THE REPUBLIC OF TURKEY
BAHÇEŞEHIR UNIVERSITY

WIND RESOURCES ASSESSMENT AND MICRO-SITING: UNCERTAINTY ANALYSIS APPROACH

Master's Thesis

MOUHAMD FOUAD ASSASA

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THE REPUBLIC OF TURKEY
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THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
ENERGY SYSTEM OPERATION AND TECHNOLOGY

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This is to certify that we have read this thesis and we find it fully adequate in scope, quality and content, as a thesis for the degree of Master of Science.

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ABSTRACT

WIND RESOURCE ASSESSMENT AND MICRO-SITING: UNCERTAINTY ANALYSIS APPROACH

MOUHAMD FOUAD ASSASA

ENERGY SYSTEM OPERATION AND TECHNOLOGY

Prof.Dr. Mehmet Barış ÖZERDEM

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This study deals with assessing the wind resource and potential wind energy production at a wind site and the uncertainty which is associated with the wind resource assessment process. All steps of the wind resource assessment process are subject to uncertainty which has an impact on the predicted wind energy production. An appropriate evaluation of the uncertainty is critical for judging the practicality and danger of a potential wind energy improvement. Thus, regard the uncertainty in the wind assessment project is greatly important to decide the possibility of success of the wind investment.

In this study, the wind resources of a site located in Turkey are assessed.Then, the uncertainty of the wind speed measurement at the target site, the uncertainty of the long-term wind data estimation of the target site, the uncertainty of the site assessment, and the uncertainty of the wind resources variability are analyzed. A method is presented for combining the uncertainty of all steps of the wind resource assessment. Then, the predicted wind energy production is determined based on these uncertainties using the probability of exceedance term and the uncertainty map of the target site is drawn using openwind software.

Keywords: Wind Resource Assessment, Wind Energy Production, Uncertainty, Probability of Exceedance.

ÖZET

RÜZGAR KAYNAK DEĞERLENDİRME VE MİKRO-YERLEŞTİRİLMESİ:
BELİRSİZLİK ANALİZİ YAKLAŞIMI

MOUHAMD FOUAD ASSASA

ENERJİ SİSTEMLERİ İŞLETİM VE TEKNOLOJİLERİ

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Bu çalışmada rüzgar kaynağı değerlendirme süreçleri ile ilişkili rüzgar sahalarındaki belirsizlikler ve bu sahalardaki potansiyel rüzgar enerji üretimi ve rüzgar kaynakları üzerine çalışılmıştır. Rüzgar kaynağı değerlendirmesi ile ilgili süreçlerin tüm adımlarında, kestirimi yapılmış olan rüzgar enerji üretimi üzerinde etkiye sahip belirsizlikler bu konu içerisinde yer almaktadır. Belirsizliklerle ilgili değerlendirmeler potansiyel rüzgar enerjisi gelişmelerindeki tehlikeler ve pratiğinin yapılması açısından yargılanması önem arz etmektedir. Bu nedenle rüzgar enerjisi değerlendirme projelerinde belirsizliklerin dahil edilmesi rüzgar enerjisi yatırımlarının başarı olasığına karar vermekte oldukça önemlidir.

Bu çalışmada Türkiye’deki rüzgar enerjisi sahaları değerlendirilmiştir. Daha sonrasında, hedef sahadaki rüzgar hız ölçümlerinin belirsizliği, hedef sahadaki uzun dönem veri tahmin belirsizliği, saha değerlendirme belirsizliği, rüzgar enerji kaynağı çeşitliliğinin belirsizliği analiz edilmiştir. Yöntem rüzgar enerji kaynağı değerlendirmesi adımlarının tümü birleştirilerek sunulmuştur. Sonraki adımda, bu belirsizliklere bağlı olarak kestirimi yapılan rüzgar enerji üretimi, ‘aşılma olasılığı terimi’ kullanılarak ve hedef sahanının belirsizlik haritası openwind yazılımı kullanılarak çizilmiştir.

Anahtar Kelimeler: Rüzgar Kaynak Değerlendirmesi, Rüzgar Enerjisi Üretimi, Belirsizlik, Aşılma Olasılığı.

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ABBREVIATIONS

AEP	:	Annual Energy Production
CFD	:	Computational Fluid dynamics
IEC	:	International Electrotechnical Commission
LIDER	:	Light Detection and Ranging
LT	:	Long-term resource estimation uncertainty
M	:	Wind Speed Measurement Uncertainty
MCP	:	Measure-Correlate-Predict
NCAR	:	National Center for Atmospheric Research
NCEP	:	National Centers for Environmental Prediction
NREL	:	National Renewable Energy Laboratory
SA	:	Site assessment uncertainties
SODAR	:	Sonic Detection and Ranging
V	:	Wind resource variability uncertainties
WAsP	:	Wind Atlas Analysis and Application Program
WRA	:	Wind Resource Assessment
WRG	:	Wind Resource Grid

SYMBOLS

Accuracy of measurement	:	k
Correlation coefficient	:	r^2
Dependent variable	:	x
Energy production	:	P_{ik} (kwh)
frequency of occurrence	:	f_{ik}
Height of the higher anemometer	:	h_2,(m)
Hub height	:	h_H ,(m)
Independent variable	:	y
Mean wind speed	:	$\overline{U}$,(m/s)
Number of the bin of the wind speed	:	N_u
Number of the years of the reference data	:	N_R
Number of the years of the target site data	:	N_T
Number of the years of the turbine lifetime	:	N_p
Power law exponent	:	α
Probability density function	:	f (u)
Regression model	:	*f(y)*
Roughness length	:	Z0 , (m)
Scale parameter of Weibull distribution	:	c ,(m/s)
Sensitivity factor of site assessment uncertainty	:	SF_{SA}
Sensitivity factor of the long-term resource uncertainties	:	SF_{LT}
Sensitivity factor of the wind resources variability uncertainties	:	SF_V
Sensitivity factor of the wind speeds measurement uncertainty	:	SF_M

Shape parameter of Weibull distribution	:	k
Standard deviation of annual mean wind	:	σ_{annual}
Standard deviation of reference data	:	σ_R
Standard deviation of target site data	:	σ_T
Standard deviation of the wind speed	:	σ
The height of the lower anemometer	:	h_1 ,(m)
The residual	:	a
Turbulence intensity	:	TI
Uncertainty	:	δ_x
Uncertainty of the wind speed	:	δU
Wind speed	:	u ,(m/s)
Wind speed at height reference hight zr	:	U_{zr} ,(m/s)
Wind speed at height z	:	U_z ,(m/s)

1. INTRODUCTION

Driven by worries over environmental change and energy security, and the increasing expense of fossil powers, renewable energy has become a very significant source of energy around the world. Lately, wind energy has ended up a standout amongst the most inexpensive renewable energy. The headmost and the most significant step to evaluating the wind farm project is to assess the wind resource (WRA). The objectives of the wind resource assessment are to explore the qualities of the wind, to determine and plan proper wind turbine farms, to evaluate the potential wind energy, and to decide the potential of achieving the wind turbines project.

The quality of assessing of the wind resources assessment at a target site is controlled by the wind resources assessment process. The harvest of the wind resource assessment process is wind condition and annual wind energy production. The financial site of the wind turbines project uses this data to calculate the economic feasibility of the wind turbines project.

The wind resource assessment process aims to check the wind resource at a target site, then, predict the long-term wind data of the target site and the potential wind energy production of the target site. This process, in whole steps, is subject to uncertainties.

Uncertainty occurs at each step of the wind resource assessment steps such as uncertainty of the wind measurement data at the target site, the uncertainty of the wind turbine power curve and others. Therefore, wind resource assessment and power curves are uncertain processes. Thus, when the wind data, power curve of the wind turbine, and energy loss are incorporated to evaluate the annual wind energy production, the uncertainties of them take part of the uncertainty of the expected annual wind energy production. Thus, the feasibility and risk of a potential wind energy investment are evaluated through a proper analysis of uncertainty.

However, it is difficult to figure out the uncertainty of a wind project. Some of the uncertainties are calculated and some of them are estimated. There is no standard to determine the uncertainty of the wind project steps, but there will be one in 2018 IEC International Electrotechnical Commission 61400-15 (Wind Resource Assessment, Energy Yield and Site Suitability Input Conditions for Wind Power Plants). The absence of standard prompts subjectivity. Thus, the outcomes rely on upon the skills and methodology.

This study will cover the steps of the wind resource assessment while looking at some of the possible methods using wind measured data which has been collected from a site near the Marmara Sea in Turkey. In this study, all sources of the uncertainty associated with the wind resource assessment are determined. The net wind energy production of the wind turbines is calculated. Then, a probability of exceedance (Pxx), which is used to express the uncertainty of the annual energy production, is calculated.

In this study, WindPRO software of EMD international A/S is used for analysis of the wind data, such as cleaning, filtering, handling, and predicting long-term wind data for the target site. Then, Openwind software of AWS Truepower is used to determine the wind flow modeling, the uncertainty of the wind flow modeling, uncertainty map, annual wind energy production and probabilities of exceedance.

In the literature review chapter, general information about the previous studies and researches about the wind resource assessment methodology are mentioned. In the data and method chapter, the explanation about the wind data and the methods that are used to estimate the wind resources on the target site are included. In the uncertainty analysis approach chapter, methods of estimating the uncertainty of the wind resource measurement and uncertainty functionality within the openwind software are explained. Method to combine the uncertainty in the wind resource is defined. In the result and dissuasion chapter, results and discussion are explained clearly.

2. LITERATURE REVIEW

Wind resources assessment evaluates the probability of the wind energy production of a target site. Zhang, M (2015) has explained in his book in details about the wind resource assessment methods. Brower, M (2012) has explained about the wind resource assessment process. Landberg, Al (2003) has recorded eight different methods that are used for assessing the wind resources of the target site.

These steps of the wind resource assessment are subject to uncertainty. Thus, the uncertainty in measurement wind data and the uncertainty in the wind turbine power curve affect the predicted energy production. Lackner, M (2007) has studied about uncertainty in the wind resources assessment steps and uncertainty of power curve. Duck, S (2009) has studied about probability models to estimate the uncertainty in the wind resource assessment and empirical probability model to estimate the uncertainty of the wind turbine power curve. Then, a numerical simulation which uses the probability model has been used. The results showed that these probability methods can efficiently evaluate the wind energy production.

The wind resource assessment uncertainty includes wind measurement data uncertainty, the uncertainty of the expected long-term wind data at hub height at a target site, uncertainty due the vertical extrapolation, uncertainty due to the wind flow model and uncertainty due to the wind resource variability. Jung, S (2012) has noted in his paper about uncertainty in the predicted wind energy due to the limited data. The long-term data for the nearby site and the limited data of the target site were used. Then, the Bayesian approach was used to estimate the wind energy production. He found that the Bayesian approach could estimate the wind energy production reliably by using limited wind data.

Taylor, M (2010) has studied about the uncertainty of the wind energy production due to the measure-correlate-predict and uncertainty of the wind shear extrapolation. It was found that for estimating the long-term wind speed uncertainty at hub height for a target site the uncertainty due to the anemometer, uncertainty due to the met mast effects, the monitoring period of the site data, and the period of the reference data should be considered. Rogers, A (2005) has studied about the uncertainty due to the measure-correlate-predict method. Agnes, F (2008) has studied about uncertainty in the wind energy production due to the uncertainty of the wind measurements and wind resource variability uncertainty. The study showed that uncertainty due to the wind measurement could be decreased by monitoring the wind measurement accurately and limiting the errors resultant by device failure. In addition, the variability was independent factor causes uncertainty. IEC method and the Monte Carlo method are used to estimate the wind energy uncertainty.

Duck, S (2010) has studied about the uncertainty of the wind resource assessment due to the wind resource variability and power performance. The probability distribution models were used to estimate the uncertainty of variability and empirical probability model to estimate the uncertainty of the wind turbine power curve. Then, a numerical simulation which uses the probability model had been used. It found that the uncertainty in the wind resource estimation could be calculated with more accuracy with regarding all the source of the uncertainty of the wind data measurement.

Dehghani, H (2014) has studied about uncertainty quantification. The five regression method had been used to calculate the uncertainty of the wind energy production.

The uncertainty of the power curve affects the wind energy production. This uncertainty is important and it must be considered to determine the wind energy production correctly. Lin, P (2014) has studied about the uncertainty of the wind turbine power curve respect to the wind data measurement of the target site. The method of bin had been used to get wind turbine power curve of the measured wind data. The method of non-parametric had been used to calculate the uncertainty of the wind turbine power curve under confidence interval. Rodrigues, C., (2013) has studied about the uncertainty of the power curve and has found that the uncertainty of power curve is to be 5 percent to 10 percent.

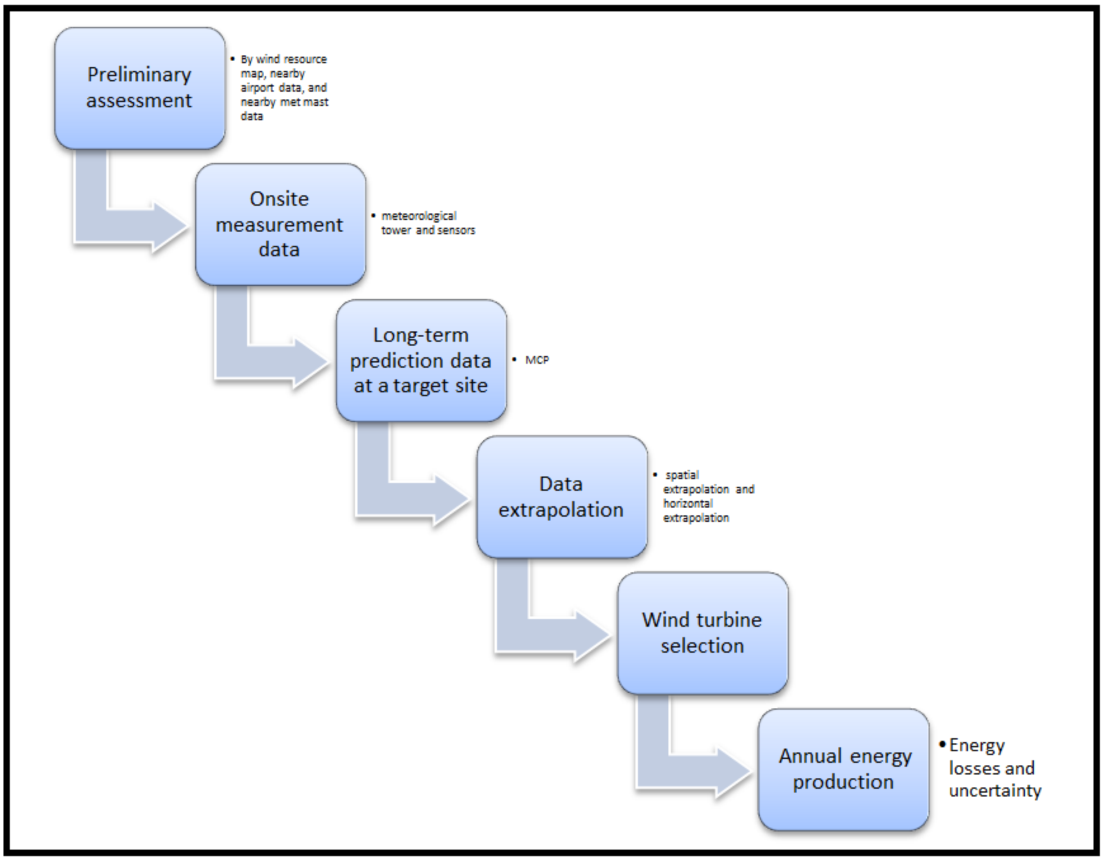
Pedersen, T.F., (2002) has studied about the uncertainty of the power curve and found that the uncertainty of power curve is to be 6 percent to 8 percent. Frandsen, S., (1992) has studied about the uncertainty of the power curve found it to be 5percent to10 percent.

