over time. Effects as blades that get dirty over time can be seen clearly. When longer periods are analyzed seasonal effects in the annual wind can become visible as well.

6.3 Part III: Uncertainty progression Flex

The theoretical power curve produced by FLEX is based on the measurements of C_L and C_D. Thus an uncertainty in this measurement will in turn result in an uncertainty in the theoretical power curve. One insight that this research provided is the sensitivity of the Annual yield to an absolute change in C_L. It was found that an absolute change in C_L of 1% results in an absolute change in AEP of [redacted]%. This was also done for an absolute change in C_D. An absolute change of 2% in C_D turned out to have an absolute change of [redacted]% in the AEP. Combined this would result in a [redacted]% error in AEP. This gives a good insight in how a change in your C_L and C_D measurements affects your AEP calculations.

List of Figures

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List of Tables

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[Manwell *et al.* 2009] J.F. Manwell, J.G. Mcgowan and A.L. Rogers. Wind energy explained - theory, design and application. Numeéro ISBN 978-0-470-01500-1. Wiley, 2009. (Cited on pages 29, 30, 32 and 39.)

[The MathWorks, Inc] The MathWorks, Inc. *norminv*. `http://www.mathworks.nl/help/toolbox/stats/norminv.html`. (Cited on page 8.)

[The Scipy community] The Scipy community. *norm.ppf*. `http://docs.scipy.org/doc/scipy/reference/generated/scipy.stats.norm.html`. (Cited on page 8.)

Appendix A

Assignment

A.1 Power curve uncertainty model

Student: Leon Eilders - UT
Duration: 3 months starting at 6 February 2012
Mentor: Frank Goezinne Suzlon A&L

A.2 Description

The Suzlon [redacted] wind turbine in Snowtown (Australia) has been measured by the certifying body DEWI in August-September 2011. DEWI has delivered the data to Suzlon, together with a report [Bégué 2011]. This report not only shows the turbine performance but also the expected uncertainty of the performance.

Suzlon used the same data to establish the power curve, using a recent developed Matlab® program.

The student will be working on further development of our (Matlab®) tool to analyze data from power curve measurements, focusing on incorporating uncertainty evaluations into our analysis.

The results will be compared against the findings by DEWI [Bégué 2011]

A.3 Deliverables

- Working Matlab® model to establish uncertainty on power curve
- Evaluation against the DEWI results
- Manual
- Report

Appendix B

Snowtown II

B.1 Filter

The following filters have been applied to the 10 minute average measurement data:

- Wind direction between [redacted] and [redacted] degrees
- Wind direction between [redacted] and [redacted] degrees
- Wind direction between [redacted] and [redacted] degrees
- Winds speed is higher then [redacted] m/s
- Availability = 100
- Grid Availability = 100

The difference between the wind speed at the nacelle and the meteorological mast was analyzed. 2 loops were performed to get rid of any outliers. 6 points were rejected, this is a reduction of 0.622%. There are 959 points left. Before data rejection mu was:[redacted] and after:[redacted]. mu changed 2.544%. Before data rejection sigma was:[redacted] and after:[redacted]. sigma changed -5.355%.

The power curve was analyzed to get rid of any outliers. 36 points were rejected.

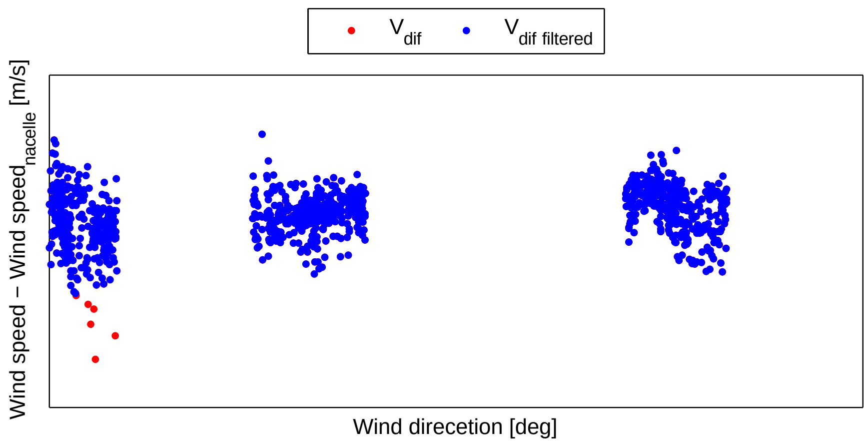

Figure B.1: Comparison of power curve before and after data rejection

This is a reduction of 3.754%. There are 923 points left. A step size of [redacted] m/s was used.

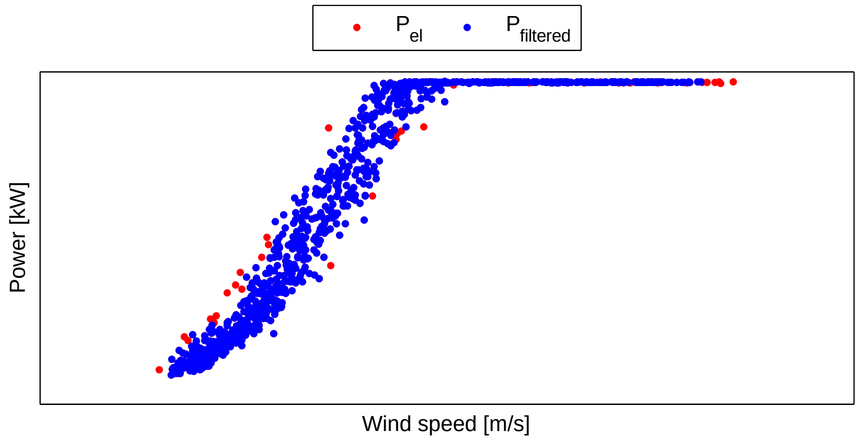

Figure B.2: Comparison of power curve before and after data rejection

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B.2 Power performance as stated in IEC 61400-12-1 for Standard Air Density ($\rho_0 = 1.225\ kg/m^3$)

B.2.1 Scatter Plot of Power Curve ($\rho_0 = 1.225\ kg/m^3$)

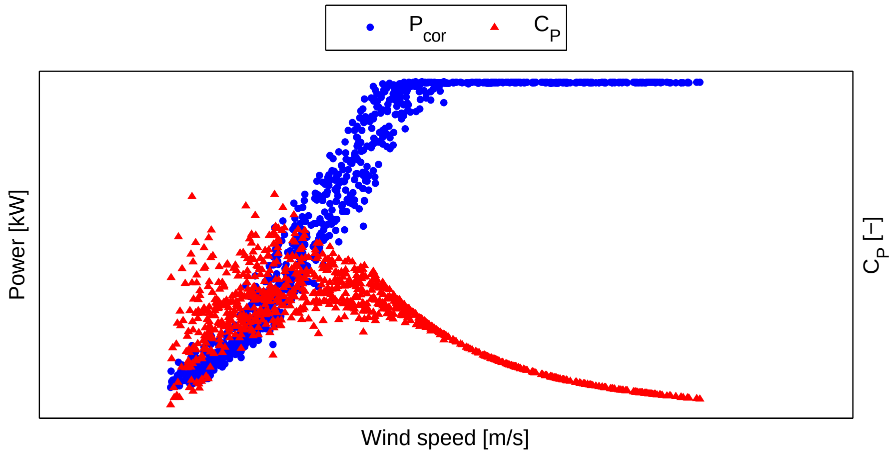

Figure B.3: Scatter plot of the power curve versus wind speed ($\rho_0 = 1.225\ kg/m^3$)

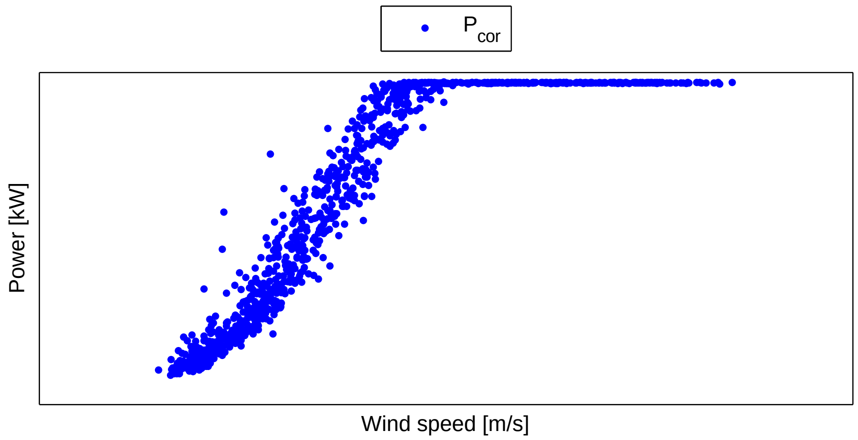

Figure B.4: Scatter plot of power curve without availability filter versus wind speed ($\rho_0 = 1.225\ kg/m^3$)

