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Wind Resource Assessment in Cold Climate Regions

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Cold climate regions have good potential for wind energy development, but icing on wind turbines is recognized as a hindrance limiting the wind energy production in ice prone regions. This master thesis work is linked with Wind-CoE project of Artic Technology Research Team and is aimed at better understanding of wind resource assessment in cold climate regions. Three years' (2013-15) field SCADA data from Nygårdsfjellet wind park, which is in an ice prone region near Narvik, is used for this study. This work encompasses both analytical and numerical analyses to better estimate the annual energy production (AEP) and study wind flow physics over complex terrain. Computational fluid dynamics based numerical techniques has been used. A good agreement is found between analytical and numerical results.

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Jiayi Jin

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1 Introduction

1.1 Research need

Low temperature and icing prone regions are not most common areas for wind turbines installation, despite the fact of having good wind resources. Cold regions have good potential for wind energy development, but icing on wind turbines is recognize as a hindrance limiting the wind energy production at elevated cold climate sites in Scandinavia as well as the Alpine regions of Europe. Heavy icing regions, where icing has a major impact on wind turbine performance and annual energy production contains 4% of installed wind turbines worldwide. The wind based electricity production in moderate to heavy icing regions is expected to grow from 11.5 GW at the end of 2012 to 19.5 GW by 2017 [1]. Therefore, improved estimation of icing related power production losses is much needed both for the proper operation of new wind parks and to provide more accurate wind energy production forecasts [2]. Ice accretion on wind turbines can lead to a number of problems including *health and safety risk from ice throw, increased fatigue on the wind turbine components from increased mass and potential imbalance, reduced power production due to changes in blade aerodynamics and complete shutdown of turbine*. Due to these risks and their economic consequences, it is important to be able to better forecast, both through real-time and with retrospective analysis, how and when ice will accrete on wind turbines and what will be its effects. The International Energy Agency (IEA) Annex 19: *'Wind energy in cold climates',* also calls for finding methods to better estimate the effects of ice accretion on wind turbine performance and resultant wind energy production.

No standard methodologies are yet available for the reliable wind resources and icing condition assessment for the cold climate regions. The complexity of wind resource assessment in cold climate regions varies greatly depending on the location of wind parks and the meteorological conditions in these regions. The planetary boundary layers of high latitude cold climate (HLCC) regions have a big difference from low latitudes, primarily due to reason that is in HLCC regions thermal energy is unavailable to drive transport processes for most of the year. These transport processes modulate the local atmospheric structure.

This master thesis project is linked with an ongoing research project (*Wind-CoE*) of Arctic Technology Research Team of University of Tromsø. WindCoE project is focused on wind energy in cold climate and is funded by *EU- INTERREG Botnia-Atlantica, Nordlandfylkes Kommune & University of Tromsø*. The wind park SCADA data used in this master thesis project is collected from Nygårdsfjellet wind park operated by NordKraftVind AS and owned by FORTUM. Nygårdsfjellet wind park is suitable for this study as it is located in an ice prone region near Narvik, Norway (*68.506 ^{0}N 17.8943 ^{0}E*). This wind park comprises 14 wind turbines at an average elevation of 400 m a.s.l with a total production capacity of 32.2 MW and annual production of 104.2 GWh. This master thesis work is focused on wind resource assessment in cold regions and has been carried out as per following main tasks.

i. Filed measurements and data analysis of meteorological parameters such as *atmospheric temperature, wind speed and wind direction* at Nygårdsfjellet wind park site.
ii. Wind park SCADA data collection and sorting.
iii. SCADA data analysis
iv. Computational fluid dynamics (CFD) based numerical simulation of wind resource assessment over Nygårdsfjellet wind park.

Following figure 1-1 shows the Gant chart of this master thesis work that has been accomplished over a period of 8 months from October 2016 to May 2017.