The uncertainty of the wind resource assessment cannot be same for all sites and it is different from the site to other. Thus, correct identification of the uncertainty is to have relied on the skills and methodologies.

3. DATA AND METHOD

Wind resource assessment like any specialized project needs an exact procedure in light of an arrangement of conditions like the timetables, spending plans and others to accomplish the sought objectives. There are six steps of the wind resource assessment process as it is shown in Figure 3.1 are followed through this study.

Figure 3.1: Steps of wind resource assessment process



Source: Jain, P 2011, p.112.

3.1 PRELIMINARY SITE ASSESSMENT

The initial step is to check the site in the event that it is suitable for development or not, windy or not, and check the site's geology and obstacle. These are done through checking the wind resource map of the target site and detailed analysis of nearby airports data and nearby met mast data.

3.2 ONSITE MEASUREMENT DATA

Wind resources are assessed for a site which is located near the Marmara Sea in Turkey where the terrain is complex, it is an open area, and the vegetation is mainly grasslands, a forest in the north and brushwood behind the village which is 4.5 Km away from the site. Two (50m) met-mast towers have been installed to measure the wind data; the distance between them is 1.5KM as it is shown in Figure 3.2. Three cup anemometers have been placed at the different height (50m, 40m, 30m) respectively. Two wind vanes have been placed at two different heights (48m, 38m) respectively. The wind data has been recorded by the data logger at a sampling rate of two seconds which is then averaged at 10 minutes. The data has been measured for one year. This wind data is given by a commercial company. Thus, there is no possibility to mention for more details such the coordinates and others due to commercial reasons.

WindPRO software is used to deal with wind measurement data. Thus, cleaning, filtering, handling, and predicting long-term wind data of the target site have been done by WindPRO software. This software has a high efficiency and is used by many commercial companies and for the purpose of scientific research. (http://help.emd.dk/knowledgebase/ accessed on 23 /06/2015).

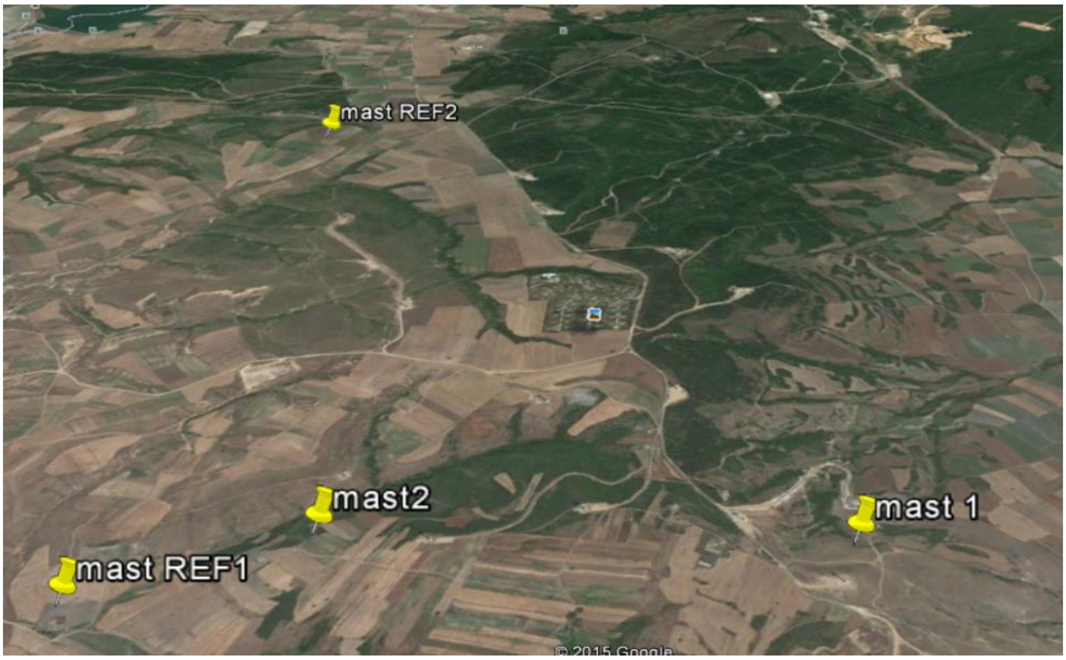
For the long-term reference data, two sources of the long-term reference data from the close sites are used. The data has been collected at 50m height for 22 years and has been recorded for 1-hour average. Figure 3.3 shows the locations of the met masts of the long-term reference data which are taken from nearby sites.

This data has been taken using WindPRO software. The WindPRO offers online data of the long-term reference data for 20 years and more. This data has been formed by various reanalysis projects. (http://help.emd.dk/mediawiki/index.php?title=Category%3AWind_Data accessed on 07/07/2015).

Figure 3.2: The locations of the met mast towers

Source: This picture is taken by Google earth.

Figure 3.3: The locations of the long-term reference data

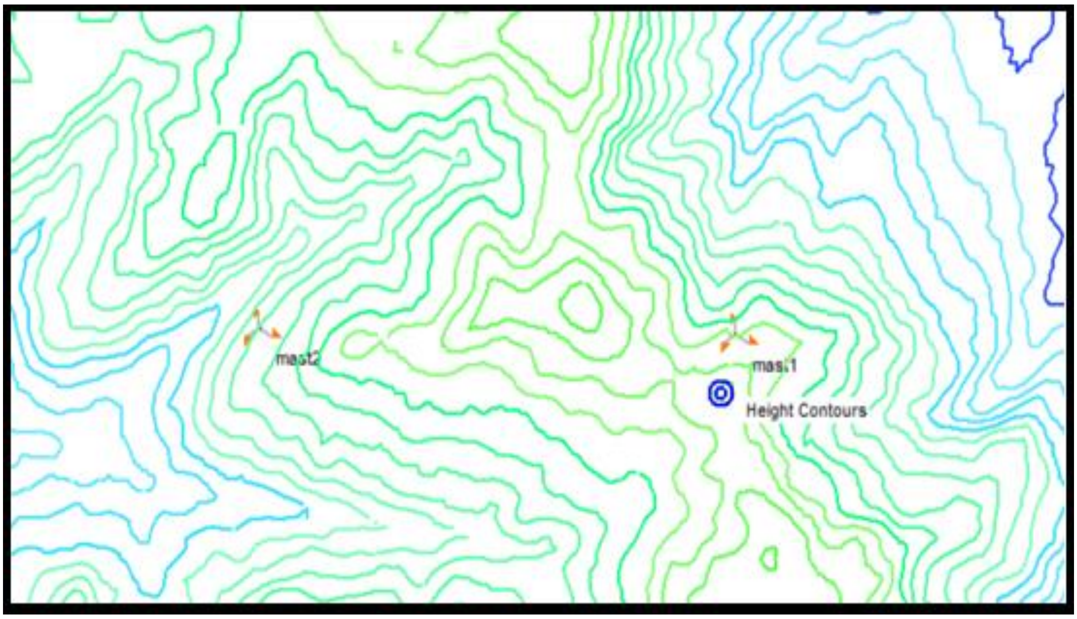


Source: This picture is taken by Google earth.

For the Contour line which is a digital map of the estimation of the region on the earth. This information is gathered by private companies or is purchased from organizations, such as the United State Geological Survey (USGS), which have already gathered the elevation in many regions of the world. During the wind project, the information about the elevation in the target site of at least 5 Km around the met mast tower is required. (https://en.m.wikipedia.org/wiki/Isotherm_(contour_line)#Temperature_and_related subjects accessed on 07/07/2015).

For this study, The contour line map is taken by WindPRO software. The WindPRO software offers digital maps for most regions of the world which are taken form USGS. The digital site of the target site is shown in Figure 3.4. (http://help.emd.dk/mediawiki/index.php?title=Category%3AOnline_Data accessed on 07/07/2015).

Figure 3.4: Digital map of the site

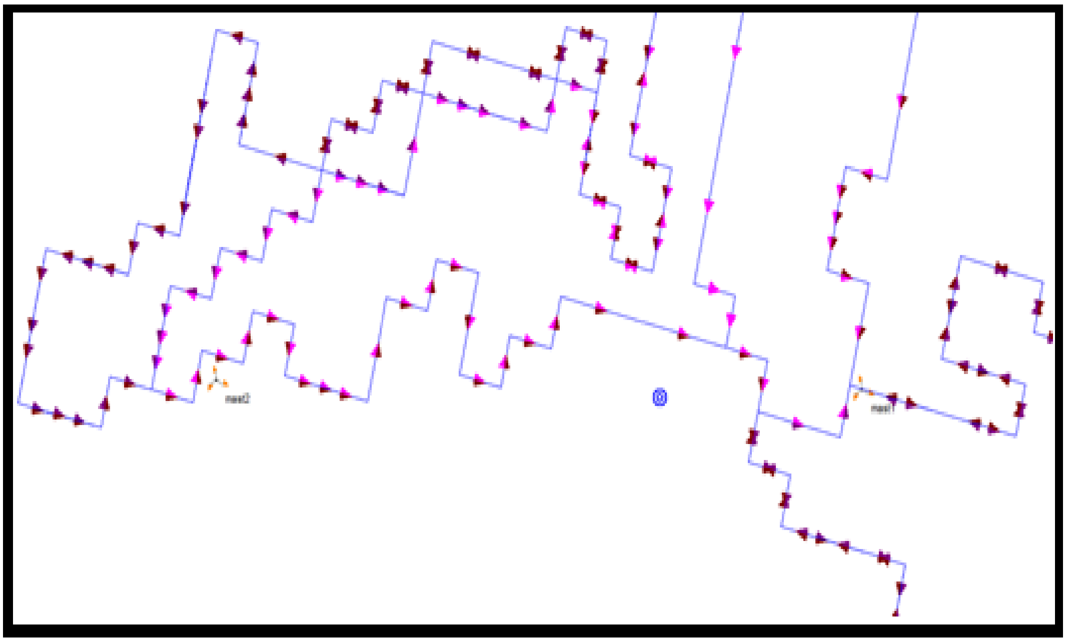


Source: WindPRo Software online data.

The roughness of the site surface has an impact on the wind flow. Thus, the vegetation types have an impact on the wind flow in different ways which means the impact of the roughness changes as the height and density of the roughness element change. The roughness classifications are defined by roughness length.

For this study, the roughness map of the site is taken by WindPRO software as it is shown in Figure 3.4. The WindPRO software offers roughness maps for most regions of the world which are taken form Corine land cover. Corine land cover is done by visual understanding of satellite imagery. It covers groups of land cover in 44 classes which has been set into roughness length to be used in WindPRO. This is map is produced by the European Environment Agency (EEA). (http://help.emd.dk/mediawiki/index.php?title=Corine_2006 accessed on 07/07/2015).

Figure 3.5: Roughness map of the site



Source: WindPRo Software online data.

3.2.1 Equipment Used for Wind Measurements

The wind data of the target site is collected by using meteorological tower and sensors to gauge wind speed, wind direction, humidity, temperature, and pressure. Based on the size of the examined site and the type of its terrain the numbers of required met mast towers are determined. Thus, if the site is large and the terrain is complex, multiple met mast tower may be necessary. The installations of the met mast tower and the sensors have to be done by following IEC 61400-12-1 standard. (IEC 61400-12-1 ,2005).

Minimum one-year measured data are required for assessing the wind resource at the target site. So, the seasonal effects may be captured during one year. If there is more than two-year data the diurnal, seasonal, and inter-annual variations in the wind resource may be captured. (Baily, B.,1997).

3.2.1.1 Meteorological Tower (Met Mast Tower)

All the sensors which are used to measure wind parameters at the target site are installed on the met mast tower. Generally, the height of the met mast tower is between (30m to 120m). The met tower which is installed for 1 to 3 years is considered as temporary tower while the met mast tower which is installed for 20 years is considered as a permanent tower.

There are two types of the met tower: (1) tubular tower (2) lattice tower. Generally, they are installed using a set of guy wires connect between the tower from several heights and the ground. The aim of those wires is to ensure the stability of the tower in the vertical direction and protect the met mast tower. (Jain, P., 2011, p.76)

The installation of the met mast tower needs a group of workers and a full day to be installed. For the raising and lowering the met tower, the gin pole which is small tubular is used. The gin pole connects between tower and winch. Many conditions should be considered before installation such as terrain, obstacles, and others.

As a rule, the met mast tower should be located at a distance equivalents to ten times of the obstacle tallness which is located in the prevailing wind direction to avoid the effects of the obstacles. (Bailey, B.,1997).

3.2.1.2 Anemometer

Anemometers are used to measure wind speed. These sensors are usually located at three or four different heights on the met mast tower, at each height two anemometers are installed the main one and redundant one which is used to avoid the impact of the tower shadow, which happens when the met mast tower affects the measurement of the main anemometer, and to avoid the errors due to anemometer fails.

The anemometer is installed on the boom which is placed on the met mast tower. In the standard, the boom length is equivalent to the six times the diameter of met mast tower. The aim of using the boom is to place the anemometer away from the tower to decrease the effects of the tower. (Jain, P., 2011, pp.77-85).

The Calibration of the anemometer is important, this procedure removes the errors resultant by manufacturing. All anemometers have to be calibrated by MEASNT calibration principle. (MEASNT, version2, 2009).

There are three types of anemometer: cup anemometer, propeller anemometer, and sonic anemometer. The most commonly used is cup anemometer. Cup anemometer includes three cups with a vertical pivot of turn. The angular velocity of the cups is commensurate to the wind speed. AC sine wave is the output of the anemometer which goes to data logger through wires. (Baily, B.,1997). The wind speed data that is used for this study has been measured by “Vector Al00LM” cup anemometer.

3.2.1.3 Wind Vane

Wind vanes are used to measure wind direction. These sensors are usually located at two different heights on the met mast tower. The wind vanes are installed under the anemometers in 2 to 4 m to avoid the wake effect on the anemometers. The analog voltage is the output of wind vane which is proportional with wind direction.

There is a north marking on the vane must be in the true north direction. If it is not so, the offset can be given in the data logger. (Jain, P., 2011, p.81). The wind direction data of the target site has been measured by “Vector W200P” wind vane.

3.2.1.4 Pressure, Temperature, and Humidity Sensors

They are installed on the met tower at a low height. The aims of measure the pressure and temperature are to calculate the air density and to figure out the icing situation which leads to errors in wind measurement data.

3.2.1.5 Data Logger

Data logger is placed on the ground near the met mast. All the sensors, which are placed on the met mast tower, are connected to the data logger in order to store the measured data.

3.2.1.6 Ground- Based Wind Speed Measurement Devices

Close to estimates of the wind data with conventional met mast tower, in the late years, newer measurement devices are used. These devices provide methods to measure wind speed at great highs proportional with 130 to 150m hub height. There are two devices are used commonly: (1) Sonic detecting and ranging. (Walls, E., 2007). (2) Lightning detecting and ranging. **(** Simley, E., 2012).

3.2.2 Statistical Analysis of Wind Data

Probability distribution function of wind velocity, which is one of the statistical models, characterizes the frequency of occurrence of wind speed at a site. The most common probability distribution functions of wind speed used in wind data analyze are Rayleigh distribution function and Weibull distribution. Weibull distribution function is described by two factors: K which is the shape factor and C which is scale factor (some references use A instead of C). Rayleigh distribution function is a special case of Weibull distribution realized when k is equal to 2. Therefore, it has just one factor which is c scale factor. Thus, Weibull distribution represents wind speed distribution better than Rayleigh. (Manwell .J., 2009.p57).