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B.2.2 Bin averaged Power Curve ($\rho_0 = 1.225\ kg/m^3$)

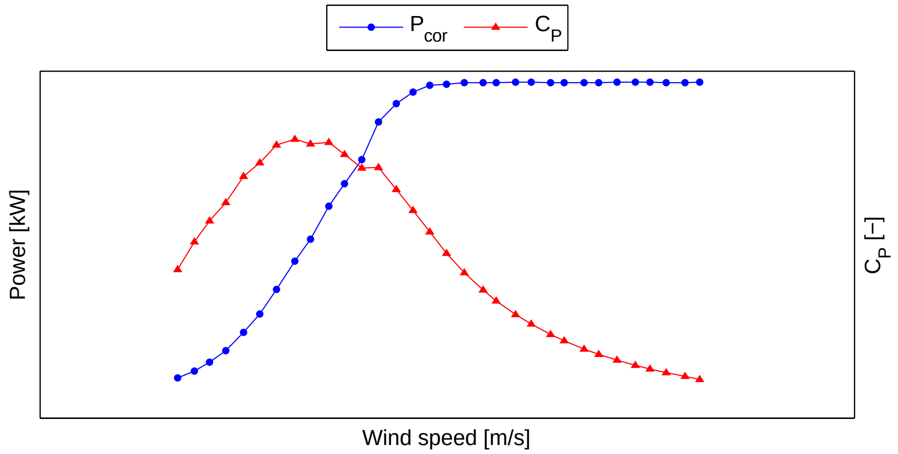

Figure B.5: Bin averaged power curve versus wind speed ($\rho_0 = 1.225\ kg/m^3$)

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B.2.3 Peak values of the Electrical Power ($\rho_0 = 1.225\ kg/m^3$)

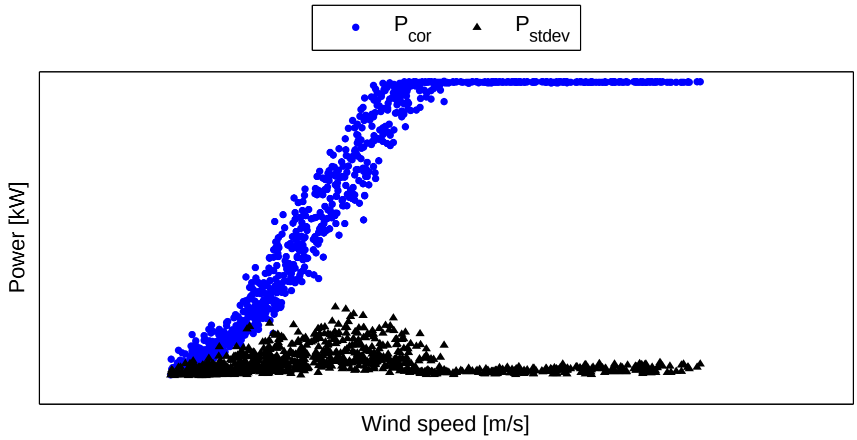

Figure B.6: Average value and standard deviation of the power versus wind speed ($\rho_0 = 1.225\ kg/m^3$)

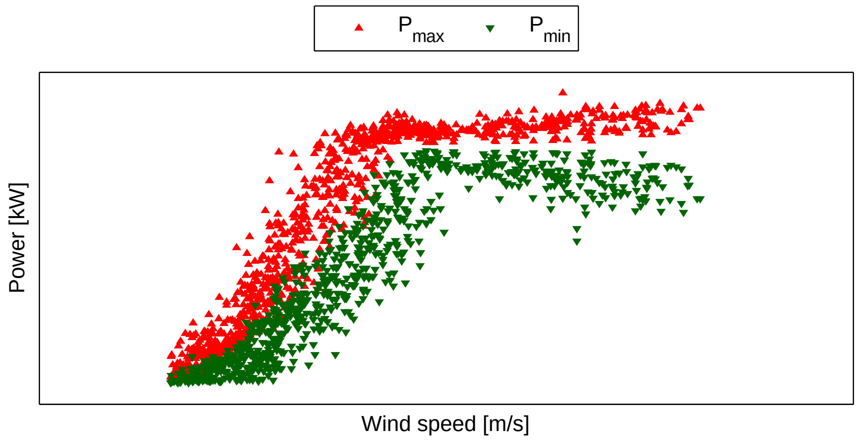

Figure B.7: Maximum and minimum of the power versus wind speed ($\rho_0 = 1.225\ kg/m^3$)

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B.2.4 Pitch Angle of the Wind Turbine ($\rho_0 = 1.225\ kg/m^3$)

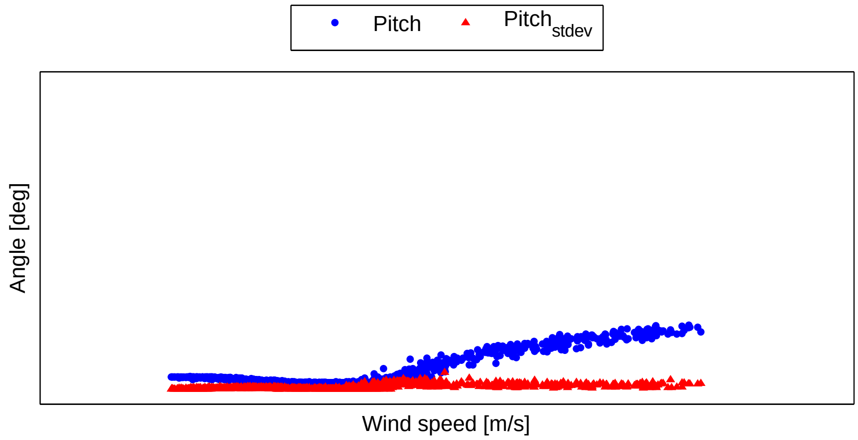

Figure B.8: Average and standard deviation of the pitch angle versus wind speed ($\rho_0 = 1.225\ kg/m^3$)

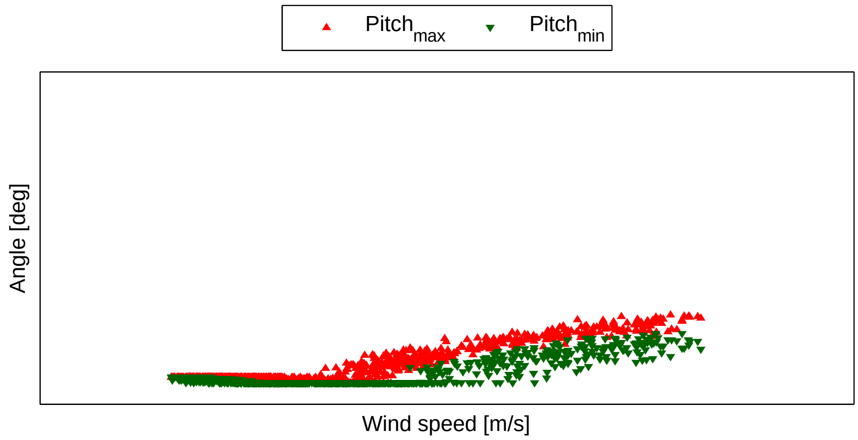

Figure B.9: Maximum and minimum of the pitch angle versus wind speed ($\rho_0 = 1.225\ kg/m^3$)

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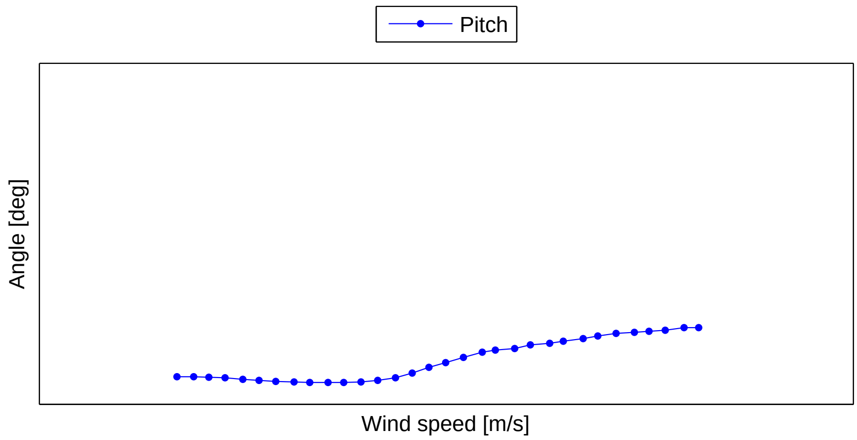