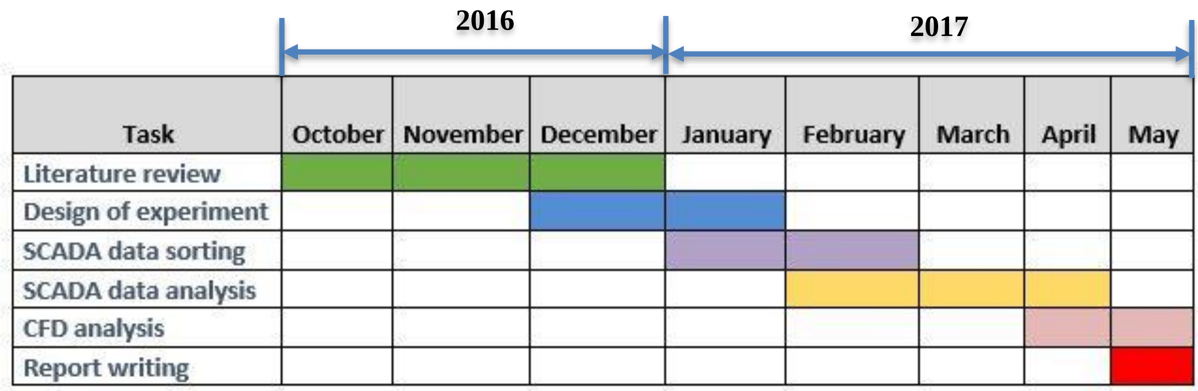


Figure 1-1 Gant Chart

1.2 Wind park site description

The Nygårdsfjellet wind park is located on complex terrain right beside E10 on Skitdalshøgda around the Skitdalsvatnet lake and near Norwegian and Swedish border. Nygårdsfjellet wind park consists of 14 wind turbines built in 2011 with total production capacity of 32.2MW. Technical details of wind turbines installed at Nygårdsfjellet wind park are specified in table 1-1. Figures 1-2 shows the terrain/location of Nygårdsfjellet wind park.

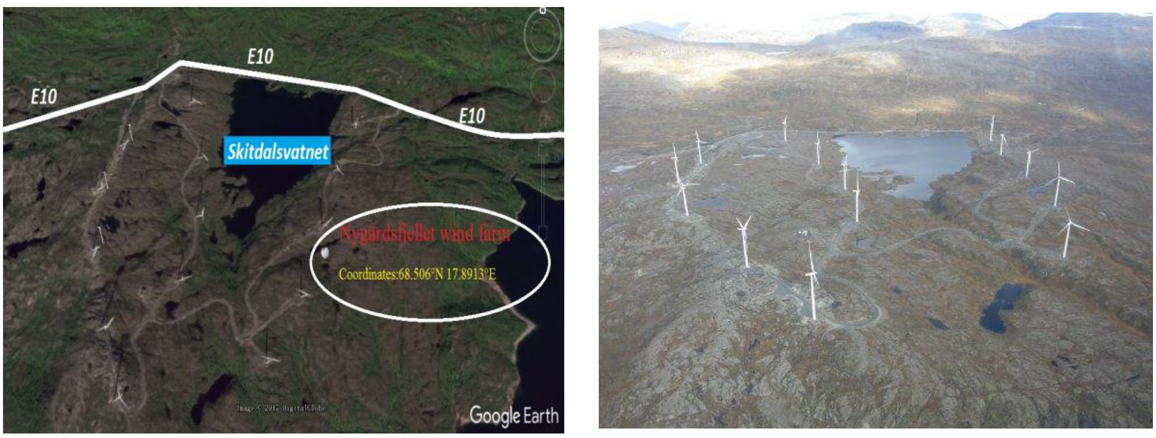


Figure 1-2 Terrain overview of Nygårdsfjellet wind park

Turbine Manufacturer	Siemens_23_93VS	**Max Production Capacity**	104.2 GWh
Tower Height	80 m	**Nacelle Weight**	83 tonn
Rotor Diameter	90 m	**Tower Weight**	158 tonn
Rotor Area	6361 m^2	**Rotor Weight**	60 tonn
Production Speed	3 ~ 25 m/s	**Total Weight**	300 tonn

Table 1-1 Technical details of wind turbines installed at Nygårdsfjellet wind park

1.3 Thesis outline

This thesis comprises of 6 chapters. Chapter 1 is introduction. Chapter 2 describes literature review study about previous work on wind resource assessment in cold regions. Chapter 3 describes the design of experiment methodology used for this master thesis. Chapter 4 describes the SCADA data sorting and analysis for three years (2013-2015). Chapter 5 describes CFD based numerical simulations of wind resource assessment using the SCADA data for year 2014. This chapter also includes a comparison of SCADA data with the CFD results, where a good agreement has been found between analytical and numerical results. Chapter 6 describes the conclusion part and future work recommendations.