For this study, Weibull distribution describes the wind velocity distribution because wind speed distribution is fitted well by Weibull distribution. In the other words, Weibull distribution fits the wind speed distribution very close to the actual wind speed distribution. (Manwell .J.,2009.p59). The Weibull distribution is determined by the following equation for u wind speed:

$$P(u) = \frac{k}{a}\left(\frac{u}{a}\right)^{k-1} . \exp[-(\frac{u}{a})]^{k} \quad , k > 0, a > 1, u > 0 \qquad (3.1)$$

3.3 LONG -TERM DATA PREDICTION

Wind data at the site is subject to variations. These variations are diurnal, seasonal, and inter-annual with taking into consideration the measurement period. Sometimes, the period of time of the measurement data into a site has not covered all the wind variations. In other words, the time period of the variations is longer than the measurement period of the wind speed at the target site.

Thus, the measurement data is not represented the actual long-term wind data. The twenty-year wind data or 30 year has high efficiency to represent the long-term data for a site which includes most of diurnal, seasonal, and inter-annual variability. The estimation of long-term data for a site is one of the objectives of wind resource assessment, therefore, the time period of the measurements should cover the period of wind variations. (Manwell, J,.2009.pp.28-32). On the other side, it is not logical to measure wind data for 20 or 30 years.

Measure-Correlate-Predict (MCP) is a method aims to estimate the long-term wind data for the target site based on the onsite measurement data and long-term reference data. (Saengyuenyongpipat, P.,2010).

The steps of the MCP method are: (Jain, P., 2011,p.127).

1. **Measure:** in this step two sources of data should be determined. The short term data which is the onsite measurement data measured for minimum one year. The long term data which is the reference data taken by a nearby site.
2. **Correlate:** it creates a functional relationship between the target site data and the reference site data for the synchronous time period. In this step, the correlation coefficient expresses the level of correlation between two data sources.
3. **Predict:** in this step, the predicted long-term data for the target site is done by applying the conversion function into the reference data.

In the WindPRO which is used for this step, there are four different MCP methods (a) Linear Regression, (b) Matrix MCP, (c) Wind Index MCP, (d) Weibull Scale.

The MCP model for WindPRO is able to submit full complete MCP analysis in few hours through the following: long-term reference data by NCEP or NCAR, measured wind data for the target site, correlation between data sources in synchronous period, prediction by using linear Regression, Matrix MCP, Weibull Scale, Wind Index MCP, then generate wind statistics from the MCP prediction.(Nielsen,p.,2013). (Thøgersen, M.L., 2007).

The linear regression and matrix methods are similar in principle. They are using the synchronous period between the data to find conversion function which converts the reference data to have same conditions of the onsite measurement data. The success of conversion process is expressed by the correlation coefficient. They make correlation based on the relation between the wind directions, and based on the frequency of the measurements at the two sites. The correlation coefficient has a value between (0 to 1). (Nielsen, p., 2013). (Thøgersen, M.L., 2007).

The wind index method is used when the quality of the reference data is poor. The wind index is expressed by the correlation factor which gives the relation between the reference data and the synchronous part of the reference data based on changing wind speed to wind energy.

Thus, the wind direction correlation is not required. This technique depends on studying the energy on the target site then scales the final result with the correlation factor. (Nielsen,p.,2013). (Thøgersen, M.L., 2007).

The Weibull parameter method is based on scaling the wind data with the Weibull distribution. This method cannot calculate the correlation between the long-term reference data and the short measurement data in the synchronous period and cannot form conversion function. Meanwhile, sometimes it can give a good prediction of the long-term data. (Nielsen,p.,2013). (Thøgersen, M.L., 2007).

For this thesis, a comparison between the linear regression method and the Matrix method is done. Then, the method which gives higher correlation coefficient is used.

Linear Regression

Linear models are used for wind direction and wind speed estimation, and they are applied sector by sector. WindPRO has improved the traditional linear regression methods by including the model of the distribution of the residuals which makes the linear regression methods catch the energy in the target site more quality than using the method without that. (Thøgersen, M.L., 2007).

Regression modeling is used to get logic fit for wind energy estimation. It is based on the following equation. (Nielsen, P.,2013)

$$x = f(y) + a \tag{3.2}$$

Where; *x*: is the dependent parameter which represents the measured wind speed at the target site.

y: is the independent parameter which represent the wind speed at the reference sit.

f(y): is the regression function.

a: is residual.

Matrix Method

This method is applied to a matrix of wind speed ranges and direction sectors from the reference time series. Thus, the wind speed-up and wind direction veer for the target site are taken as a function to the wind speed and wind direction of the reference site. (Thøgersen, M.L., 2007).

3.4 DATA EXTRAPOLATION

There are two types of the wind data extrapolation that should be applied on the wind data: spatial extrapolation and horizontal extrapolation.

3.4.1 Spatial Extrapolation

The wind data is measured at the point which the met mast placed in. Therefore, the wind data should be determined at the locations where measurements were not measured. In other words, the wind data should be determined at the location where the wind turbines will be installed.

The terrain could cause a difference in the wind resource between the met mast location and the final turbine location(s). Flow modeling is used to adjust the wind resource according to the verify terrain, obstacles, and roughness at the target site. This process is called spatial extrapolation of wind data.

3.4.2 Vertical Extrapolation

The hub height of the wind turbine is higher than the met mast tower. Usually, the wind data is measured at the lower height than the hub height. Since the wind conditions change with changing the height the wind shear modeling is used to extrapolate the wind condition at the hub height of the wind turbine. This is process is called vertical extrapolation of wind data.

Wind speed increases with height increase. The wind energy increases with increasing of the wind speed where the wind energy is Proportional to the cube of the wind speed. Thus, the higher hub height of wind turbine is preferable to be used in order to capture more energy.

On the other hand, increasing the hub height of the turbine without increasing the height of the met mast tower will increase greatly the probability of uncertainties in the vertical extrapolation process. (Lubitz, WD., 2006).

There are two models used to model vertical profile of the wind speed: Logarithmic Profile (log law) and power-law profile. Both of them are subject to the uncertainties occurred through extrapolation process. (Manwell, J., 2009.p47).

Logarithmic Profile (log law) is used in the boundary layer flow in fluid mechanics research and atmosphere research and found based on the theoretical and empirical studies. It is given by the following equation.

$$\frac{U_z}{U_{zr}} = \frac{\ln(\frac{Z}{Z_r})}{\ln(\frac{Z_r}{Z_0})} \tag{3.3}$$

Where; U_Z: is the wind speed at height z which is the hub height of the turbine.
U_{Zr}: is the wind speed at the reference height z_r which is the height of the met mast tower.
z_0: is the roughness length.

Power law profile is used by many wind energy research and it is given by the following equation.

$$\frac{U_z}{U_{zr}} = (\frac{Z}{Z_r})^{\alpha} \tag{3.4}$$

Where; α: is the power law exponent.

Experiences and research have proven that the power law exponent varies with elevation, nature of the terrain, wind speed, time of day, season, temperature, and various thermal and mechanical parameters. (Lubitz, WD., 2006).

3.5 SELECTION OF THE WIND TURBINES

Wind turbines are selected once the wind resources are estimated, the goals of the developer to get maximum energy production and the durability of turbines. The wind turbine is described by its power curve which defines the relation between the output power of the wind turbine and the incoming wind speed. The location of the wind turbine, air density, turbulence intensity, and the wind shear can affect the power curve of the wind turbine.

Furthermore, the cost of the wind turbine is affected by the wind resources at the site. The more turbulence and wind sites require more expensive wind turbine. (Paiva, LT., 2014). The IEC 61400-1 standard provides the wind turbine classes based on the wind speed and the turbulence intensity. (IEC 61400-1., 3rd Edition,2006).

Table 3.1: IEC 61400-1. Classification of the wind turbine

Class	**I**	**II**	**III**	**IV**
Mean wind speed (m/s)	10	8.5	7.5	6
50 years- Extreme wind speed (m/s)	50	42.5	37.5	30
Class	Class A		Class B	
I_{15}	0.18		0.16	

Source: IEC 61400-1. 3rd Edition, 2006

Where,

I_{15} : is the turbulence intensity at 15 m/s.

Class A: indicates the class for higher turbulence intensity.

Class B: indicates the class for midium turbulence intensity.

3.6 ANNUAL ENERGY PRODUCTION

The Gross annual energy production, net annual energy production, capacity factor, and probability of exceedance are calculated.

3.6.1 Gross Annual Energy Production

The most important target of the wind resource assessment process is to compute the annual energy production of the wind farm. The annual energy production is calculated by P_{ik} energy production for each bin wind speed (***i***) and the wind direction sector (***k***), and f_{ik} the frequency of occurrence for each bin wind speed (i) and the wind direction sector (k) as the following equation: (Zhang,M.,2015.p.143).

$$AEP = H.\sum_{i}^{N_B} P_{ij}.f_{ij} \tag{3.5}$$

Where, N_B : is the number of the bin of the wind speed.
H: is the number of the hours in one year 8760.

3.6.2 Net annual Energy Production

The net annual energy production is calculated by substrate losses of the energy production from the total energy production. There are several factors lead to lose energy from wind turbine energy production. These losses must be added to calculate the net wind energy production.

These losses are (A) Electrical losses: due to problems in electrical transmission from the wind turbine to battery, substation, or another endpoint. (B)Availability losses because of shutdown for outside reasons, for example, maintenance. (C) High wind speed hysteresis: the wind turbine close downs when the wind velocity expands more than cut-off wind speed promptly, however, does not work until wind speed reductions well. (D) Icing and blade degradation: change in the blade of the turbine due to the accumulation of snow.

(E) Wake losses or array losses from other wind turbines where upstream turbines reduce the energy available for the downstream turbines. Generally, these losses are between10 percent to 30 percent. (Zhang, M., 2015.pp.143-147).

3.6.3 Capacity Factor

The capacity factor (CF) of the wind farm is the ratio of the net annual wind energy production (AEP) to the maximum annual wind energy production (MAEP) which is achieved when the wind farm works at same nameplate capacity. The capacity factor of the wind farm is 30 percent to 59.3 percent. The 59.3 percent is called Betz's law which determines the maximum power that can be taken from the wind farm. Where, there is no wind turbine can extract more than 59.3 percent from the kinetic energy of the wind. (Boccard, N., 2009)

$$CF = \frac{AEP}{MAEP} \tag{3.6}$$

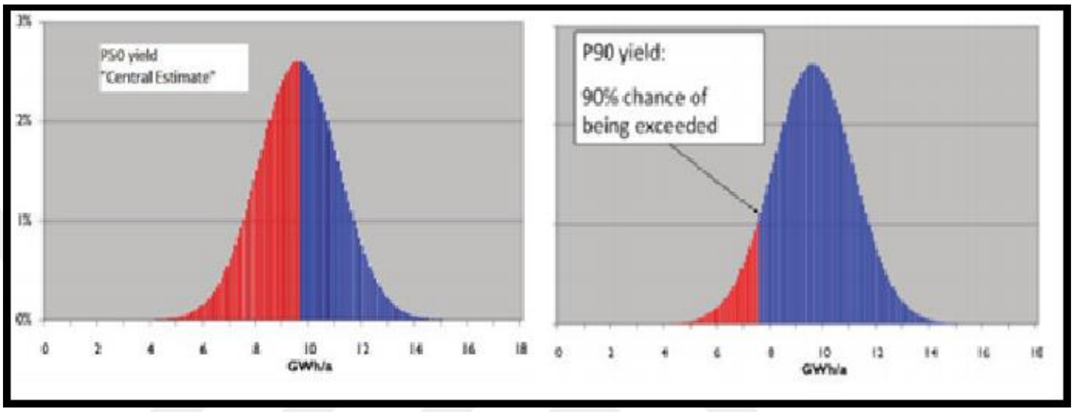
3.6.4 Exceedance Probability of Energy Yields(pxx)

The uncertainty of the annual energy production is important for evaluating the risk of the wind energy investment. The wind resources, power curve, and energy losses are uncertain, therefore, they cause uncertainty in the annual energy production. The uncertainty of the AEP is a critical factor for determining the risks which are associated with the success of the wind project. To evaluate the potential impact of the uncertainties of the annual energy production of the target site, the "Probability of Exceedance" values based around a normally distributed energy prediction is used. (Zhang,M.,2015.pp.151.153).

The central estimate is considered to have the probability of exceedance of P50 which is used to express the net annual energy production which is calculated with considering the energy losses and it means that this annual energy production has a 50 percentto be accomplished through one year as it shown in Figure3.6. Note that, P50 is too much risk for the investors.

Thus, it is preferable to consider other probability of values such as P75 (accomplished 75 percent of the time) and P90 (accomplished 90 percent of the time). P75 means that this annual energy production has 75 percent to be accomplished. P90 means that this annual energy production has 90 percent to be accomplished as it shown in Figure3.6. (Stangroom, P., 2011)

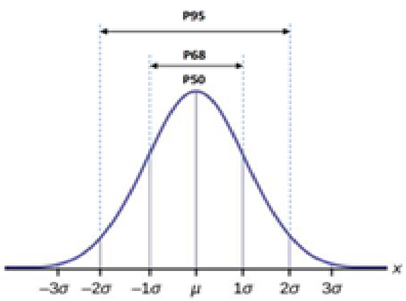
Figure 3.6: Probability of Exceedance values



Source: (Stangroom,P.,2011).

It is assumed that the uncertainty is a normal distribution. Thus, the uncertainty is defined as standard deviation about the mean of the annual energy production (P50 is the mean value of the distribution) as it shown in Figure 3.7. The uncertainty of the wind resource assessment process should be combined to determine the overall uncertainty of the wind project. (Zhang, M., 2015.pp.151-153).

Figure 3.7: Normal distribution of the annual energy production



$$P50 = \mu$$
$$P75 = \mu - 0.67\delta$$
$$P95 = \mu - 1.28\delta$$

Source: (Zhang,M.,2015.p152).

4. UNCERTAINTY ANALYSIS APPROACH

This chapter explains in details the uncertainty analysis approach in the wind resources assessment process. Thus, a comprehensive set of potential sources of the errors and the uncertainties in the wind resources assessment are explained. Method to combine the uncertainty in the wind resources is explained. Wind flow uncertainty is determined using Openwind software.

4.1 OVERVIEW OF ERRORS AND UNCERTAINTY TYPES

The errors which happen in measurement are determined as the variation between the true value and the measured value. Generally, the size of errors is unknown; uncertainty term is used to express the size of the errors. There are two types of errors in measurement: the random error and the systematic error.

4.1.1 Random Error

Random errors in measurement are produced by unexpected and unknown changes in the measuring devices or in the measurement environment during the measurement process. For instance, a spring balance may show a variation in measurement because of fluctuations in temperature or fluctuations in the conditions of loading and unloading. Thus, less fluctuation in device measurements leads to greater precision measurements. (Taylor, J.,1997.p.3). Random error is also called as a statistical error.

The statistical models are used to estimate the random errors in the measurements. Thus, the mean and the standard deviation of the measurements are used as well. For instance, x has to be measured with taking into consideration that systematic errors have been determined and decreased to be negligible thus the remaining errors are random errors. These errors should be decreased by repeating the measurement process N times ($x_1, x_2, \ldots\ldots x_N$). Then, the best value of x is equal to the mean value $\bar{x}$ which is calculated as the following equation: (Taylor, J.,1997.p.97).

$$\bar{x} = \frac{\sum_1^N xi}{N} \quad (4.1)$$

The standard deviation of the measurements $(x_1, x_2, \ldots\ldots x_N)$ is an estimate of the uncertainty in the measurements. The standard deviation of the measurements is determined as following: The difference $(d_i = x_i - \bar{\bar{x}})$ between the mean value $\bar{x}$ and the measured value x_i is called residual or deviation of the measurement process. This d_i tells about the process precise. When it is small the process is precise when it is large the process is not precise. Note that, $\sum d_i$ is equal to zero, because d_i can be negative or positive value, therefore, it is not used to describe the reliability of measurements. Thus, the standard deviation of the measurements $(x_1, x_2, \ldots\ldots x_N)$ can describe the reliability of measurements as the root mean square of measurements (RMS) and it is calculated as the following equation: (Taylor, J.,1997.p.97-10)

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^N (d_i)^2}{N}} \quad (4.2)$$

The standard deviation of the measurements $(x_1, x_2, \ldots\ldots x_N)$ describes the average uncertainty of a single measurement due to random errors $(\delta_x = \sigma_x)$. These errors as assumption have a normal distribution about the true value. [Taylor, J.,1997.pp.101.102]. Thus, 68 percent of the measurements will be into the first standard deviation ($x_{true} \mp \sigma_x$) and 95.4 percent of the measurements will be into the second standard deviation ($x_{true} \mp 2\sigma_x$). (Taylor, J.,1997.pp.137).