Figure B.10: Pitch angle versus wind speed ($\rho_0 = 1.225\ kg/m^3$)

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B.2.5 Rotational Speed of Wind Turbine ($\rho_0 = 1.225\ kg/m^3$)

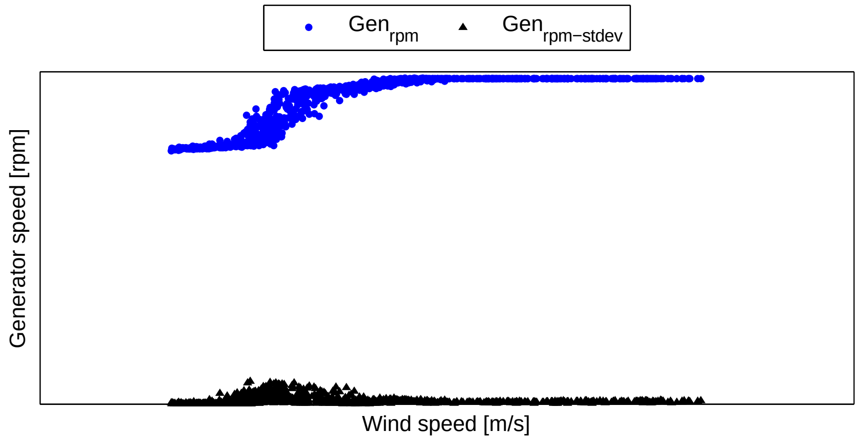

Figure B.11: Average and standard deviation of rotational speed versus wind speed ($\rho_0 = 1.225\ kg/m^3$)

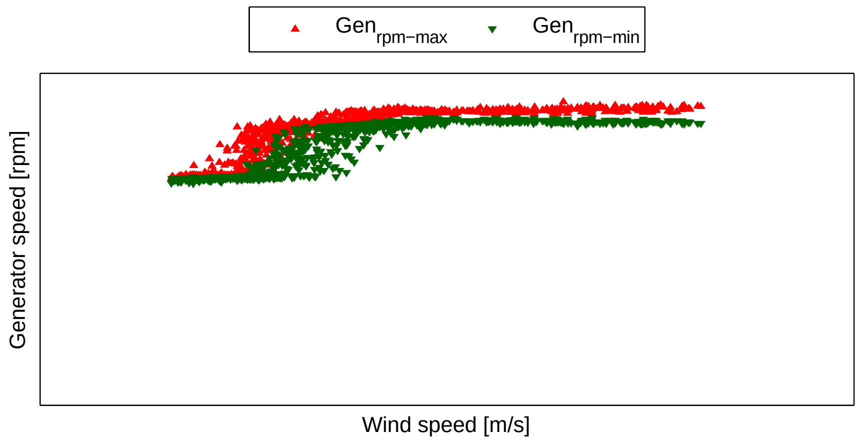

Figure B.12: Minumum and maximum of rotational speed versus wind speed ($\rho_0 = 1.225\ kg/m^3$)

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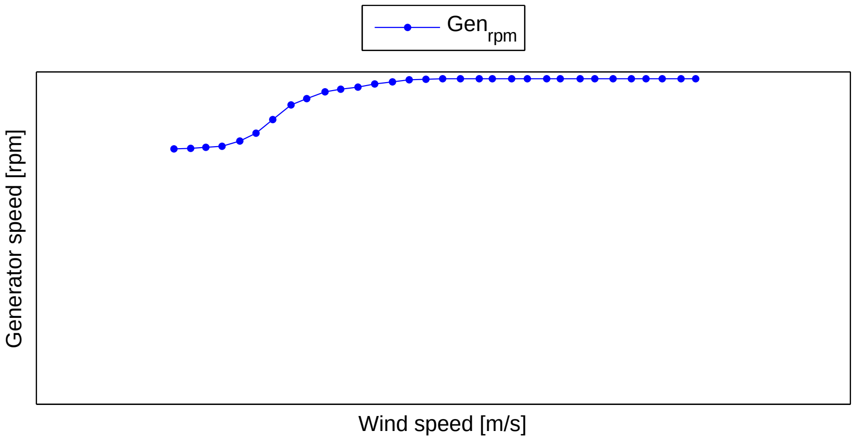

Figure B.13: Rotational speed versus wind speed ($\rho_0 = 1.225\ kg/m^3$)

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B.2.6 Atmospheric Conditions

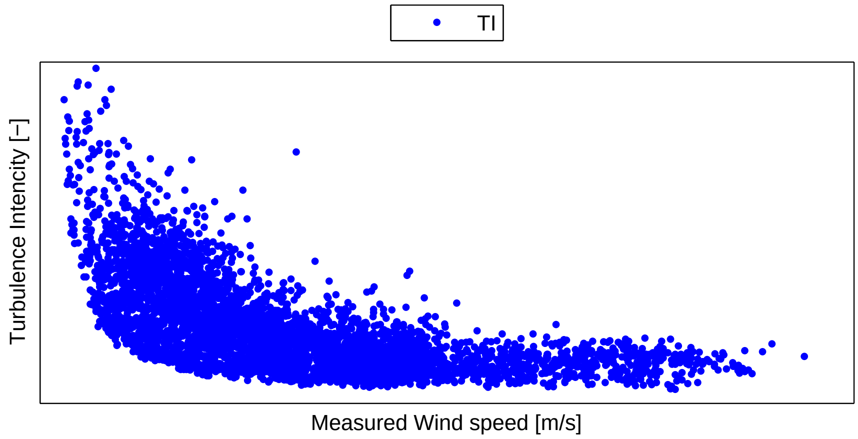

Figure B.14: Turbulence intensity versus measured wind speed

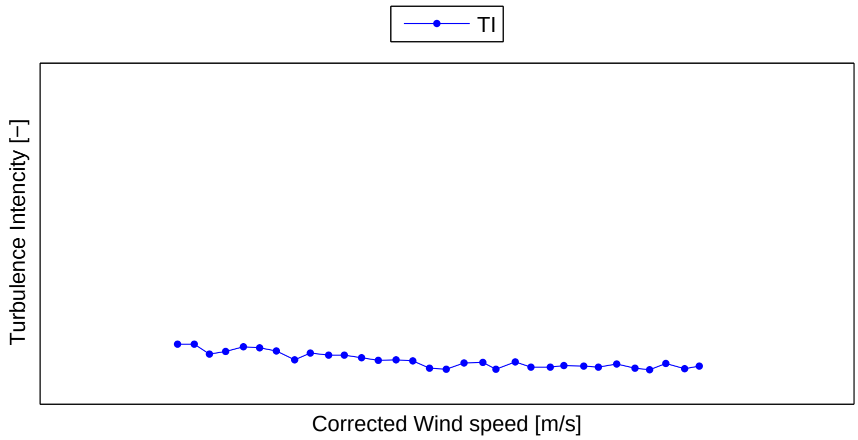

Figure B.15: Turbulence intensity versus density corrected wind speed

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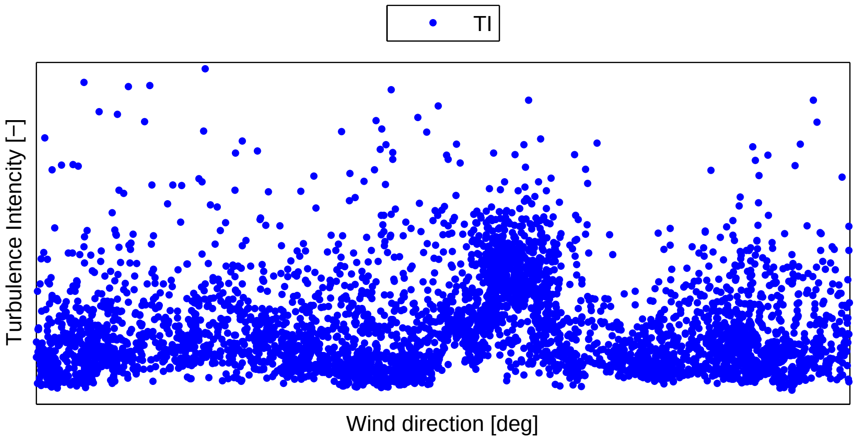