2 Literature Review

2.1 Wind energy & ice prone regions

Due to increasing demand of electrical power and efforts to protect the environment, there has been an increasing need of rapid expansion of better use of renewable energy sources to cut the toxic emissions [3]. The cold climate regions around the world like *Finland, Germany, Slovak Republic, Norway, Czech Republic, UK, Sweden, Bulgaria, Hungary, Russia, Canada and USA* have great potential of wind resources. Estimated wind energy capacity in cold climates is about 60 GW[4]. Cold climate conditions mainly affect wind park site access, wind turbine operations, working and maintenance, finances, noises, health and safety of workers. Cold climate wind energy projects need to take into consideration the high safety standards in addition to other undertakings in the normal operating climate. Cold climate regions have good resources of wind energy but still have reasons that stop financers from investing on wind energy projects in ice prone cold regions mainly due to non-existence of appropriate wind resource assessment and reliable ice forecasting methods for better estimation of wind turbine production losses under icing conditions.

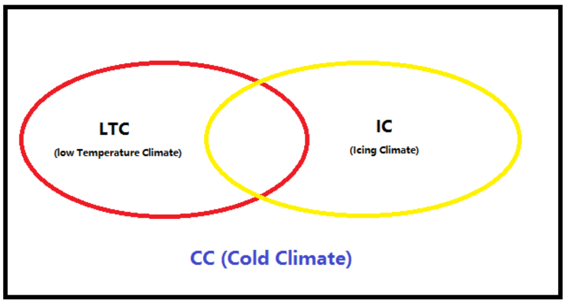


Figure 2-1 Cold climate classification [4]

Safe operation of wind turbines under icing conditions requires improved wind turbine design and special safety procedures as ice accretion on wind turbines can lead to possible ice chunk fall, which is hazardous to human safety. The most common effects of ice accretion on wind turbines include [5]:

a. Increasing the static load on wind turbine rotor that can lead to alteration of the dynamic balance of the rotor leading to possible structural fatigue.
b. Disrupted blade aerodynamics due to ice accretion, which can lead to change in its aerodynamic performance and resultant wind energy production.
c. Ice chuck fall, which is hazardous for humans and can strike the rotor blade.

The International Energy Agency (IEA) Annex 19: *'Wind energy in cold climates',* also calls for finding methods to better estimate the effects of ice accretion on wind turbine performance and resultant wind energy production. Following table 2-1 highlights the main targets of IEA task 19 [6]:

No.	Target
1	To collect information on ice mapping.
2	To collect information and experiences related to the forecasting of icing conditions.
3	To find some new solutions under power supply, sensor options and detection of ice.
4	To develop some coating solutions under anti- and de-icing conditions.
5	To review the current standards and recommendations in CC regions.
6	To find methods for better estimation of the effects of icing on the wind production.
7	To clarify the significance of the extra ice loading.
8	To initiate a market survey for the technology of CC wind production.
9	To improve the considerable of the risks in extreme climate.
10	To update the state-of-the-art report and studied the expert group.

Table 2-1 Top 10 targets shows in IEA Task 19

The wind park classification based upon icing events and resultant production losses is an important deliverable of IEA task 19 report. Table 2-2 shows the IEA wind park site classification based on icing events [6, 7]:

IEA Ice class	Meteorological Icing	Instrumental icing	Production loss
	% of year	% of year	% of annual production
5	>10	>20	>20
4	5~10	10~30	10~25
3	3~5	6~15	3~12
2	0.5~3	1~9	0.5~5
1	0~0.5	<1.5	0~0.5