The mean value , which is the best value $\bar{x}$, and σ_x the standard deviation of the measurement, which describes the average uncertainty of the single measurement, are calculated. Then, the standard deviation of the mean SDOM which describes the uncertainty in the final answer of the value $\bar{x}$ is calculated as the following: (Taylor, J.,1997.pp.101.102).

$$SDOM = \delta_x = \sigma_{\bar{x}} = \frac{\sigma x}{\sqrt{N}} \tag{4.3}$$

Random errors are classified as type A uncertainty. Type A uncertainty is estimated by using a statistical model, usually from repeated readings. (Bell,S., 2001).

4.1.2 Systematic Error

Systematic errors in measurement are produced by an error in a device calibration, wrong in the data handling system, and the improper use of the measurement device by the experimenter. The systematic errors can be corrected by scaling the measured values with the bias. The bias can be determined by making a comparison with an unbiased device or with measurements from multiple devices. The bias is constant across every measurement, not like the random error which is different with each measurement and can be determined from measured data.

Usually, the uncertainty due to systematic errors is estimated based on experience. In this study, this next assumption is followed; all devices can be exposed to an unknown bias, this bias of the group of those devices is assumed to be a normal distribution with a mean value equal to zero.

The standard deviation of the unknown bias may be determined when many devices are used at the same time. Anywise, if only a one device is used, the uncertainty is determined roughly. The unknown bias is characterized by a normal distribution, and so the standard deviation is the measurement of the uncertainty. (Taylor, J., 1997. p.106).

Systematic errors are type B uncertainty. Type B uncertainty is estimated from any other information which may exist such as previous measurement data, past experience of the measurements, materials and instruments, specifications of manufacturer, and data provided in calibration reports. Systematic error with unknown bias is to be classified as type B uncertainty. Type B uncertainty is described by an uncertainty limit.

Thus, the distribution is rectangular distribution. The standard uncertainty of the rectangular distribution is given by the following equation where σ_x is the semi-range between the upper and lower limits. (Bell, S., 2001)

$$\delta_x = \frac{\sigma_x}{\sqrt{3}} \tag{4.4}$$

4.1.3 Combining Uncertainty Components

Total uncertainty is able to be calculated after defined all sources of uncertainties. For parameter *f*, which is a function of several variable $f = f(x_1, \ldots x_N)$, the absolute uncertainties of the variables are independent. Thus, the absolute uncertainties of variables $(\delta_1^*, \ldots \delta_N^*)$ are combined to calculate the total uncertainty as the following equation (Taylor, J.,1997.p.73-79). (Bell, S.,2001)

$$\delta f = \sqrt{\left(\frac{\delta f}{\delta x_1} . \delta x_1\right)^2 + \cdots + \left(\frac{\delta f}{\delta x_N} . \delta x_N\right)^2} \tag{4.5}$$

The equation (4.5) can be non-dimensionalized when the uncertainty is expressed by fractional uncertainty. For parameter *f*, which is a function of several variable $f = f(x_1, \ldots x_N)$, the uncertainty of the variables $(\delta_1, \ldots \delta_N)$ are fractional uncertainties. The fractional uncertainties of variables are combined to calculate the total uncertainty as the following equation:

$$\delta f = \sqrt{\left(\frac{\delta f}{\delta x_1} \frac{x_1}{f} \delta x_1\right)^2 + \cdots + \left(\frac{\delta f}{\delta x_N} \frac{x_N}{f} \delta x_N\right)^2} \tag{4.6}$$

The partial derivatives and the fractions are referred as sensitivity factor because they measure how the sensitive changes in f are to changes in the variables. The sensitivity factor may be negative or positive to refer to the change in variable leading to increasing or decreasing in *f*.

This index does not affect the equation because of the presence of the square in the equation. The sensitivity factor is non-dimensional. For instance, f has a linear dependence on a variable then the sensitivity factor is one. f has a quadratic dependence on a variable then the sensitivity factor is two. (Taylor, J.,1997.p.73-79). (Bell, S.,2001)

For this thesis equation (4.6) is used to combine uncertainties. And all sources of uncertainties have a normal distribution. Most notably, there is no specific method to combine both types of uncertainty. Taylor and Frandsen (1997) have recommended equation (4.6) as the best way.

4.2 UNCERTAINTY OF WIND RESOURCE ASSESSMENT

Wind resources assessment is the headmost and the most significant step in the wind site estimation process which includes using the onsite wind measurement data to estimate the long-term hub-height wind data. The wind characteristics are changing from year to year so evaluation of long-term wind data at the target site is crucial to determine the annual energy production of the target site correctly.

Broadly, wind resources assessment is a process that takes a long time and includes uncertainties. There are four categories of uncertainties that occur during the process of assessing wind resource. (a) Uncertainties of wind speed measurements δU_M. (b) Uncertainties of long-term wind resource estimation δU_{LT}. (c) Uncertainties due to site assessment δU_{SA}. (d) Uncertainties due to the wind resource variability δU_V. Within each category, there are several individual uncertainty sources. Those individual components are identified in this chapter. (Lackner, M., 2007).

4.2.1 Uncertainties of Wind Speed Measurements (δU_M)

The wind speed at a site is measured by taking 10 minutes average of wind speed sampled. Thus, a time series of these 10-minute averages is used to present wind data. (Baily, B.,1997). U_M is used to refer to the 10 minute averaged wind speeds.

Thus, $\overline{U_M}$ is used to refer to the mean wind speed of the measured wind speeds at the site. The uncertainty of the wind speed measurements occurs due to the uncertainty of the anemometers, the uncertainty due to the met mast effects, the uncertainty due to the booms, and the uncertainty due to the data reduction.

4.21.1 Anemometer uncertainty

Anemometer Uncertainty Due to Calibration Uncertainty (δU_1)

All cup anemometers which are used for wind assessment should have a current calibration. The calibration uncertainty occurs as a result of variations between anemometers of a given model. While, the general transfer function which exists for a model of anemometer may not give the exact performance for a specific anemometer which leads to unknown bias. As an alternative, an anemometer is calibrated in the wind tunnel. Thus, the errors through the calibration may occur and cause errors in the transfer function which leads to unknown bias. (Pedersen, T.F., 2006).The calibration uncertainty is considered as type B uncertainty because it is the result of unknown bias.

IEC 61400-12-1 of power performance testing first edition, 2005, Annex F "Cup anemometer calibration procedure" has determined an equation to calculate the uncertainty of the cup anemometer due to the calibration as a function to the mean wind speed.

$$\delta U_1 = \frac{(0.05 + 0.005\bar{u}).k}{\sqrt{3}} \tag{4.7}$$

According to the IEC 61400-12-1 standard, cup anemometers have been classified based on the accuracy of measurement k and the type of the terrain. The value of k has to be given by the manufacturer of the anemometer. The wind speed data, that is used for this study, has been measured by "Vector A100LK" cup anemometer and the site terrain is complex. Pedersen, T,. (2007) has determined the value of the k of Vector A100LK for a complex terrain (k=4.5).

Anemometer Uncertainty Due to Dynamic Over-Speeding (δU_2)

Over-speeding phenomena are the increasing of the rotational of anemometer immediately when it faces higher wind speed and not slowing down rapidly when it faces lower wind speed. Thus, it is causing an overestimation for the wind speed measurement. (Jain, p., 2011,p.86). The over-speeding is related to the turbulence intensity in the wind. Because, the over speeding happens as a result of wind turbulence. Turbulence intensity represents the non–dimensional relationship between the standard deviation of the wind speed σ defined over 10 minutes and mean wind speed $\overline{U}$ to quantify the degree of turbulence in the wind flow through a specific period of time as the following equation: (Jain, p., 2011,p.101).

$$TI = \frac{\sigma}{\overline{U}} \quad (4.8)$$

Turbulence intensity is related to the mean wind speed, the roughness, the stability of the atmosphere, and the terrain's features. Turbulence intensity has three Cartesian components: longitudinal, lateral, and upward. The longitudinal has the same direction of the mean wind speed, the lateral is horizontal to it, and the upward is tilted from the vertical by the mean inclination angle. The standard deviation of each component should be calculated in order to compute the total standard deviation and then compute the turbulence intensity as equation (4.8). The over-speeding is related just to the longitudinal component. (IEC 61400-12-1.,2005)

The longitudinal turbulence component causes errors in the horizontal component of the wind speed measurement U_{bias} (δ_u). And, The vertical turbulence component causes errors in the vertical component of the wind speed measurement w_{bias} (δ_w). The effects of the turbulence components on the wind speed measurement can be determined by the physical characteristics of the anemometer. (Papadopoulos, K., 2001).

As previously mentioned, the over-speeding is related just to the longitudinal component which has the same direction of the mean wind speed.

The over-speeding is proportional with the square of the longitudinal turbulence intensity. Thus, as the longitudinal turbulence increases in a site the over-speeding increases. (Kristensen,L,.1999)

The distance constant of the anemometer plays an important role for determining the effect of the longitudinal turbulence intensity in the anemometer. The distance constant of the anemometer is a physical characteristic of the anemometer that determines how rapidly the anemometer responds to the changes in the wind speed. The large distance constant of the anemometer responds slowly, but the small distance constant of the anemometer responds faster. Thus, the small distance constant of anemometer responds the over-speeding rapidly thus the errors are to be less. (Papadopoulos, K., 2001)

The over-speeding is related to the longitudinal component of the turbulence intensity which is related to the distance constant. The over-speeding causes unknown bias in the wind speed which is between 0-1percent. The 0.5 percent bias in the wind speed measurement is assumed for the target site. This type of uncertainty is type B. Thus, the uncertainty is calculated by the equation (4.4) to be δU_2= 0.3percent.

Anemometer Uncertainty Due to Vertical Turbulence Effects (δU_3)

The vertical component of the turbulence intensity has an impact on the measurement wind speed. The physical characteristics of the anemometer Identify how much the influence of turbulence intensity is. As it is mentioned, the longitudinal component of the turbulence intensity has an impact on the over-speeding of the cup anemometer. The distance constant of the cup anemometer, which is a physical characteristic of cup anemometer, determines the effects of the longitudinal component of the turbulence intensity on the cup anemometer. The vertical component of turbulence intensity has an impact on the cup anemometer. The impact of the vertical component of turbulence intensity is determined by the angular response of the cup anemometer.

The angular response of cup anemometer is a physical characteristic which determines who rapidly the anemometer response to the flow turbulence. With the comment that, the vertical turbulence generates positive and negative bias not like in the case of over-speeding. (Kristensen, L,.1999).

The vertical component of turbulence intensity causes an error in the wind speed measurement which leads to differing between the measured wind speed and the actual wind speed. This bias is referred as *w* bias. This bias is proportional with the square of the vertical intensity. Moreover, this bias is based on the angular response of the anemometer. (Kristensen,L,.1999). For more explanation of the vertical turbulence intensity Albers , A,.(2000) has done lots of scientific tests.

For tow anemometers (The first Thies and the Vector A100 anemometer) have different specifications and they are calibrated with the vertical flow. It was noted that, there is a 2 percent difference between the read of the first anemometer and the second one in the flat terrain at 65m height above the ground and same result approximately for the complex terrain. This difference is not totally understood which turbulence characteristics does cause it. However, there are indicators that it is based on the impact of the vertical flow due to the turbulence.

The anemometers which are ranked as 2D (*u*,*v*), average horizontal wind speed sensors, have smaller errors due to the impact of the vertical turbulence than the anemometers which are ranked as 3D (*u*,*v*,*w*), vector wind speed sensors. Therefore, the value of the *w* bias is determined based on the type of the used anemometer. (Kristensen,L,.1999)

Thus, for the 2D anemometer, the measured wind speed is approximately equal to the horizontal wind speed component. Thus, the errors *w* caused by the vertical turbulence can be assumed to be 0 percent. There is a variation in the value of *w* bias around 0 percent. Therefore, the uncertainties in the mean wind speed by the vertical turbulence is assumed to be 0 percent. (Albers ,A,.2000).

For the 3D anemometer, the measured wind speed gets affected by the vertical turbulence. The *w* bias exists and it differs based on the type of the terrain. For the flat terrain, Albers, A,.(2000) has found in his compression between the 3D anemometer and 2D anemometer that, there is 2 percent *w* bias in the measurement of 3D anemometer in comparison with the measurement of 2D anemometer. This value (2 percent) has been estimated under the assumption that there is no flow inclination and the turbulence levels are low. Therefore, this 2 percent is the minimum value. This bias is unknown bias and type B uncertainty. Thus, the uncertainty as equation (4.4) is to be 1 percent. (Albers ,A,.2000)

For the complex terrain, there is 7 percent bias in the measured wind speed between different anemometers. (Papadopoulos, K., 2001). As assumption if the bias in the measured wind speed is 4 percent the uncertainty according to equation (4.4) is to be 2 percent.

4.21.1.1 Uncertainty Due to The Met Mast Tower effects (δU_4)

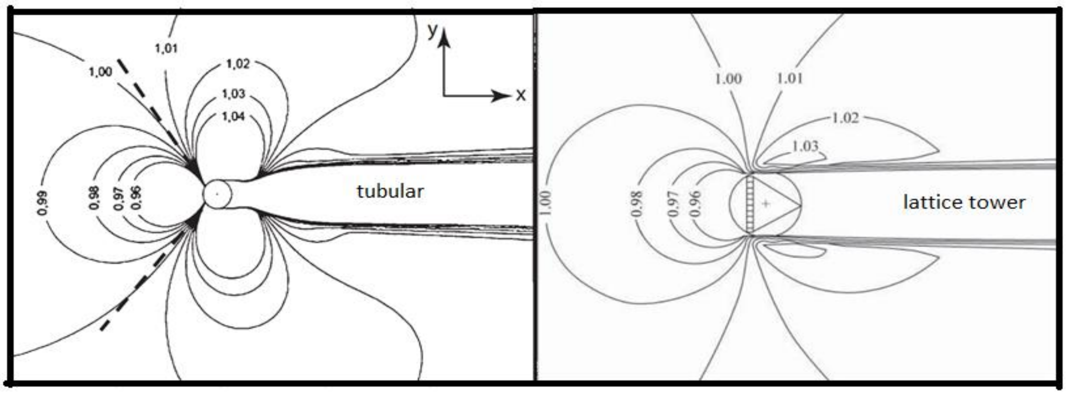
The tower shadow or the wake of the met mast tower is one of the most important sources of errors in the wind speed measurement. Figure 4.1 shows the ISO-speed graphs of the wind flow around the tubular tower and lattice tower.

The figure 4.1 shows the distortion of the wind flow upwind of the met mast along the x-direction, and the increasing in the wind speed along positive and negative of the y-direction. Thus, according to IEC, for the tubular tower, the best location of the first boom is at an angle 45º of the incoming wind and for the second boom at an angle between 90º-180º of the first boom. For the lattice tower, the best location of the booms is at 90º of the incoming wind and for the second boom at an angle between 90º-180º of the first boom.. (Zhang.M.H.,2015.pp180-181).