Figure B.16: Turbulence intensity versus wind direction

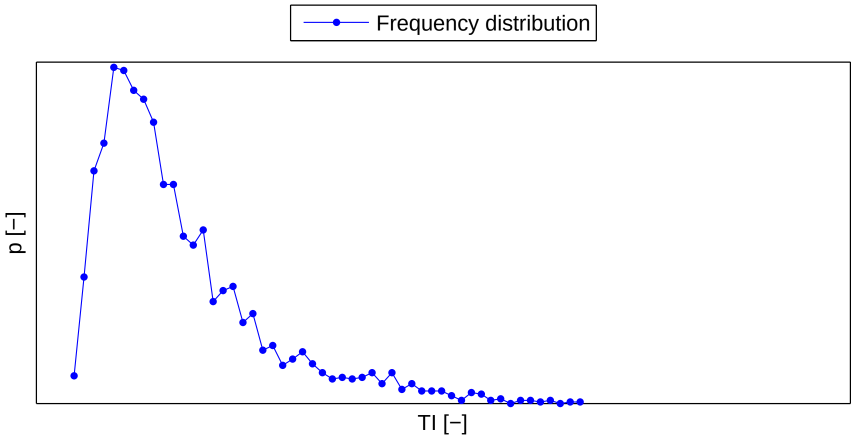

Figure B.17: Frequency distribution of the turbulence intensity

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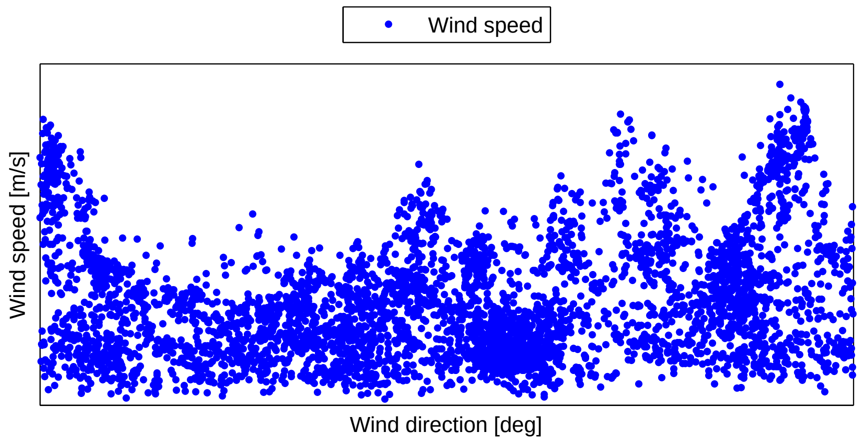

Figure B.18: Measured wind speed versus wind direction

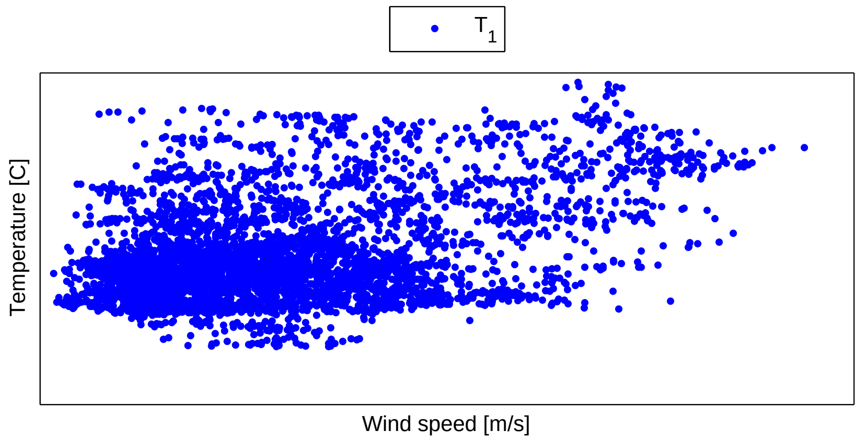

Figure B.19: Air temperature versus wind speed

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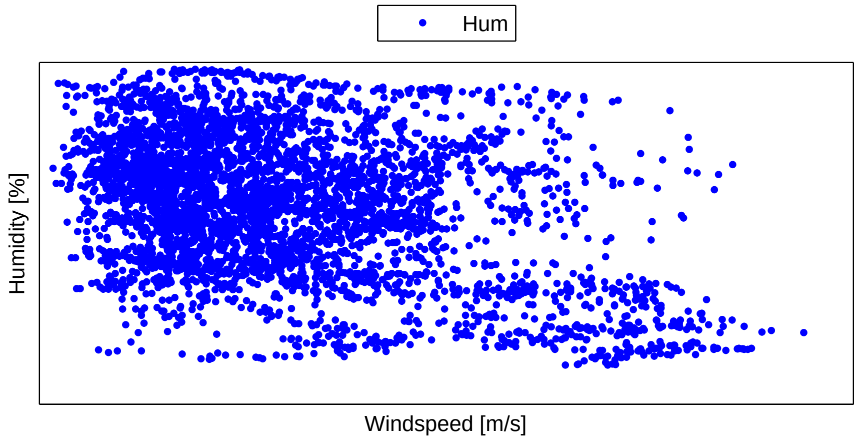

Figure B.20: Humidity versus wind speed

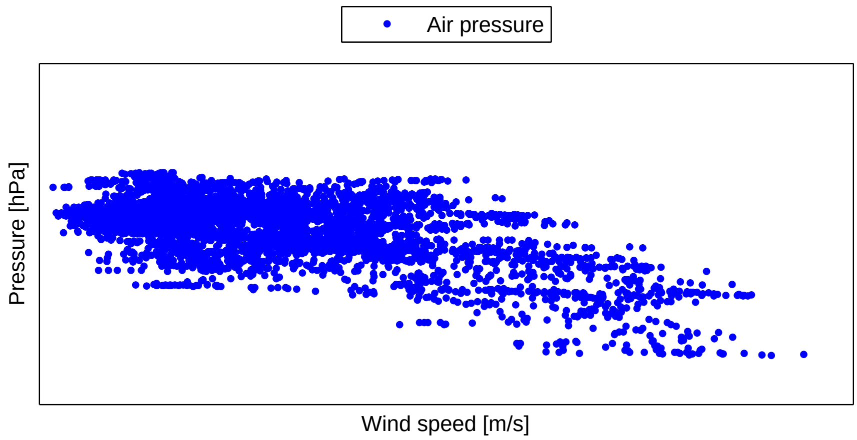

Figure B.21: Air pressure versus wind speed

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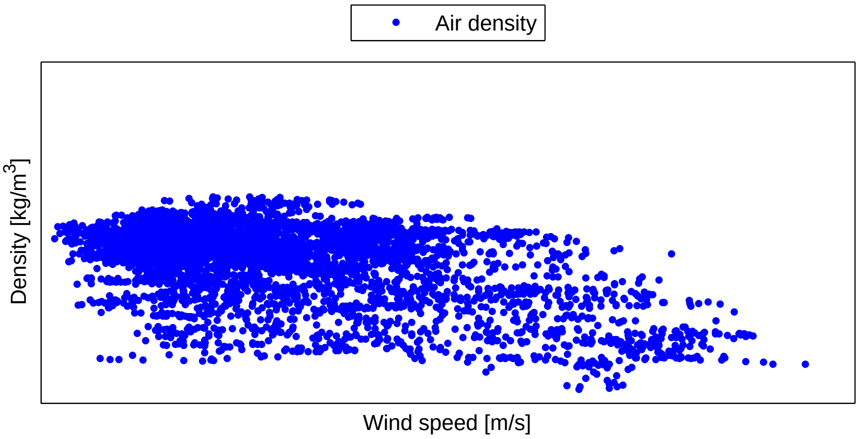

Figure B.22: Air density versus wind speed

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B.2.7 Evaluation of Wind Shear