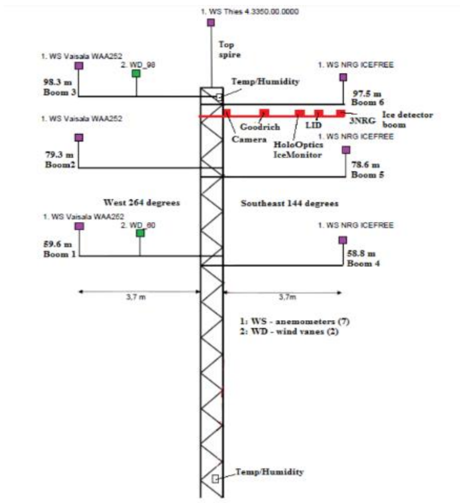
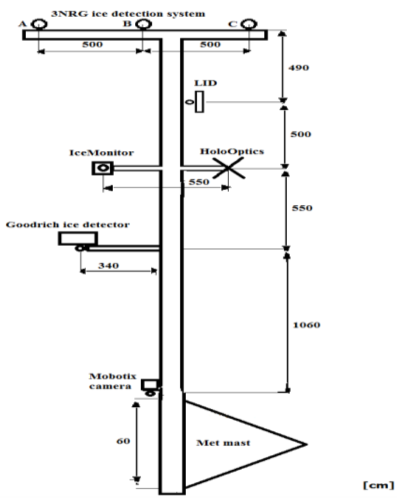
Table 2-2 IEA site classification [6]

2.2 Field measurements

Field measurements are important part of wind resource assessment in cold regions. To carry out high-quality and reliable field measurements in cold regions, special meteorological equipment is required[8] . In addition, we also need to consider special met mast design for icing conditions.

2.2.1 Met mast design and instrumentation

Special met mast design is required to support heavy snow, ice loads and high wind speeds at ice prone cold climate sites [4]. Meteorological measurement instrumentation mainly consists of: *1) heated anemometer, 2) non-heated anemometer (for comparison), 3) CCTV camera, 4) Ice load sensor, 5) Temperature sensor, 6) Relative humidity sensor*. Depending on the requirement and ice loads, different types of met mast can be used such as: *small masts, tubular hi-masts and lattice masts* [9]. Table 2-3 shows three different classifications of met mast that have been used in Sweden [7].

Installer	Feature	Figure
Granliden	1). The most equipped mast in regard to ice detectors; 2). Mobotix camera MXM12D; 3). 3NRG ice detection system.	 

<table>
<tr>
<td>Blakliden and Föboberget</td>
<td>1). 50 turbines at Blakliden wind park, 40 turbines at Föboberget;

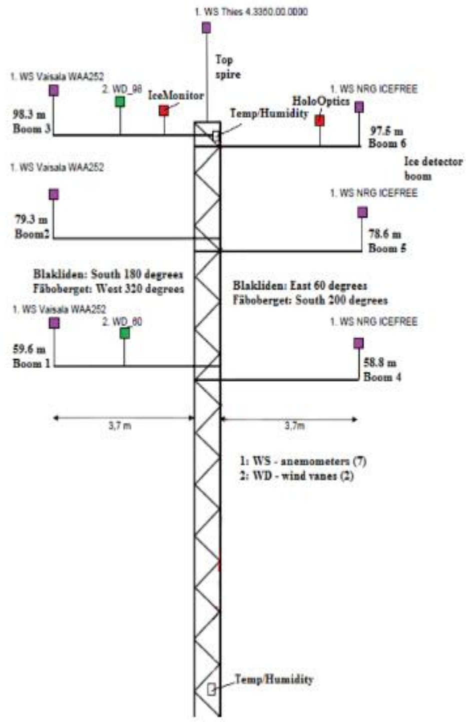
2). Different booms towards different directions. Boom 1,2,3 are directed towards 320 degree (west), while 4,5,6 are directed towards 200 degree (south) in Föboberget; but in Blakliden, 1,2,3 are directed towards 180 degree (south) , while 4,5,6 are directed towards 60 degree (east).</td>
<td>
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Table 2-3 Met mast and instrumentation examples for icing regions [6].