A boom which is placed on the met-mast tower must not be close to the met-mast tower. For the tubular met mast tower, the boom should be placed at a distance more than 6 times mast diameters.

For the lattice met mast tower, the boom should be placed at a distance more than 5 times mast diameters. Thus, 5 percent errors are produced by the tower shadow will be reduced. (Zhang.M.H.,2015.pp180-181).

Figure 4.1: ISO-speed graphs of the wind flow around the tubular and lattice tower



Source: Zhang.M.H.,2015.p180

Besides the side-mounted anemometers, the top mounted anemometer is used. It is placed on the top of the met mast tower. When the top mounted anemometer is installed the met mast tower effects are neglected. With the comment, the lightning rods are mounted at the highest point in the met-mast which used to protect the equipment from the lightning. Lightning rods can distribute the wind flow near the top anemometer. It is found that, the top-mounted anemometer causes errors in the measured wind speed by 2.7 percent.(Lubitz,W.D.,2009)

The errors of the met mast tower effects can be reduced by using the long boom and two anemometers. (Jain, P, 2011, p84). There are lots of research have been done For proof that. In one study, two side-mounted anemometers have been installed on the booms. The angle between them 180º. The second anemometer (redundancy) is used to reduce the errors of the tower effects. These two anemometers are connected to the data logger. The higher reading of two anemometers of the wind speed in 10 minutes interval is selected to be recorded by the data logger. Thus, if one of the anemometers is in the tower shadow more than averaging period its reading is neglected. In that way, the biased value is not read. (Rogers A.L., 2006) .

The potential flow fluid dynamic theory can be used to determine the errors in the wind speed measurement due to the met mast effects. This theory is based on modeling the wind flow around the cylinder placed at a position of 0º from a uniform free stream flow direction. Thus, when the uniform free stream touches the cylinder the speed of the flow decreases, at the same time the flow acceleration changes around the cylinder to be in maximum speed at a position of 90º from the free stream flow direction. This theory stipulates that the flow is decelerated by 0.8 percent at a position of 0º from the uniform free stream flow direction and accelerated by 0.8 percent at a position of 90º from the uniform free stream flow direction. Thus, the wind speed is biased by $\mp 0.8\, percent$ which is the maximum different between the measured wind speed and the real one if the free stream flow comes from one direction. (Rogers A.L., 2006). This bias is unknown bias thus this uncertainty is type B uncertainty. According to the equation (4.4) the uncertainty is 0.5 percent. Actually, the wind flow does not come from the one direction thus the bias due to the tower effects is to be less.

4.21.1.2 Uncertainty Due to Boom Effects (δU_5)

The length and the direction of the booms are determined by understanding the wake and flow distortion caused by the met mast tower. Those booms cause flow distortion and errors in the wind data measurement. The degree of the flow distortion is based on the separation distance between the sensor and the boom and the direction of the boom. Experiments say that the separation distance should be 12 to 15 of boom diameter. The uncertainty due to the boom mounting is to be 0.5 percent. (Zhang.M.H.,2015.p181).

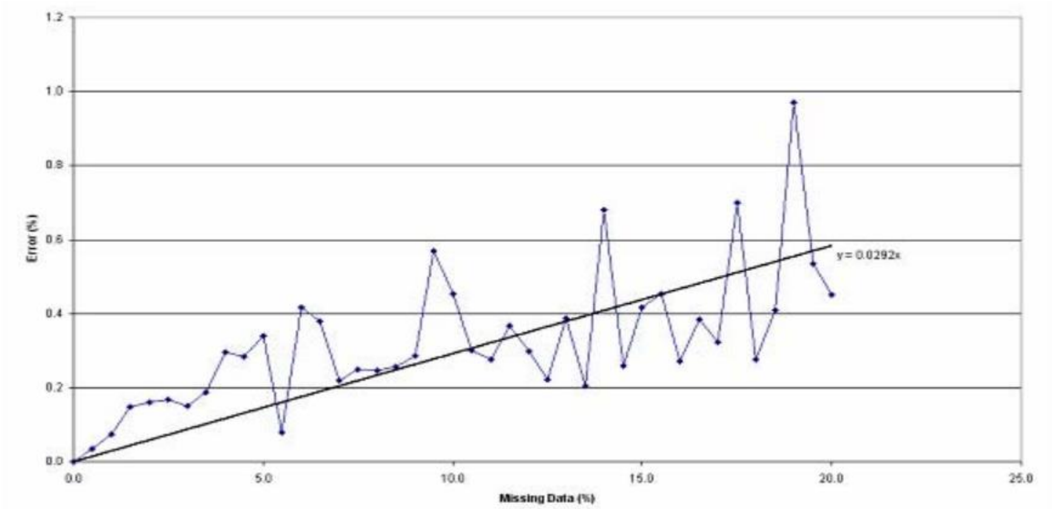
4.21.1.3 Uncertainty Due to Data Reduction (δU_6)

The wind data measurements are collected and transferred by the data loggers. The recorded data can include errors due to the data logger failures, transmission failures, and sensors failures. Thus, this data must be filtered and cleaned to decrease the likelihood of uncertainty in the wind assessment. (Istchenko, R., 2006).

Istchenko, R., (2006) has found the uncertainty of the data reduction. Seven groups of measured data for one year are chosen. For each group of data, a random time points are chosen. Then, for each random time point, a certain part of data is taken away as missing data from the groups of data.

The amount removed as missing data is increased to 20 percent with 0.5 percent increase. Then, the ratio of the mean wind speed of the missing data to the mean wind speed of the seven groups of data is computed. This step has been repeated 10 times for each group of data. So for each percentage amount of data removed, there are ten random initial time points selected. Then, the mean and standard deviation of the results of the seven groups of data has been determined. Then, the standard deviation of the ratio of the mean as a function to the real mean of missing data is determined to indicate that the percentage error is 0.03 times the percentage of the missing data as it is shown in Figure 4.2. Thus, the uncertainty of the missing data can be calculated as δU_6 = 0.03*missing data. Generally, this uncertainty is neglected when there is no great amount of missing data.

Figure 4.2: The standard deviation of the ratio of the mean as a function to the real mean of missing data



Source: Istchenko,R.,2006

4.21.2 Uncertainty of Long-Term Wind Resources Estimation (δU_{LT})

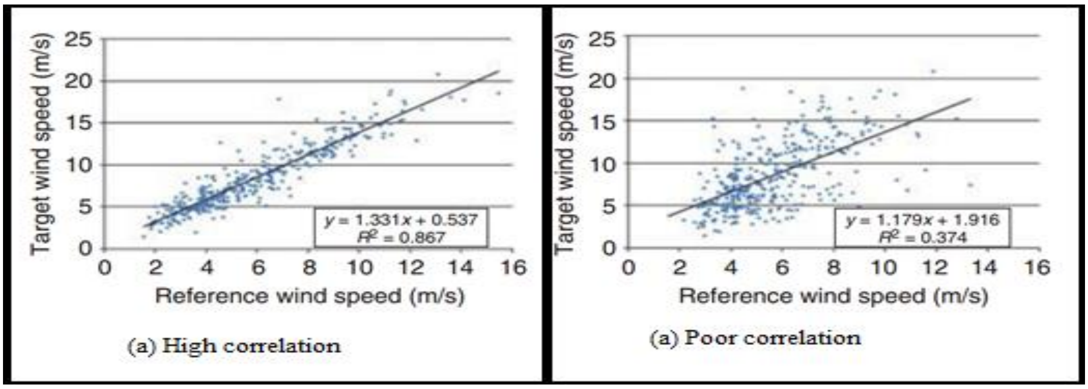
Measure-correlate-predict MCP is used to predict the long-term wind data at the target site $\overline{U}_{LT}$ using the onsite measurement wind data and the long-term wind resource data of the neighbor site that is measured for twenty years or more which is called reference site data. Using the long-term reference data leads to uncertainties. The estimation of the long-term wind data at the target site using MCP causes uncertainties.

MCP uses the long-term reference site to estimate the long-term data for the target site. MCP finds a statistical relationship between the target site and the reference site by using synchronous data set. The wind speed of the target site is estimated as a function of the wind speed of the reference site in this relationship. Thus, to estimate the long-term wind data at the target site that relationship is applied on the reference data. (Taylor, M, 2010).(Rogers A., 2005).

The reference wind data and the site wind data must be in the same wind climate and have synchronous wind data records. This synchronous period should be enough, usually one year or more, to capture the seasonal variations. Sometimes, the reference data and the site data are not in the same wind climate, for example, the target site may be on the mountain top and all neighbor reference sites on the valleys or the target site may be in the coast and all neighbor reference sites are islands.(Rogers,A.,2005).

The quality of the correlation can be estimated by drawing a time series of the target site and the reference sites as it is shown in figure 4.3. Also, the correlation coefficient (R^2) which is the fraction of the variation in the values of one variable is used to determine the quality of correlation.

Figure 4.3: The relationship between the target site and reference site. (a) High .(b) poor correlation



Source: Brower, M.,2012.p.161.

If the target site has a flat terrain, it is easy to find reference data site that has same wind climate. If the target site has complex terrain, it is difficult to find reference site that has same wind climate. Thus, the correlation between the target site and the reference site can be low. Thus, the uncertainties in the long-term target data increase. The uncertainty in the long-term target data estimation is given in the following equation. (Brower,M,.2012.p.161).

$$\delta U_{LT} = \sqrt{\frac{r^2}{N_R}.\sigma_R + \frac{1-r^2}{N_T}.\sigma_T} \qquad (4.9)$$

Where, r^2: is the correlation coefficient.

N_R: is the number of the years of the reference data.

N_T : is the number of the years of the target site data which should be one year and more.

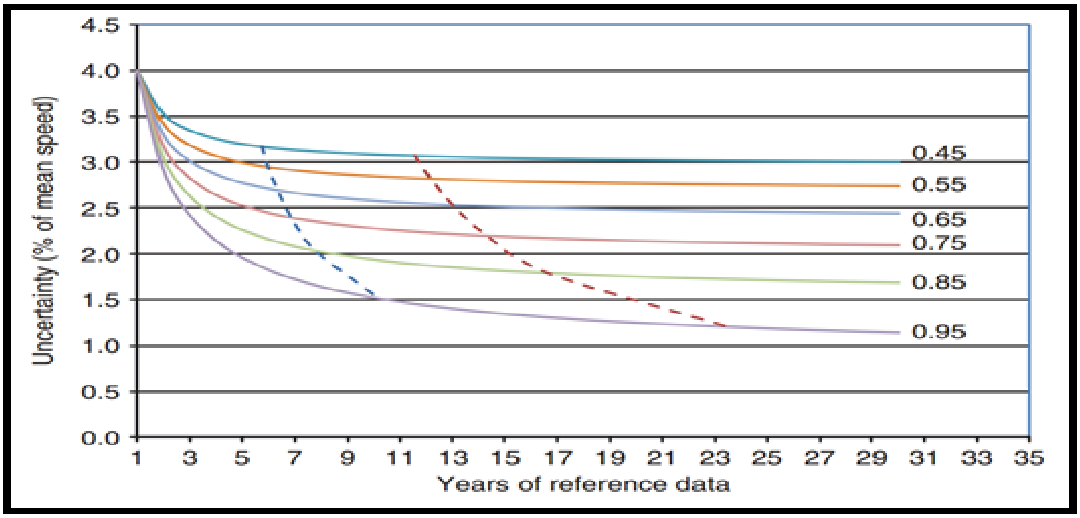
σ_R, σ_T : is the standard deviation of the mean wind speeds of the target and the reference site.

The equation (4.9) can be given in the following form, where, σ_{annual} :is the standard deviation of the annual mean wind speeds.(Zhang, M.,2015.p.136).

$$\delta U_{LT} = \sigma_{annual} \sqrt{\frac{r^2}{N_R} . + \frac{1 - r^2}{N_T}} \tag{4.10}$$

The numbers of the years of the reference site affect the uncertainty. As the numbers of the years of the reference data increase the uncertainty decreases as it is shown in the equation 4.10. Using MCP model can reduce the uncertainty compared to not using MCP as it shown in Figure 4.4. It shows the relation between the uncertainties in the mean wind speed and years of reference data for the range of values of r^2 (0.45-0.95) and $N_R = 1\ to 30\ years$. The equation 4.10 is used with the assumptions that $\sigma_R = \sigma_T = 0.4$ and $N_T = 1$. In Figure4.4 the red dash curve gives the number of years required to reduce 90 percent from the uncertainties. The blue dash curve gives the number of years required to reduce 80 percent from the uncertainties compered to no MCP. Thus, the blue dash curve for all r^2 is achieved when the number of years less than 10. The red dash curve with $r^2 \leq 0.85$ is achieved when the number of years less than 17.

Figure 4.4: The relation between the uncertainty and the number of the years of reference data



Source: Brower, M., 2012.p.165.

4.21.3 Uncertainty due to site assessment (δU_{SA})

The met-mast tower has lower height than turbine hub height. Thus, the wind data is measured at the lower height then it is extrapolated to the turbine hub height using wind shear modeling. Thus, there are uncertainties generated by vertical data extrapolating. Furthermore, the met-mast does not have same location of the turbine(s). Therefore, there is a horizontal extrapolation of the data which generates uncertainties. There are two types of uncertainties due to the site assessment: (a) Uncertainties due to Topographic effects. (b) Uncertainties due to the wind shear modeling.

4.2.3.1Uncertainties due to Topographic effects (δU_8)

The met-mast tower has not been located at the same location of the wind turbine(s). Thus, the topographic may cause different wind conditions at the different locations of the wind turbines. The topographic effect is essentially based on the type of terrain on the site. The wind data is horizontally extrapolated at each potential location of a wind turbine using flow modeling such as Wasp, CFD, and wind map.

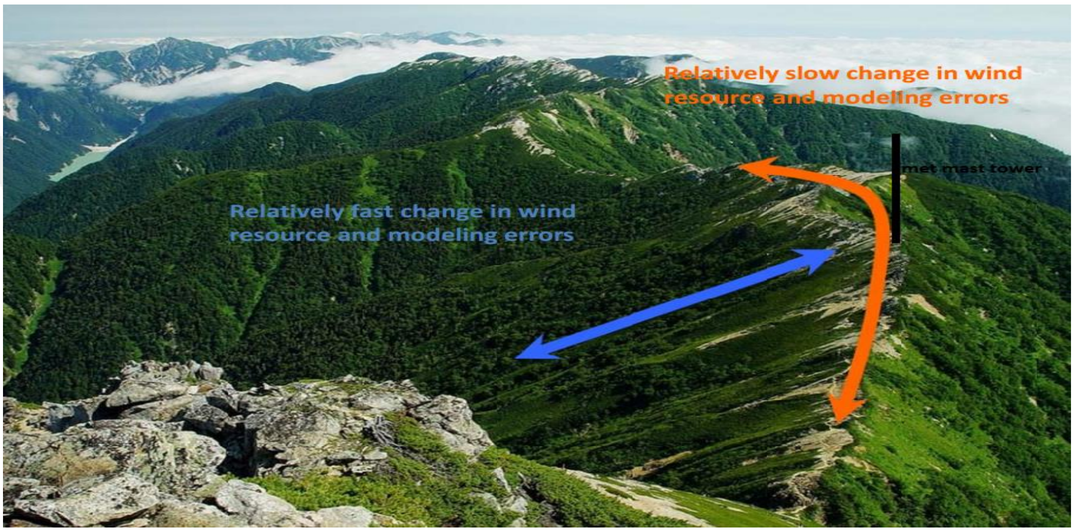
The wind flow modeling uncertainties may be in the range between 2 percent for the open flat terrain to 10 percent in the complex terrain. Thus, this type of uncertainties is basically site dependent and it is related to resolution of the used model, location of the masts, digital contour map, roughness map, and wind turbine characteristics. (Beaucage, P., 2014).