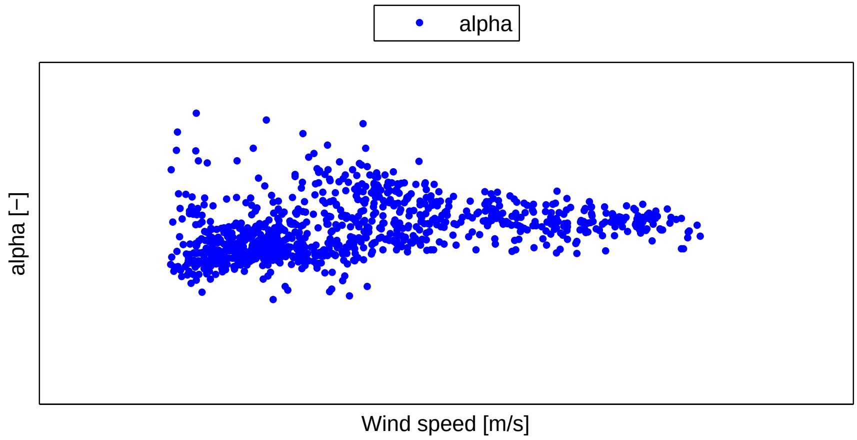

Figure B.23: Wind shear exponent α versus measured wind speed

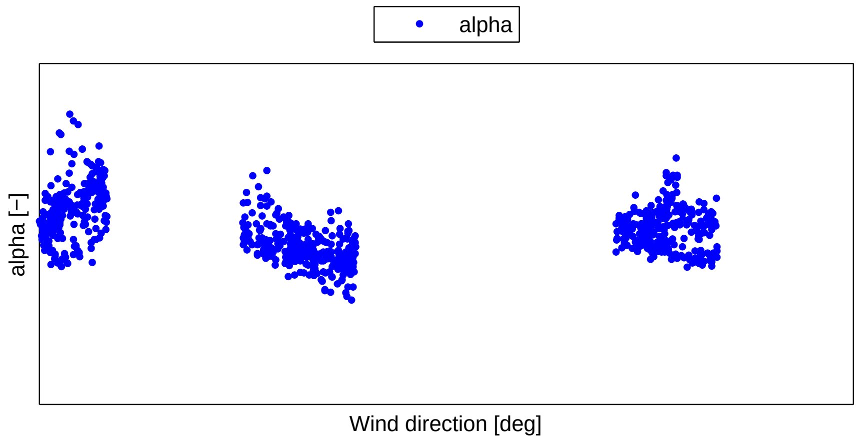

Figure B.24: Wind shear exponent α versus wind direction in the measurement sector

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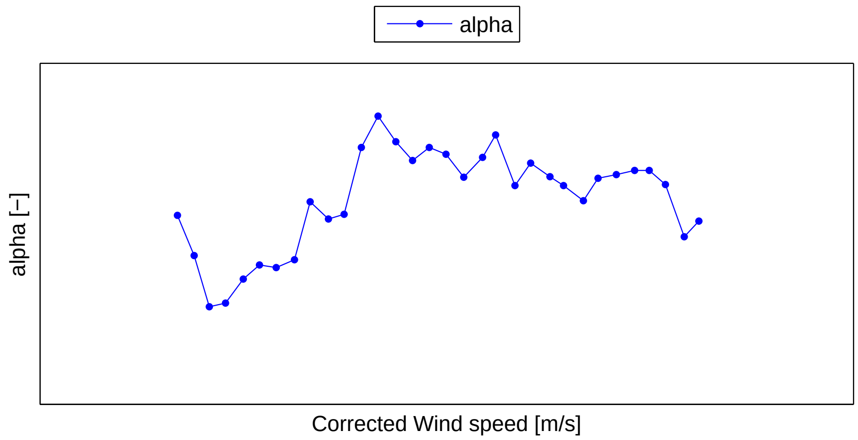

Figure B.25: Wind shear exponent α versus wind speed binned

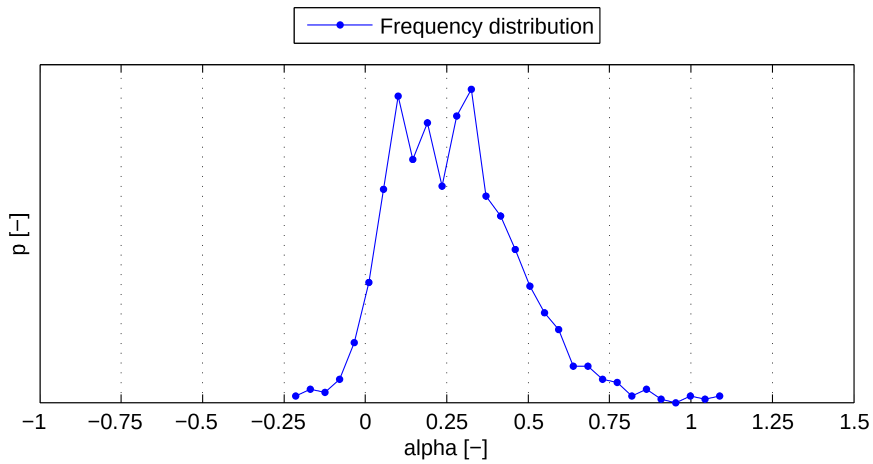

Figure B.26: Frequency distribution of the wind shear exponent α

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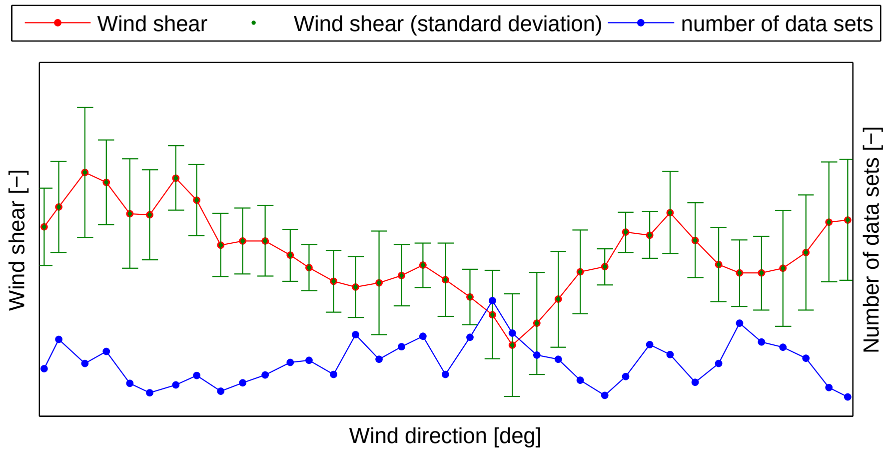

Figure B.27: Wind shear exponent α versus wind direction

B.2.8 Self Consistency Test

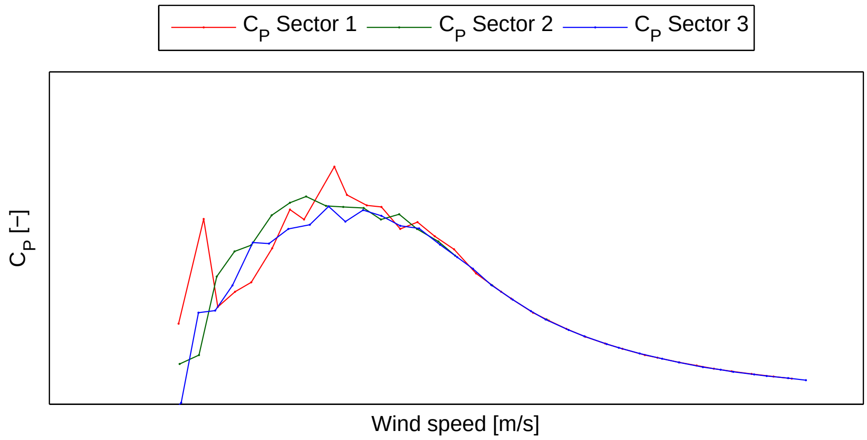

Figure B.28: Comparison of the C_P curves for the measurement sectors

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B.3 Uncertainty in Measurements

B.3.1 Measurement Uncertainty of the Site Calibration

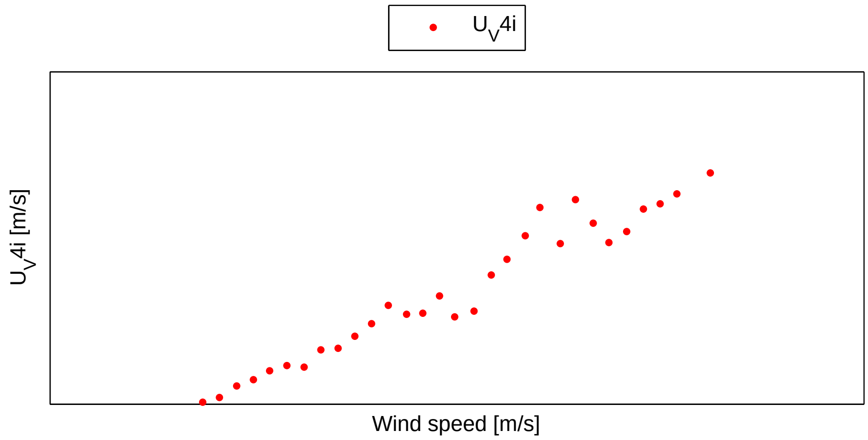

Figure B.29: Site calibration uncertainty according to IEC [IEC 2005] Procedure for each wind speed bin of the power curve

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B.4 Measurement Uncertainty of the Power Performance Evaluation

B.4.1 Measurement uncertainty for Standard Air Density ($\rho_0 = 1.225\ kg/m^3$)

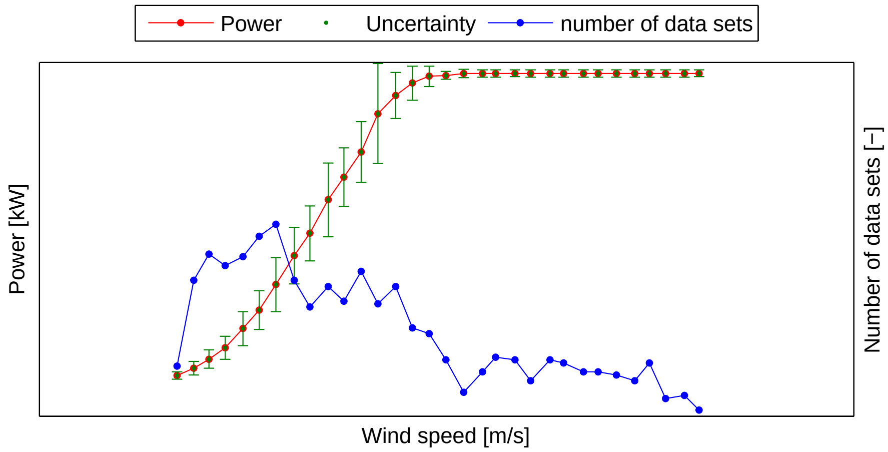

Figure B.30: Graph of the measured power curve and the calculated combined uncertainty

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B.5 Annual Energy Production (AEP)

AEP estimations have been made for hub height annual average wind speeds of 4, 5, 6, 7, 8, 9, 10 and 11 m/s.

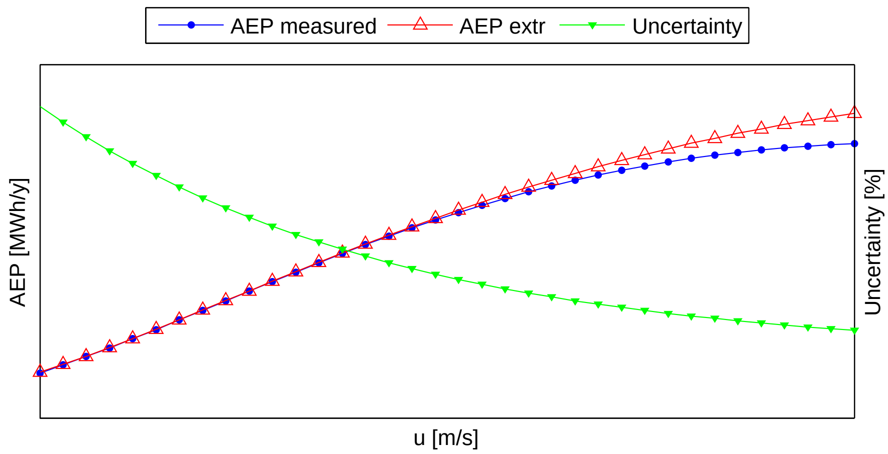

Figure B.31: Calculated annual energy production and calculated combined uncertainty versus the average annual wind speed at hub height

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B.6 Extra Analysis

Presenting the data according to the IEC standard gives a good overview of the data analysis. In some areas a more in dept analysis is required to obtain a better understanding.

B.6.1 Wind speed versus Wind direction

In the presentation of data as dictated by the IEC standard, the wind speed is shown versus the wind direction. Even though this is a clear graph, showing the wind speed for only the measurement sector will give a more clearer overview of the data points used in the analysis.(Figure B.32)

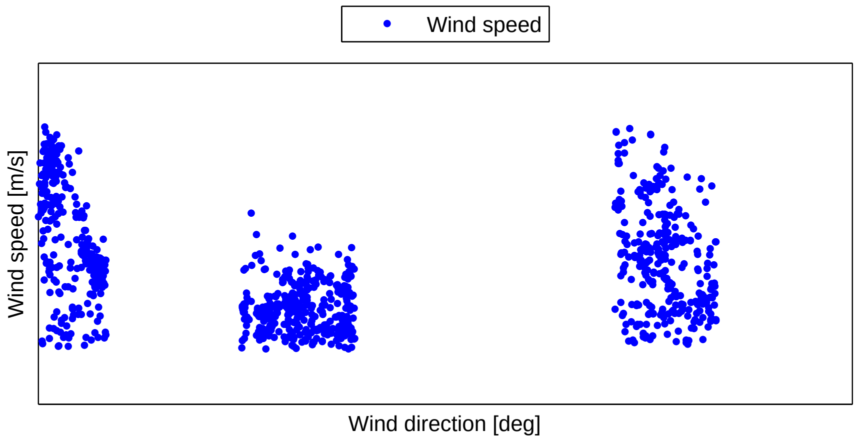

Figure B.32: Turbulence intensity versus wind direction (filtered)

B.6.2 Uncertainty Components

Although the uncertainty is well presented in the standard, it is unclear what the main contributors to uncertainty are. Therefore all components and their contribution to the total uncertainty are shown in Figure B.33 to Figure B.37. From Figure B.33 it becomes immediately clear that the uncertainty in the wind speed measurements is the main contribution to the uncertainty. From Figure B.35 it becomes clear that the flow distortion due to the terrain is the main contributor to the uncertainty in the anemometer measurements.

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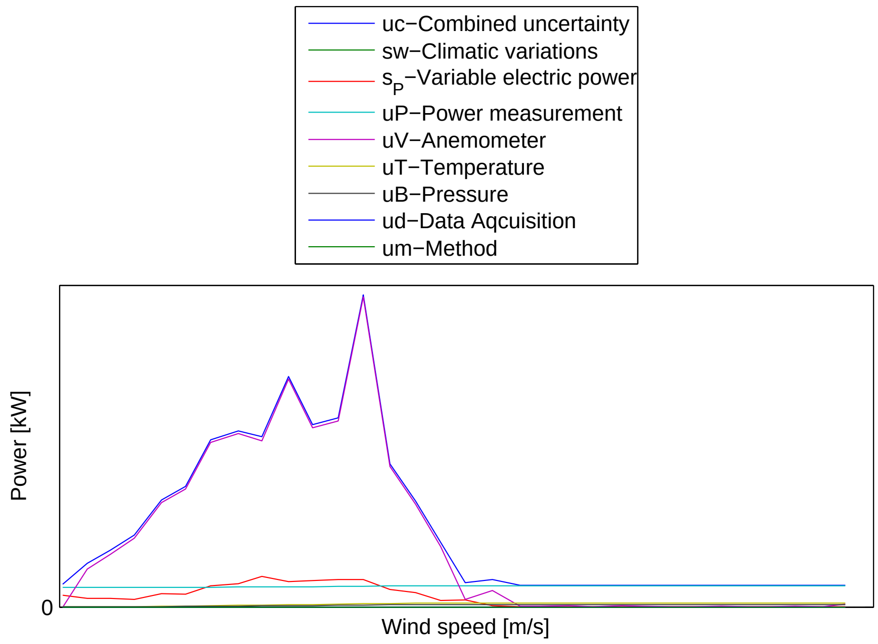

Figure B.33: The combined uncertainty and its components versus wind speed

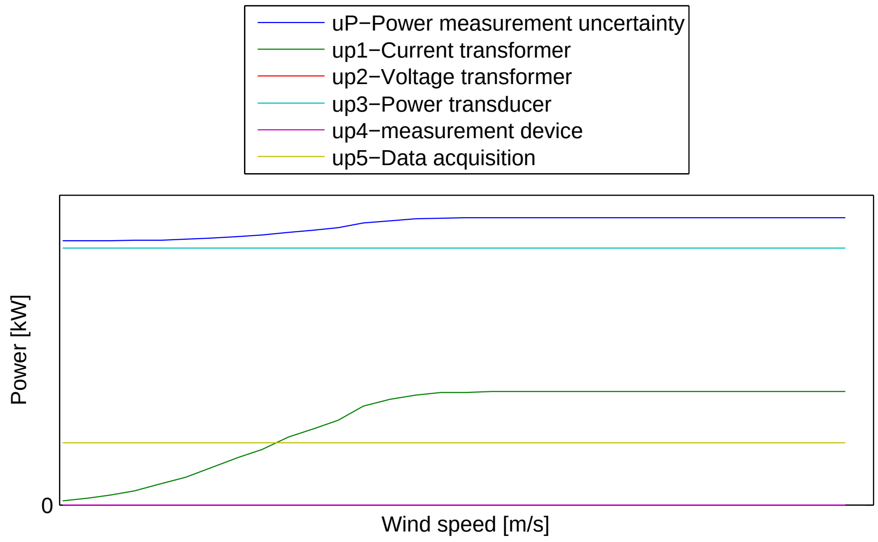

Figure B.34: The uncertainty in the power measurements and its components versus wind speed