The uncertainty of the wind flow model is commensurate with the expected variance in the wind resource between two points. In the other words, the uncertainty is proportional to the distance in the resource space. More explanation is in the following examples.

The first example, in Figure 4.5, there is a ridge and there is a met mast tower located at the top of this ridge. Using this met mast tower and the wind flow modeling the variations in the wind resource at the site are predicted.

Thus, the uncertainty in that prediction is likely to appear like that, (A) moving along the top ridge, the resource is likely to be very similar to the resource at the met mast thus the wind flow modeling uncertainty will be fairly small. (B) Moving a similar distance directly down the slope, the uncertainty is changing very fast along the resource. It becomes basically more challenging for the wind flow modeling to get the resource right and the uncertainty increases.

Figure 4.5: The wind flow modeling on the ridge



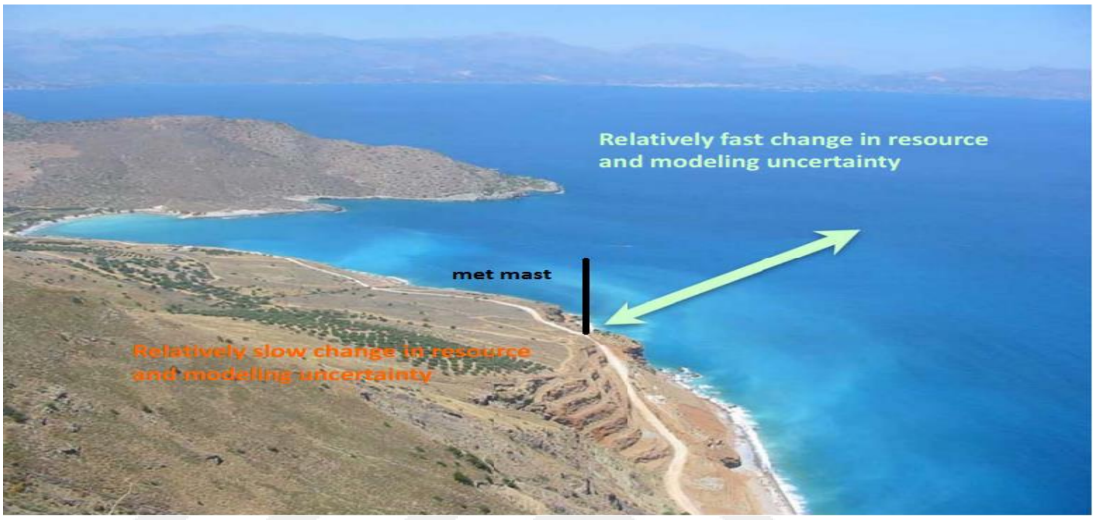
Source: Brower, M., 2015.

The second example, in Figure 4.6 there is coastline and there is a met mast tower located at the shore. Clearly, the wind resource at the other points along the shore is likely to be quite similar to that observed at the mast. It is reasonable to conclude that, the wind flow model will be accurate along the shore line. But as moving offshore, the wind resource could change quite a lot both in speed and direction and model is likely to have much difficulty predicting. Thus, the uncertainty on the offshore will be larger than along the coastline.

The uncertainties in the horizontal extrapolation in the flow modeling are guessed based on the type of the terrain and the distance between the mast and wind turbine(s) location(s). In this study, the uncertainty of the wind flow modeling is analyzed using openwind software. In the openwind software, the wind flow modeling is calculated and added by using the modeling uncertainty.

Modeling uncertainty means, how the uncertainty increases as moving away from the met mast. Basically, this uncertainty is tied to the wind flow modeling that is used to extrapolate the wind data in the target site.

Figure 4.6: The wind flow modeling on the coastline



Source: Brower, M., 2015

The wind flow modeling uncertainty is various across a wind project site due to two main reasons. Firstly, the terrain, land cover, land-water boundaries, and other factors can have a strong influence on the wind. Prediction of that influences is the job of the wind flow models. However, they are not perfect. In other words, how the uncertainty of the wind flows modeling prediction is not easy to determine. Secondly, the different met mast towers of wind measurement system have different uncertainties characteristics.

Combining those uncertainties with the wind flow modeling uncertainties in a properly weighted and blended uncertainty map is a harder task. Recently, Openwind has made a lot of progress in both areas.

The uncertainty of the wind flow model is proportional to the predicted difference in the wind resource between two points. In the other words, the uncertainty is proportional to the distance in the resource space. These concepts are put into practice by openwind. There are two ways to measure the difference in the source between two points:

The root mean square speed deviation which is the measure of how the wind speed changes as moving away from the met mast position across the wind resource grid.

$$\text{TD} = \sqrt{\sum_{i=}^{ND}(f_i^R(\frac{v_i^T}{v_i^R} - 1)^2)} \tag{4.11}$$

The root mean square direction deviation which is the measure of how the directional of the wind rose changes as moving away from the met mast position across the wind resource grid.

$$\text{DD} = \sqrt{\sum_{i=}^{ND}((f_i^T - f_i^R)^2)} \tag{4.12}$$

Where; T: is target point (it can be the turbine location).

R: reference point (it can be the met mast location).

ND: number of direction.

f: frequency.

v: wind speed.

These two measures capture two different types of change, a change in the wind speed and a chance in the wind direction. Both make it harder for the wind flow model to predict the wind resource accurately.

Openwind has done many types of researches to find the uncertainty of the wind flow modeling. Openwind has found that the uncertainty wind flow of the wind flow modeling is calculated by the following equation:

$$\delta_{WFM} = \sqrt{\delta_D^2 - 0.02^2} \tag{4.13}$$

Where; δ_D^2: is the uncertainty includes the topographic difference and the directional difference and given by the following equation:

$$\delta_D = 0.121\left[1 - 0.411.\frac{0.071}{\text{DD} + 0.071} - 0.423\frac{0.097}{\text{SD} + 0.097}\right] \qquad (4.14)$$

The uncertainty modeling approach of the openwind is valid just for the wind flow which is modeled by SiteWind. Otherwise, you have to find your own uncertainty function using the previous equations.

In this study, the wind flow is modeled by the wind map modeling. Thus, the Equations (4.11) and (4.12) are calculated for the wind data. Then, equations (4.14) and (4.13) are used respectively to calculate the wind flow modeling for the target site. Thus, the wind flows modeling uncertainty for the target site is equal to 5 percent.

4.2.3.2 Uncertainty due to the wind shear modeling (δU_9)

The met-mast tower has a lower height than turbine hub height. Thus, the wind data is measured at the lower height then it is extrapolated to the turbine hub height using wind shear modeling. Thus, there is uncertainty generated by extrapolating data. This uncertainty is greatly based on the predictability of the wind shear modeling.

Wind shear is related to the climate change, the terrain effects, and the wind speed. Thus, the uncertainty of the wind shear is related to the terrain type and the uncertainty caused by the effects of the mast and the booms in the anemometers thus the measured wind speed. (Antoniou, I,.2009). These uncertainties are to be between 3 percent to 10 percent.(Zhang, M.,2015.p.157). The uncertainties of the wind shear based on the terrain types and for each 10m different between the wind turbine hub height and the height of the met mast are given in Table 4.2. (Zhang, M.,2015.p.157).

Table 4.1: Uncertainties of the wind shear for every 10m difference regarding terrain type

Terrain type	Uncertainties for every 10m difference
Flat terrain	0.3%
Smooth hill	0.5%
complex	1.0%

Source: Matthew Huaiquan Zhang.2015.pp.157.

The uncertainty of the wind speed at the wind turbine hub height δU_9 is to be calculated based on the uncertainties of the wind shear Δ_σ as the following equation where the h_H is the hub height and h_2 is the anemometer height: (Zhang,M.,2015.p.15).

$$\delta U_9 = \left[\left(\frac{h_H}{h_2}\right)^{\Delta_\sigma} - 1\right] * 100\% \qquad (4.15)$$

4.2.4 Uncertainty due to the wind resources variability (δU_V)

The wind resource on the site may change with the change in climate in the future. Thus, there is a potential change in the mean wind speed as a result of climate change over the project lifetime.

The estimation of the long-term mean wind speed for the target site is based on the number of the years of the reference site. Basically, the long-term wind resource for the target site is estimated by using a sample of yearly mean wind speeds. In contrast, the predicted long-term reference data may not represent the actual long-term wind data in the site. Also, the predicted long-term target data may not represent long-term wind data over the project lifetime. Therefore, there are two types of uncertainties should be considered (a) Uncertainties due to Inter-Annual Variability (b) Uncertainty over Turbine Lifetime.

4.2.4.1 Uncertainties Due to Inter-Annual Variability(δU_{10})

The mean wind speed on the site changes from year to year. This change is called inter-annual variation. The long term reference data may not represent the actual long-term wind data. Thus, the used long-term reference data should be accurate and for a long period of time, such as 20 years to decrease the impacts of the inter-annual variability. The inter-annual variability is to be 1 percent to 7 percent. (Fontaine, A., 2008). The inter-annual variability uncertainties of multiple years of onsite measurement data can be calculated as the following equation where N_M : is the number of years of reference data. (Stangroom, P.,2011).

$$\delta U_{10} = \frac{6\%}{\sqrt{N_M}} \quad (4.16)$$

4.2.4.2 Uncertainty Over Turbine Lifetime(δU_{11})

The predicted long-term wind data of the target site may not represent actual long-term wind data over the project lifetime. The type of uncertainties δU_{11} can be calculated using the following equation where N_p is equal to the turbine lifetime which is usually 20 years. (Brower,M,.2012.p.161)

$$\delta U_{11} = \frac{6\%}{\sqrt{N_P}} \quad (4.17)$$

4.2.5 Estimation of the uncertainties of mean wind speed of the target site

The uncertainties of the long-term wind resource at the target site δU are calculated after the estimation of the long-term wind resources at the target site as the following: (Lackner,M., Rogers,A., &Manwell,J,.2007).

The root sum square (RSS) method is used to determine the overall uncertainties caused by the each individual category of the previous four categories with considering that the sensitivity factor for each source is equal to one as the following equations:

$$\delta U_M = \sqrt{((\delta U_1)^2 + (\delta U_2)^2 + (\delta U_3)^2 + (\delta U_4)^2 + (\delta U_5)^2 + (\delta U_6)^2)} \quad (4.18)$$

$$\delta U_{LT} = \sqrt{((\delta U_7)^2} \quad (4.19)$$

$$\delta U_{SA} = \sqrt{((\delta U_8)^2 + (\delta U_9)^2} \quad (4.20)$$

$$\delta U_V = \sqrt{((\delta U_{10})^2 + (\delta U_{11})^2} \quad (4.21)$$

The overall uncertainties of the mean wind speed of the long-term hub height on the target site is to be calculated by the following equation with taking in consideration the sensitivity factor for each category:

$$\delta U = \sqrt{((SF_M * \delta U_M)^2 + (SF_{LT} * \delta U_{LT})^2 + (SF_V * \delta U_V)^2 + (SF_{SA} * \delta U_{SA})^2} \quad (4.22)$$

The sensitivity factor of the long-term resource uncertainties is equal to one when the linear regression model is used in the MCP and it is recommended to be used when the overall wind resources uncertainties are evaluated. The sensitivity factor of the wind resource variability uncertainties and the sensitivity factor of the site assessment uncertainties are equal to one.

The sensitivity factor of the wind speed measurement uncertainty is great than one since the measured wind data is extrapolated by wind shear model to estimate the long-term mean wind speed at hub height. Thus, the errors in the measured data affect the estimation of the long-term mean wind speed at hub height. Essentially, using the uncertain wind data to calculate the wind shear model causes that effect not any errors in the wind shear models. The following equation is used to calculate the sensitivity factor of wind speed measurement.

As the h_3 is the hub height wind turbine, h_2 is the height of the higher anemometer, h_1 is the height of the lower anemometer.

$$SF_M = \sqrt{\frac{2\left(\ln\left(\frac{h_3}{h_2}\right)\right)^2 + \left(\ln\left(\frac{h_2}{h_1}\right)\right)^2 + 2\ln\left(\frac{h_2}{h_1}\right).\ln\left(\frac{h_3}{h_2}\right)}{\left(\ln\left(\frac{h_2}{h_1}\right)\right)^2}} \qquad (4.23)$$

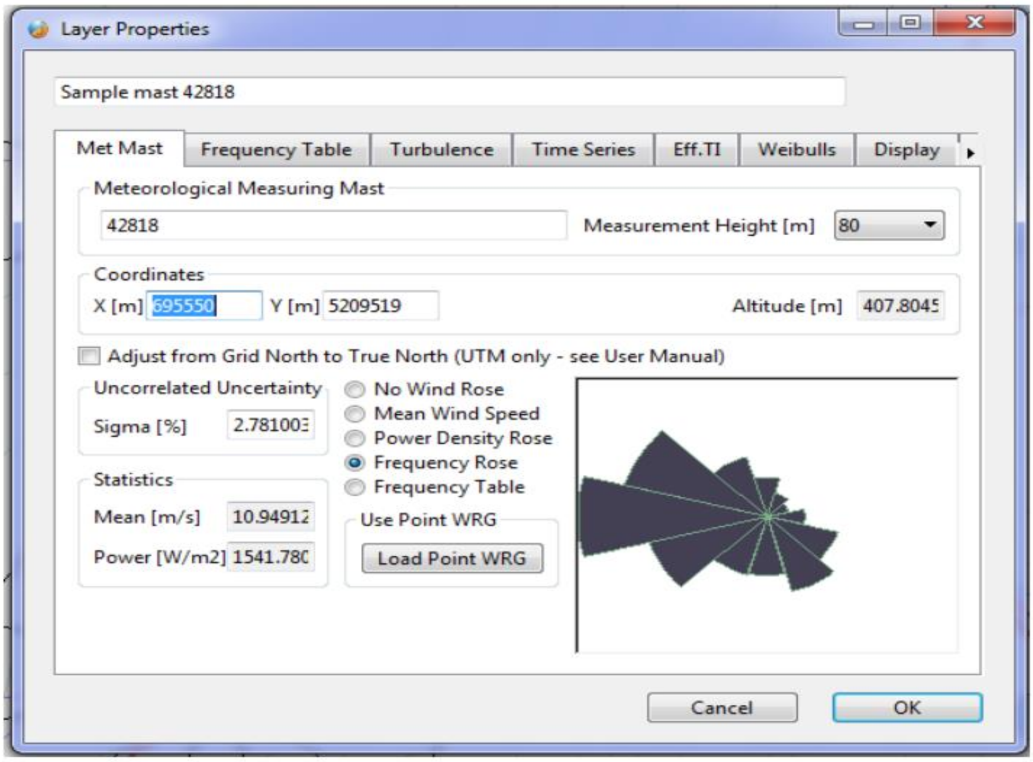
4.3 UNCERTAINTY FUNCTIONALITY WITHIN OPENWIND SOFTWARE

Within openwind there are three sources of wind resources uncertainty. First is coming from the met masts themselves as it is seen in Figure 4.7. Thus, within each met mast properties, uncorrelated uncertainty can be determined. Uncorrelated uncertainty means that all the independent errors such as the uncertainty of the anemometers and the uncertainty of the met mast tower effects, the uncertainty of the boom effects, and the uncertainty due to data reduction are considered as uncorrelated uncertainty.

The second type is correlated uncertainty as it is seen in Figure 4.8. Correlated uncertainty means that all the dependent errors such as the uncertainty of the MCP model, the uncertainty of the wind shear, the uncertainty of the wind flow model, and the uncertainty of the wind resource variability are considered as correlated uncertainty. This uncertainty is to be added to all met mast tower.

The third type is wind flow modeling uncertainty as it seen in Figure 4.8. Modeling uncertainty means that the uncertainty is increasing with moving away from the met mast.