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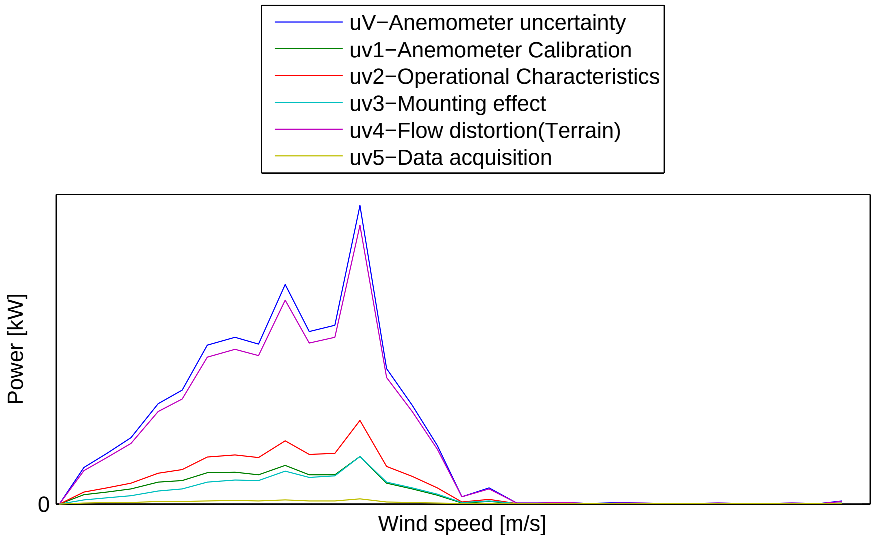

Figure B.35: The uncertainty in the wind speed measurements and its components versus wind speed

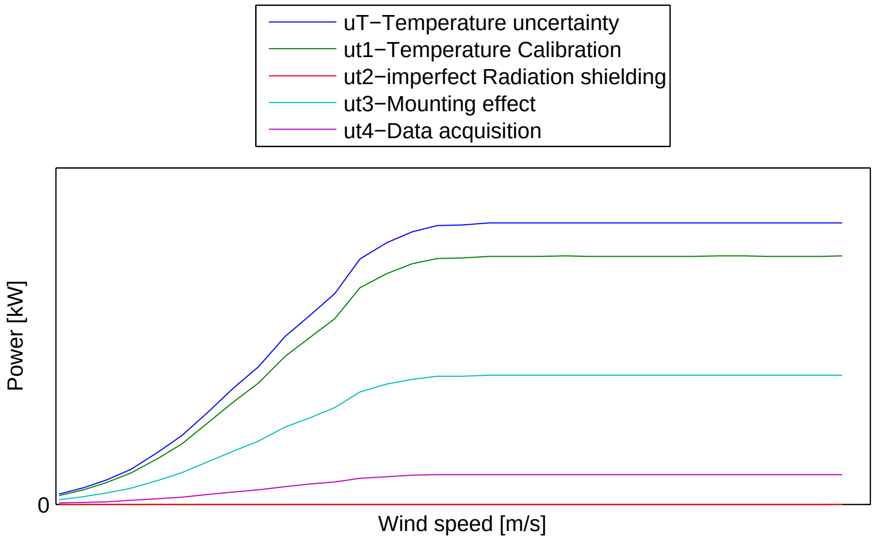

Figure B.36: The uncertainty in the temperature measurements and its components versus wind speed

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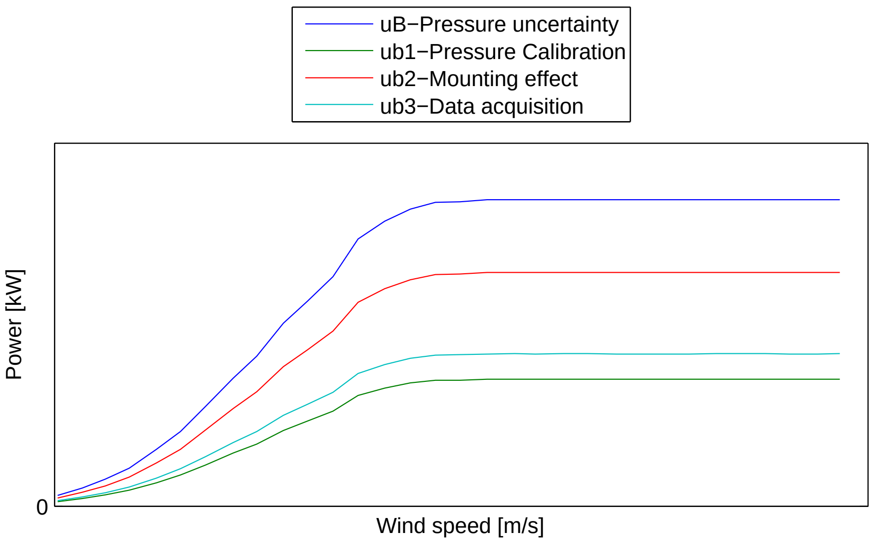

Figure B.37: The uncertainty in the pressure measurements and its components versus wind speed

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B.6.3 Uncertainty in the power curve

The IEC standard translates the uncertainty in the wind speed to an uncertainty in electric power. Presenting the uncertainty in this way gives a wrong impression to where the uncertainty in the power curve really comes from. It is therefore more convenient to present the uncertainty in both electric power and wind speed via vertical and horizontal error bars.(Figure B.38)

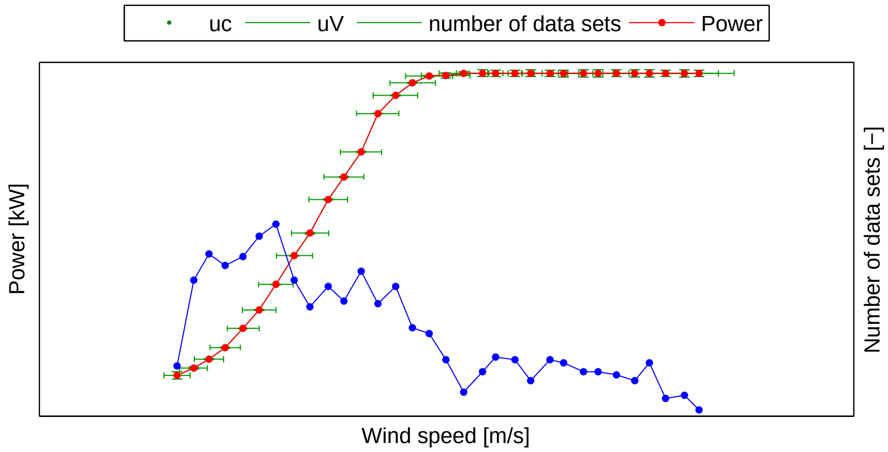

Figure B.38: Graph of the measured power curve and the calculated uncertainty

Presenting the uncertainty in both the electric power and wind speed results in the same error band but shows clearly that the main uncertainty comes forth from the uncertainty in the wind speed measurement as concluded in subsection B.6.2.

The uncertainty has a mayor effect on the AEP. To show its extent the minimal and maximal power curve according to the error band were calculated, as well as the AEP resulting from that power curve. The results are shown in Figure B.39.