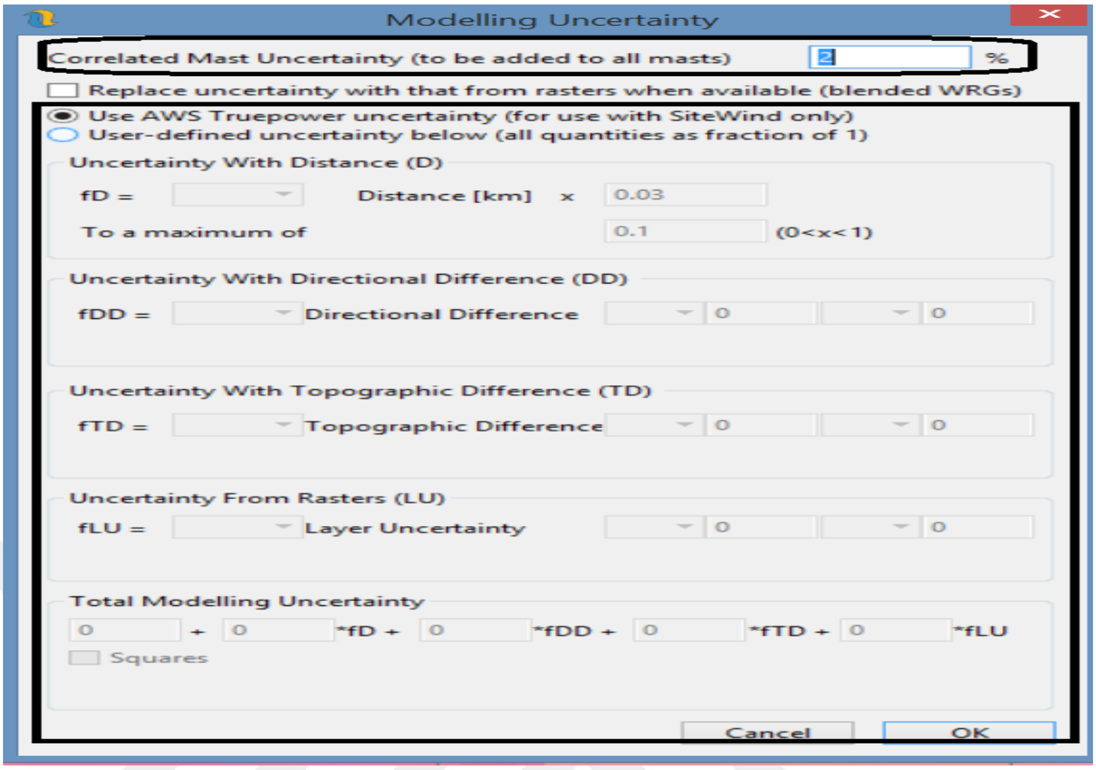
Figure 4.7: Uncorrelated uncertainty



Source: OPENWIND USER MANUAL version1.7.p56.

Thus, tow sources of uncertainty are used. The directional difference from point to point (DD) which is the measure of how much the directional of the wind rose changes as moving from the met mast position across the wind resource grid. The topographic difference from point to point (TD) which is measure of how much the wind speed changes as moving from the met mast position across the wind resource grid. It should be noted that, the modeling uncertainty is used just with SiteWind flow model and for another flow modeling the uncertainty function should be found.

Figure 4.8: Modeling uncertainty Dialog



Source: OPENWIND USER MANUAL version1.7.pp130-131.

By applying uncertainty functionality within the openwind the uncertainty map is formed. This uncertainty map can be used to (a) Get exact evaluation to the wind flow modeling uncertainty. (b) Objectively, identify gaps and pick the location for new masts to reduce uncertainty in the energy production. (c) Guide layout design to maximum P90 production.

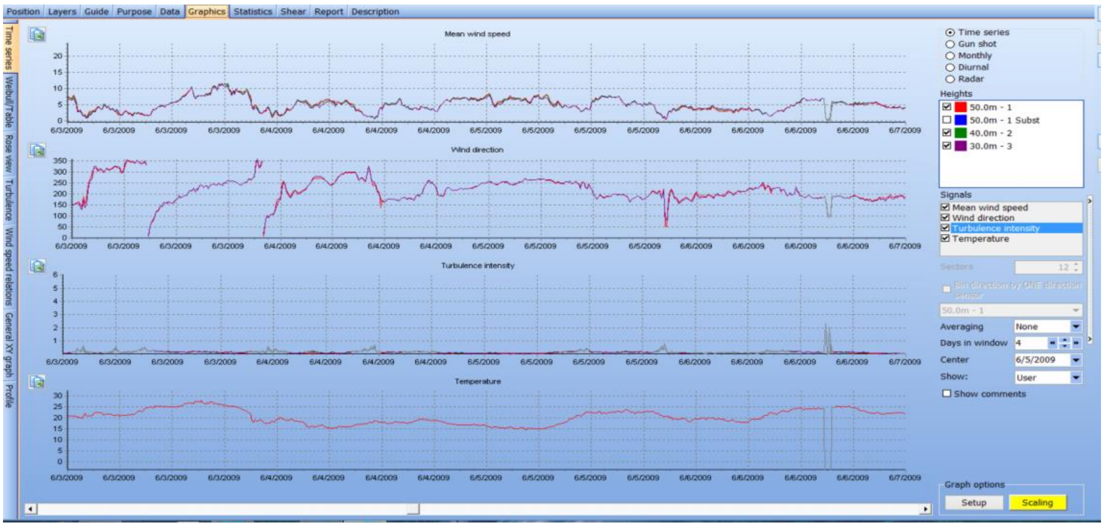
5. RESULTS AND DISCUSSION

Measurements of wind speed, wind direction, temperature, and pressure have been measured for one year at the site near the Marmara Sea in Turkey. This data was used to evaluate the potential wind energy at the target site. The uncertainty in the wind resource assessment process and the uncertainty in the annual energy production.

5.1 DATA PROCESSING

WindPRO software has been used to deal with wind measurement data. Thus, cleaning, filtering, and handling have been done by WindPRO software. Two met-mast data of the target site are imported to the WindPRO. The slope and the offset of the anemometer and the wind vane are added to the data. Then, the data are cleaned by removing the errors of the measured data due to the data logger failures, transmission failures, and sensors failures as it is shown in Figure5.1. In 06/06/2009, the wind speed has decreased suddenly then increased again to be back in the same range of the wind speed measurement. This may be considered as an error in the wind measurement data and may be excluded.

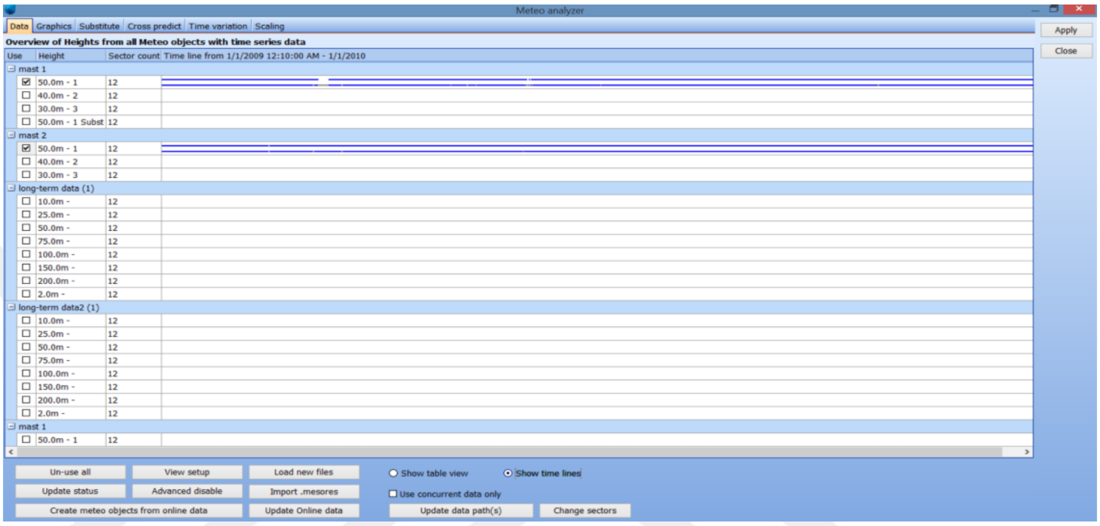
Figure 5.1: Mean wind speed, Wind direction, Turbulence Intensity, and Temperature for the mast1



Source: WindPRO software.

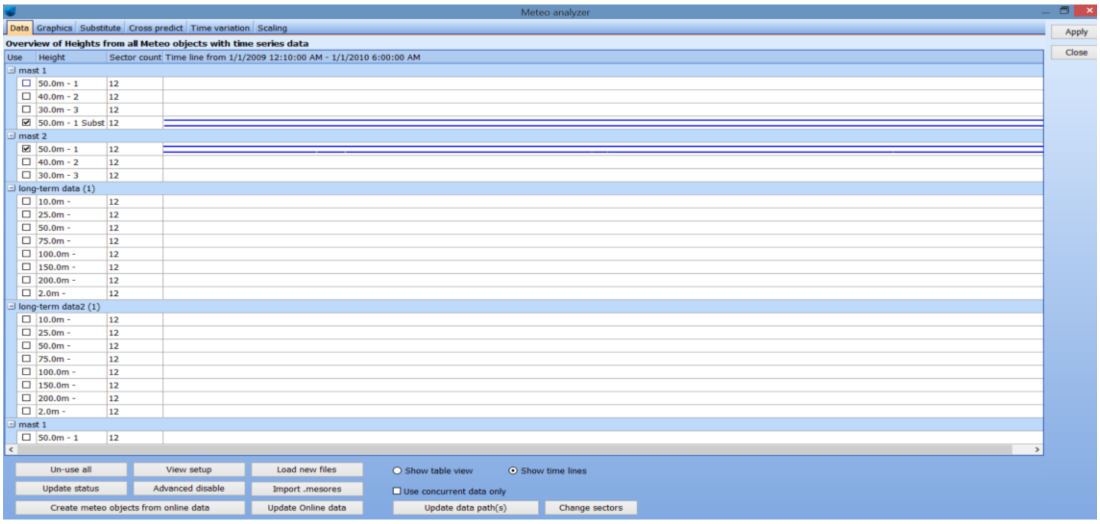
There was a gap at the mast1; some data are missed, as it shown in Figure 5.2. This gap is filled using the data of the mast 2. Therefore, MCP model is applied for the mast 1 and mast 2. Thus, the substituted time series of the mast1 is formed without gap using wind data of the mast 2 to fill that gap as it is shown in Figure 5.3.

Figure 5.2: Missing data in the data of the mast1



Source: WindPRO software.

Figure 5.3: Filling the gap of the mast1 by mast 2 data

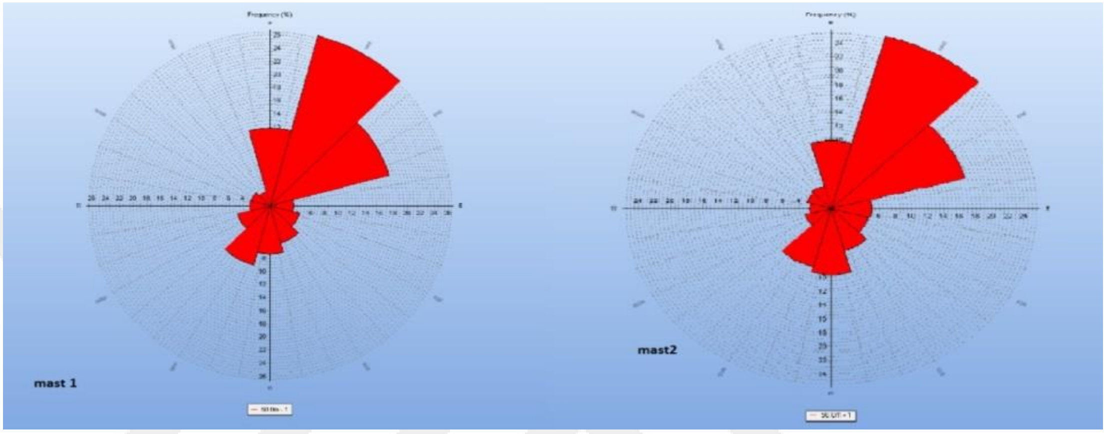


Source: WindPRO software.

5.2 WIND ROSE AND ENERGY ROSE

The relation between the wind speed and wind direction for the met mast 1 and met mast 2 are drawn in 2D histograms in polar coordinates as it is seen in Figure 5.4. The dominant wind direction is from the north-northeast.

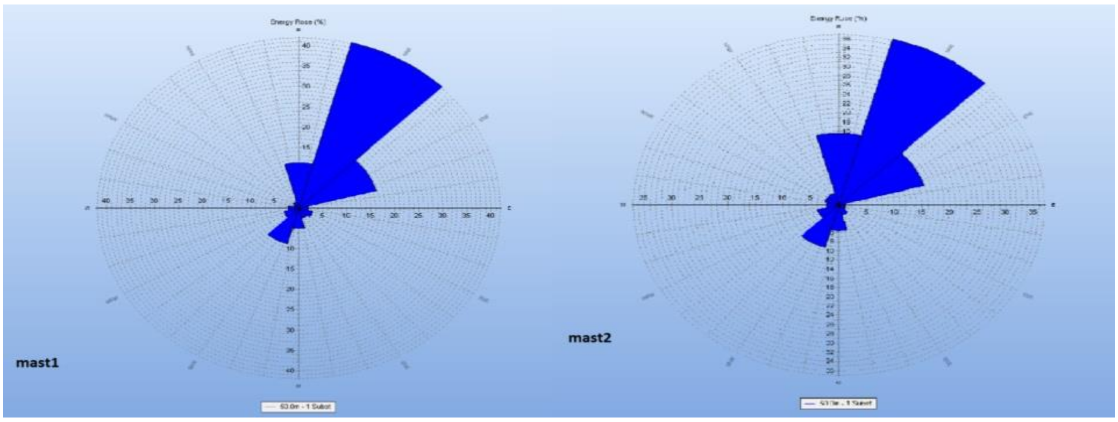
Figure 5.4: Wind rose for the wind direction for each met mast



Source: openwind software.

The relation between the wind direction and wind energy for the mast1 and mast2 are drawn in 2D histograms in polar coordinates as it is seen in Figure 5.5. It is clear that, the wind speeds of the north-northeast direction generate the largest amount of wind energy. Therefore, depending on energy rose, all the wind turbines should be oriented toward NNE.

Figure 5.5: Energy rose of wind speed at the target site



Source: WindPRO software.

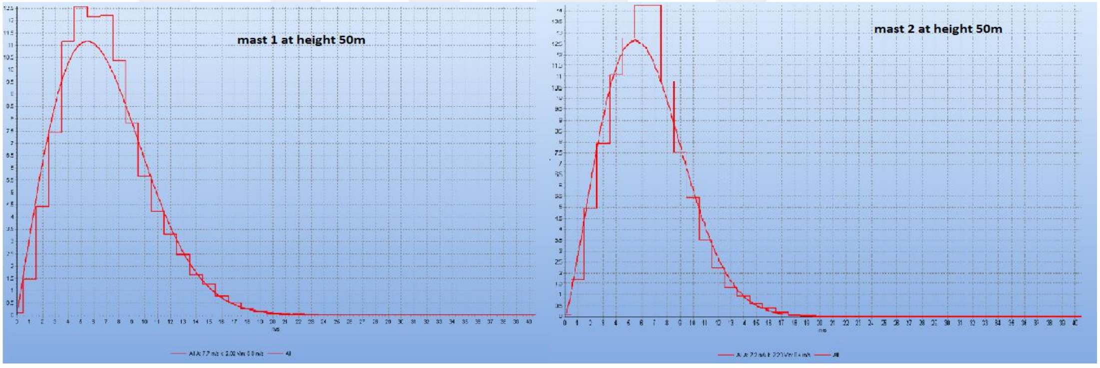
5.3 THE WIND SPEED DISTRIBUTION

The wind speed histograms at 50m height for each met mast tower at the site, and the Weibull distribution function is fitted to the wind speed distribution as it is shown in Figure 5.6. The mean wind speed and standard deviation of the wind speed for each met mast at height (50.0 m) are summarized in Table 5.1.