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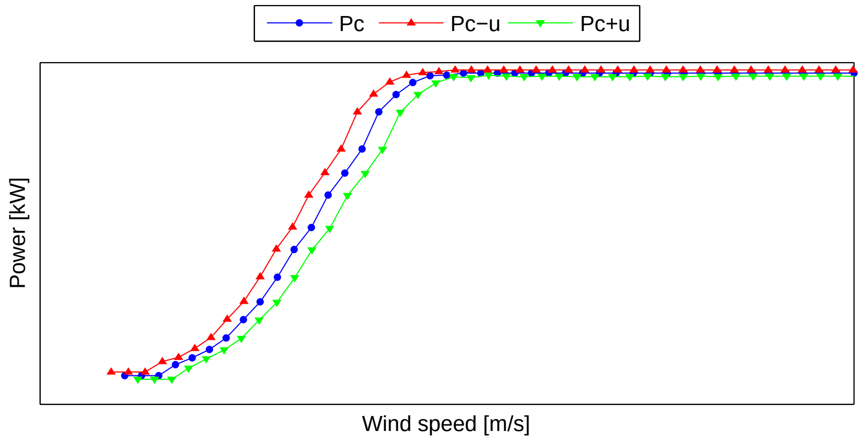

Figure B.39: Graph of the extrapolated- minimum, maximum and measured power curve

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B.6.4 Comparison with the theoretical power curve

A comparison with the theoretical power curve is made.

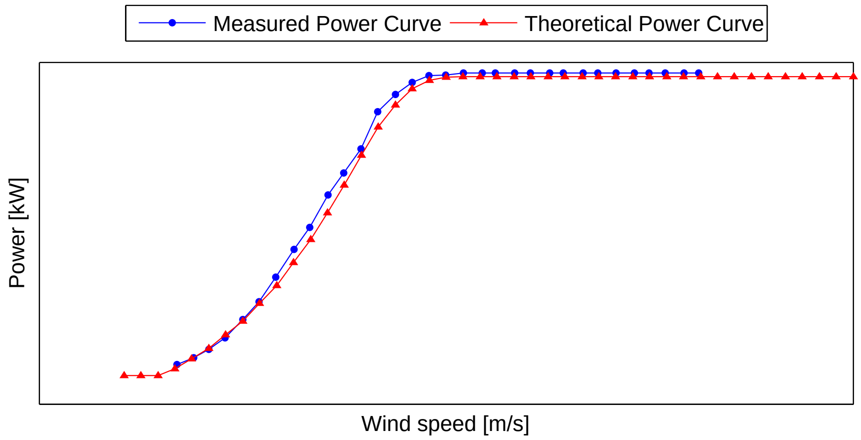

Figure B.40: Measured power curve and Theoretical power curve versus wind speed

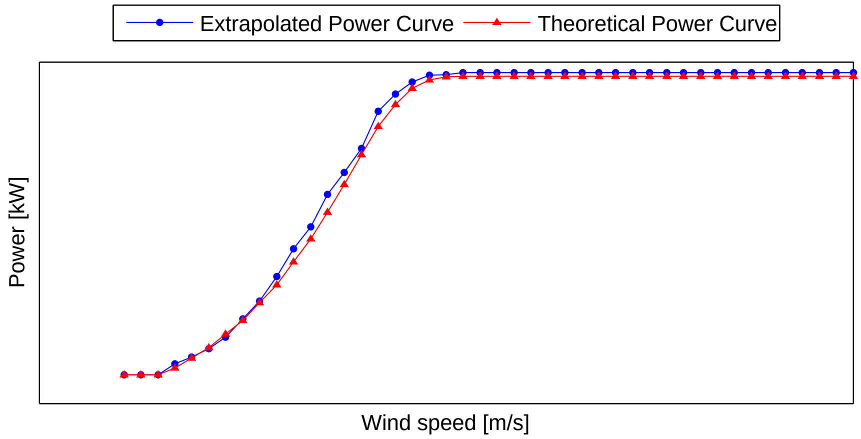

Figure B.41: Extrapolated power curve and Theoretical power curve versus wind speed

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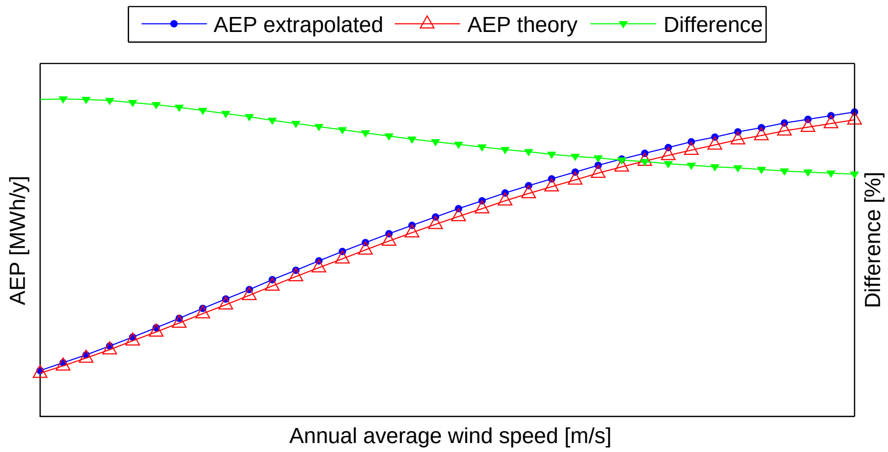

Figure B.42: Calculated annual energy production for the extrapolated and theoretical power curve

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Appendix C

Matlab® Code Trend Analysis

```
%% Time analysis
SegDur=24*7;                    %Duration of one segment
PeriodStep=24;                  %Step size

for SegWS=min(Vmea30):max(Vmea30)

    VPeriod=0;
    PPeriod=0;
    TPeriod=0;
    tindex=0;
    PPer=0;
    TPer=0;
    VPer=0;

    PTh=Ptheor(Vtheor==SegWS);
     scatter(Time30(Vmea30>(SegWS-0.5)&Vmea30<(SegWS+0.5)),Pmea30(Vmea30>(SegWS-0.5)&Vmea30<(SegWS+0.5)))
     hold on
     line(Time30,ones(1,size(Time30,1))*PTh,'color','k')

    filter=find(Vmea30>(SegWS-0.5)&Vmea30<(SegWS+0.5)); %Filter for current period
    VPeriod=Vmea30(filter);
    PPeriod=Pmea30(filter);
    TPeriod=Time30(filter);

    maximumTime=max(TPeriod);    %Total time

if ~isempty(VPeriod)  % If there is data in this period
    for t=1:(maximumTime)/PeriodStep
        tindex=find(TPeriod>=(t-1)*PeriodStep & TPeriod<=(t-1)*PeriodStep+SegDur);
      PPer(t)=mean(PPeriod(tindex));
      TPer(t)=(t-1)*PeriodStep;
      VPer(t)=mean(VPeriod(tindex));
    end
        p = polyfit(Time30(filter),Pmea30(filter),2);
        q = polyval(p,Time30(filter));
     YValue(SegWS)={q};
     XValue(SegWS)={Time30(filter)};
     plot(Time30(filter),Pmea30(filter),'r-')
     hold on
     plot(Time30,ones(1,size(Time30,1))*PTh,'b-')
     plot(TPer,PPer,'k-')
```

```
      plot(Time30(filter),q,'g-')
      title(sprintf('Trend analysis: Period %3.0fh, Segment %3.0fh, wind
           speed: %2.0fm/s.',PeriodStep,SegDur,SegWS))
      xlabel('Time [h]')
      ylabel('Power [kW]')
      pause; close;

end
end

s={0};
h=0;

list=jet(SegWS-4);
figure,hold on
for i=1:SegWS-4

s{i}=sprintf('%2.0f m/s',i+4);
h(i)=  plot(XValue{i+4},YValue{i+4},'color',list(i,:));
end
legend(h',s')

      grid on
      title('Trend analysis: filtered')
      startDate = datenum(YEAR,MONTH,DAY);
      endDate = datenum(YEAR,MONTH,DAY);
      xData = linspace(startDate,endDate,6);
      set(gca,'XTickLabel',datestr(xData,'dd mmm'))
      xlabel('Time [d]')
      ylabel('Power [kW]')
 pause; close;
```

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Appendix D

Math example

The workings of Equation 5.29 can be shown by using a simple formula Equation D.1.

$$y(x) = x^2 + 2x = f(x) + g(x) \tag{D.1}$$

If a is defined as:

$$a(x) = 2x \tag{D.2}$$

y can be rewritten as:

$$y(x) = f(x) + g(a(x)) \tag{D.3}$$

The derivative can then be expressed as:

$$\frac{\partial y(x)}{\partial x} = \frac{\partial f(x)}{\partial x} + \frac{\partial g(a(x))}{x} \tag{D.4}$$

With the chain rule this equal to:

$$\frac{\partial y(x)}{\partial x} = \frac{\partial f(x)}{\partial x} + \frac{\partial g(a(x))}{a} \frac{\partial a(x)}{x} \tag{D.5}$$

$$\frac{\partial y(x)}{\partial x} = 2x + 1 * 2 \tag{D.6}$$

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