Table 5.1: Wind speed statistics at the target site

Wind statistics	Mast1	Mast2
Mean wind speed (m/s)	7.4	7.2
Standard deviation (m/s)	0.27	0.40

Figure 5.6: Wind speed histogram and Weibull distribution at the target site



Source: WindPRo software.

5.4 IMPLEMENTATION OF MCP MODEL

Predicted long-term data of the target site is calculated by applying MCP model. Thus, two long-term reference data from the nearby sites are used. By checking two long-term data, the best one which gives higher correlation will be used.

The MCP model includes four methods for prediction: linear regression, Matrix, index wind, and Weibull parameters.

Linear regression and matrix methods are implemented to know which one gives the best correlation. In Table 5.2, the results of applying linear regression model and matrix model for met mast 1 and met mast 2 with the first long-term reference data Emd1 are shown.

Table 5.2: MCP methods with first long term reference data Emd1

Methods	Description	Measure height(m)	Predicted mean wind speed (m/s)	Correlation coefficient (R^2)
Linear regression	Mast1&Emd 1	50 m	7.88	0.87
Matrix	Mast1&Emd 1	50 m	7.86	0.86
Linear regression	Mast2&Emd 1	50 m	7.34	0.92
Matrix	Mast 2&Emd 1	50 m	7.32	0.87

In Table 5.3, the results of applying linear regression model and matrix models for met mast 1 and met mast 2 with the second long-term reference data Emd 2 are shown.

It is clear in Table 5.2 that, for the mast1 and mast2, linear regression model has higher correlation coefficient than matrix model. It is clear in Table 5.3that, for the mast1 and mast2, linear regression model has higher correlation coefficient than matrix model. Thus, predicted long-term data of the target site using linear regression model will be used to continue the calculation.

Table 5.3: MCP methods with second long term reference data Emd2

Methods	Description	Measure height(m)	Predicted mean wind speed (m/s)	Correlation coefficient (R^2)
Linear regression	Mast1&Emd 2	50 m	7.86	0.85
Matrix	Mast1&Emd 2	50 m	7.84	0.84
Linear regression	Mast2&Emd 2	50 m	7.32	0.91
Matrix	Mast 2&Emd 2	50 m	7.28	0.86

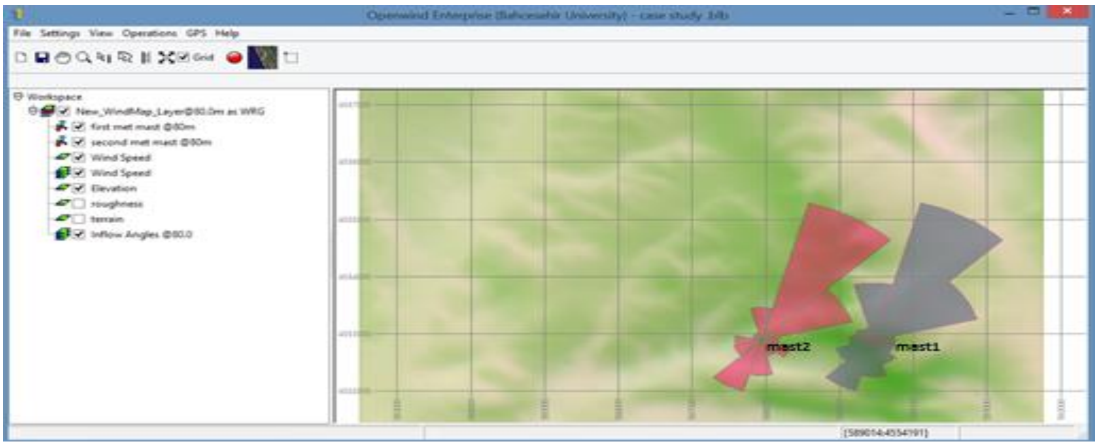
By comparison the long-term reference data, it clear that the correlation coefficient of linear regression model with Emd1 reference data is higher than the correlation coefficient of the linear regression model with Emd2 reference data. Therefore, predicted long-term data of the target site using the linear regression model and Emd1 reference data is to be used to continue the calculation.

5.5 WIND RESOURCE GRID OF THE SITE (WRG)

WRG includes predicted frequency of occurrence and Weibull parameters-shape and scale- of speed distribution at each grid point of the area of the target site and for each 16 or 12 directions. It is modeled by numerical wind flow models like Wasp and CFD. (Brower,M.,2012)

For this study, the wind flow modeling of the AWS Trupowe (wind map) is used. This wind map flow model combines mesoscale and microscale model. The wind map flow model gives the same result of Wasp for simple terrain and more accurate results than Wasp for the complex terrain. The wind measurement data of the two met mast, the roughness layer of the site, and the terrain elevation layer of the site are used to create the wind map then wind resource grid. The wind resource grid is shown the following Figure 5.7.

Figure 5.7: WRG of the target site using OpenWind software



Source: Openwind software.

5.6 SELECTION OF THE WIND TURBINES

The mean wind speed at the site is approximately 7.88 m/s. By using Table 3.1of IEC classification of the wind turbine, the IIA wind turbine is recommended. Siemens SWT (3.2MW/113m) which is classified as IIA is selected to build the wind turbine layer and then calculated the wind energy. (Siemens SWT platform).

Usually, the capacity of the sites in Turkey is between 30 MW and 50 MW. Thus, 16 Siemens SWT (3.2MW/113m) with 80.0m hub height are selected.

5.7 ANNUAL ENERGY PRODUCTION OF THE SITE

The energy losses should be added to calculate net annual energy production.

5.7.1 Losses

The annual wind farm energy yield includes losses. Openwind software takes into account the following losses:

1. **Wake effect:** this loss calculates for the wake effect from turbines in the wind farm. For this study, it is equal to 6.4 percent as is suggested by Openwind software.
2. **Availability:** (a) The contractual turbine availability, the period of the downtime of the wind turbine is considered under availability warranties, is taken into account. (b) Non-Contractual Turbine Availability, the period of the downtime of the wind turbine as a result of maintenance and repairs because of unexpected high wind speed, is taken into account. For this study, they are equal to 4.3 percent as is suggested in Openwind software. For this study, other losses which are considered in availability by the Openwind are neglected.
3. **Electrical losses:** (a) Electrical efficiency "these losses occur in all electrical parts of the wind farm include substation transformer, pad-mounted transformer, and control system" For this study, it is equal to 2.7 percent as is suggested by Siemens company. (b) The power consumption of extreme weather package "sometimes, in the icing events, there is an equipment for heating the blades

used energy from the wind turbine" For this study, this loss is neglected since there is no icing events.

4. **Environmental Losses:** (a) Icing is neglected since there are no noticeable icing events through analyzing the wind data. (b) Blades degradation is considered. (c) Lighting is neglected since there is a protection system used in the turbines. For this study, these losses are equal to 1 percent as is suggested in Openwind software.
5. **Turbine performance:** (a) power curve adjustment is neglected since the wind turbines, that are used, are adjusted to the air density of the target site. (b) High wind control hysteresis losses are not taken into account and expected to be low as "High Wind Ride Through" system is used for the assessed turbine. As cut out wind speeds are higher than standard controlling system losses caused by high wind cut-outs expected to be negligible. (c) Sub-Optimal Operation losses due to control issues are to be 1 percent as is suggested by Openwind software.

The net wind energy production is calculated with consideration of the energy losses as it shown in Table 5.4. As it is shown in Table 5.4, the net energy production is 172.1 GWh/yr. This annual energy production is calculated without considering the uncertainty of the wind resource assessment process. Thus, there is a risk in the investment if the wind farm will be installed based on that value. Because, this value is calculated without taking into account the uncertainty. Therefore, for decreasing the risk of the wind farm project, the uncertainties which have occurred through the assessment process must be considered in the annual energy production calculation.

Table 5.4: The energy production of the wind farm

Total energy production (GWh /yr)	198.2 GWh/yr
Net energy production (GWh /yr)	172.1 GWh/yr
Capacity factor %	38.36%

5.7.2 Uncertainty

The values and the equations of the uncertainty of the wind resource assessment process that are found during this study are shown in the following Table 5.5.

Table 5.5: Uncertainty of the wind resource assessment process

Uncertainty source	Uncertainty
Uncertainty due to anemometer calibration	δU_1 = Equation (4.7)
Anemometer uncertainty due to anemometer dynamic over-speeding	$\delta U_2 = 0.3\%$
Anemometer uncertainty due to the vertical turbulence effects	$\delta U_3 = 2.0\%$
Uncertainties due to the met mast tower effects	$\delta U_4 = 0.5\%$
Uncertainties due to the boom and mounting effects	$\delta U_5 = 0.5\%$
Uncertainties due to the data reduction accuracy	$\delta U_6 = 0.03\%$(missing data)
Uncertainty due to the MCP	δU_7 = Equation (4.9)
Uncertainties due to the wind flow modeling	δU_8 = 3% to 10%
Uncertainties of the wind shear modeling	δU_9 = Equation (4.15)
Uncertainties due to the Inter-annual variability	δU_{10} = equation(4.16)
Uncertainties over turbine lifetime	δU_{11} = Equation (4.17)

The values and equations which have been found in Table 5.5 are applied for the wind data to calculate the uncertainty of the wind resource assessment process as it shown in Table 5.6.

Table 5.6: Results of Uncertainty of the each source of the WRA for the target site

Uncertainty source	Uncertainty of mast1	Uncertainty of mast 2
Uncertainty due to anemometer calibration	$\delta U_1 = 0.215\%$	$\delta U_1 = 0.213\%$
Anemometer uncertainty due to anemometer dynamic over-speeding	$\delta U_2 = 0.3\%$	$\delta U_2 = 0.3\%$
Uncertainties due to the met mast tower effects	$\delta U_3 = 2.0\%$	$\delta U_3 = 2.0\%$
Uncertainties due to the met mast tower effects	$\delta U_4 = 0.5\%$	$\delta U_4 = 0.5\%$
Uncertainties due to the boom and mounting effects	$\delta U_5 = 0.5\%$	$\delta U_5 = 0.5\%$
Uncertainties due to the data reduction accuracy	$\delta U_6 = 0.09\%$	$\delta U_6 = 0.06\%$
Uncertainty due to MCP	$\delta U_7 = 2.56\%$	$\delta U_7 = 2.48\%$
Uncertainties due to Topographic effects	$\delta U_8 = 5\%$	$\delta U_8 = 5\%$
Uncertainties of the wind shear modeling	$\delta U_9 = 3\%$	$\delta U_9 = 3\%$
Uncertainties due to Inter-annual variability	$\delta U_{10} = 1.27\%$	$\delta U_{10} = 1.27\%$
Uncertainties over turbine lifetime	$\delta U_{11} = 1.3\%$	$\delta U_{11} = 1.3\%$

The uncertainty of the wind speed measurement, the uncertainty of the long-resource estimation, the uncertainty of the wind resource variability, and the uncertainty of site assessment are calculated using Equations (4.17),(4.18),(4.19),(4.20) respectively.

In addition, the sensitivity factor of the wind speed measurement is calculated using Equation (4.23). Then, the overall uncertainty of the wind resource assessment is calculated using equation (4.22) as it shown in Table 5.7.

Table 5.7: Uncertainty value for each category

Category of uncertainty	Uncertainty of mast 1	Uncertainty of mast 2
Uncertainty of the wind measurement	$\delta U_M = 2.42\%$	$\delta U_M = 2.41\%$
Uncertainty of the long-term data	$\delta U_{LT} = 2.56\%$	$\delta U_{LT} = 2.48\%$
Site assessment uncertainty	$\delta U_{SA} = 5.8\%$	$\delta U_{SA} = 5.8\%$
Uncertainty of wind resource variability	$\delta U_V = 1.8\%$	$\delta U_V = 1.8\%$
Sensitivity factor of the wind speed measurement	$SF_M = 1.27$	$SF_M = 1.27$
Overall uncertainty	$\delta U = 7.13\%$	$\delta U = 7\%$

These values are added to the Openwind software to calculate the energy production and probability of exceedance. Thus:

1. The uncorrelated uncertainty of the mast1 is 2.42 percent.
2. The uncorrelated uncertainty of the mast 2 is 2.41percent.
3. The correlated uncertainty which is added to each met mast tower is 4.2 percent.
4. There are two sources of uncertainty added in the Openwind software, the topographic difference and the directional difference, to be considered as the uncertainty of the wind flow modeling.
5. Then, there are some processes that have been done to calculate the annual energy production and uncertainty map as it seen in the figure 5.6. (openwind user manual, version 1.6A, uncertainty section).

In the wind project, the terms of probability of exceedance value (pxx) is used to express the uncertainty of the annual energy production. Thus, that is a good way to present the uncertainty of the wind project by giving the probability of exceedance in terms of expected annual energy production for the wind project.

The net energy production is P50 is calculated without considering the overall uncertainty which means that 50 percentchance for the value to be achieved. For the P75 means that there is 25 percent chance that p75 level will not be achieved. P90 means that there is a 10 percent chance that p90 level will not be achieved.

Table 5.8: Probability of exceedance of the AEP

Probability of exceedance	P50 Net Energy	P75 Net Energy	P90 Net Energy
The net energy production	172.1 GWh/yr	164.08 GWh/yr	159.7 GWh/yr

The greatest AEP is achieved with P50. From another side, the risk of achieving of this energy is larger. There is 4.9 percent energy loss with P75 net annual production compared to the P50 net annual energy production. But, the risk is lower. For P90, there is 9 percent loss with P90 net annual production compared to the P50 net annual energy production. But, this energy is to be achieved 90 percent during the time and the risk of the project achievement is lowest.

The uncertainty map of the target site is seen in Figure 5.6. The uncertainty map shows that there is a green area around each met mast which means low uncertainty. In the pink area, the uncertainty is increasing. The uncertainty is increasing as moving away from the met mast as it is shown in figure 5.6. One of the benefits of the uncertainty map is to pick and suggest the new met mast position to reduce the uncertainty at the target site.

Figure 5.8: Uncertainty map of the target site

Source: Openwind software.

6. CONCLUSION

There are unavoidable uncertainties connected to each step of wind resource assessment, from measuring the wind data at the target site to evaluate the predicted energy production of the wind resources at the target site. Using appropriate and calibrated measurement devices to measure the wind data at the target site can significantly reduce the uncertainty of the wind measurement data. International standards have submitted recommendations about the measurement devices and how should be manufactured, calibrated, installed, and used to get a correct measurement data.

The quality of the long-term reference data and the model that is used to predict the long-term at the target site, have uncertainties and theses uncertainties should be considered. The wind speed is changing yearly, seasonal, monthly, and daily, thus, a good understanding of the wind data variability at the site is important to estimate the uncertainty of wind resource variability correctly. The horizontal and the vertical extrapolation of the wind data at the site have an uncertainty which has an impact on the AEP calculation.

In this study, the wind data of the site located near Marmara sea is assessed. All the uncertainty sources through the assessment process are considered to calculate the annual energy production. The uncertainty map of the target site is formed to figure out the areas which have high uncertainty at the target site.

An uncertainty analysis is an important piece of a potential wind energy improvement. Thus, appropriate evaluation of uncertainty is critical for judging the practicality and danger of a potential wind energy improvement.

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