Above mentioned three different met mast installations have three-cup anemometers on the top of the met masts that can possibly identify ice directly. For the Granliden, the HoloOptics & IceMonitor are connected to Goodrich, LID and 3NRG and a camera. In Blakliden and Föboberget, the met mast is quite different. The HoloOptics and IceMonitor are separated on both sides of the ice detector booms.

2.3 Meteorological data

Generally meteorological instruments used for wind resources assessment collect and sample the data on regular intervals. For example in some cases, they log data for every 10 minutes and sample data for every 30 minutes. There are different techniques for data sorting and analysis. The normal data analysis techniques use SCADA system to analyze database and use wind rose plots to show the wind directions with different wind speeds. In addition, statistical methods like *mean, standard deviation, regression, sample size determination and hypothesis testing* are applied to calculate the databases in daily, monthly and annually time intervals.

2.3.1 Icing conditions

Icing events are defined as time periods when the atmospheric temperature is below 0°C and the relative humidity is above 95% [10]. There are two ways to calculate the icing conditions: meteorological icing (M_{icing}) and instrument icing (I_{icing}). Table 2-4 briefly describes this.

Condition	Characteristics
Meteorological icing (M_{icing})	a. The total amount of ice accreted on a standard event in the period of the icing problem; b. The conditions of meteorological; c. The average and/or maximum the accretion rate.
Instrument icing (I_{icing})	An instrument to keep ice-free under the icing conditions.

Table 2-4 Icing Characteristics

According to ISO 12494 standards, the site icing index should be classified as per table 2-5 (*from EUMETNET/SWS II Report*). This classification simplifies the way to find out icing severity and helps wind park operators and wind turbine manufactures to find out the icing conditions and to modify the design and safety requirements for the wind park accordingly.

Site icing index	Days with meteorological icing/year	Duration of meteorological icing %/year	Intensity of icing g/100 cm^2/h (typical)	Icing severity
S5	>60	>20	>50	Heavy
S4	31-60	10-20	25	Strong
S3	11-30	5-10	10	Moderate
S2	3-10	<5	5	Light
S1	0-2	0-0.5	0-5	Occasional

Table 2-5 Icing index classification

2.3.2 SCADA method

SCADA (*Supervisory Control Andi Data Acquisition*) system in general is not only a system of data acquisition and monitoring, but also is a computer based system to complete process control and automation. In order to implement the data acquisition, equipment control, data measurement, parameter adjustment and various signal alarms, it can monitor and control the wind turbine operation. In the normal area, the SCADA data analysis system contains:

a. ***Database management system*** that has fast data reading and establishing a relationship between the data; also has a grid data model and standard access interface and so on.
b. ***Internet management system*** that uses COM interface with other applications, transmitting data which are received by the network layers.
c. ***Figure management system*** that has very friendly graphics editors and geographic information systems.

d. ***System management system*** which has high-safety distributed network management, as well as self-diagnosis system management and timing task management.

However, in the cold climate ice prone regions, the wind turbines are operated differently than in the normal regions. When running the SCADA data analysis, we need to consider not only the low-temperature and icing climates but also the ice accretion on rotor blades and instruments. Therefore, the wind production in CC regions demands lubricants and cold start-up procedures. This makes the SCADA data analysis more complicated and specialized. SCADA data are often used to optimize the performance of the wind turbines, as Table 2-6 shows below: [11]

Methodology		**Explanation**
1.Analysis of the production data	Identification of ice-induced downtime	Each 10-minute record in the SCADA database is 'flagged' as being associated with either 'available to operate', 'un-available due to icing' or 'un-available due to non-icing'
	Identification of ice-induced power curve degradation	Each record in the SCADA database is flagged as being associated with a specific measurement consistency period, systematic performance variation period or a specific intermittent performance issue, or not being affected by any performance issue (i.e. 'normal performance').
	Quantification of ice-induced energy loss	Quantify the energy loss incurred due to icing-induced un-availability and power curve degradation.
2.Production data ice induced energy loss investigations		Combined with the geographic location and hub height altitude, SCADA estimation could be applied to build the icing map, using the relationship between the average annual losses observed in the operation data and altitude.
3.Analysis of pre-construction meteorological data		Icing periods are identified by comparing the wind speeds and directions between sensors at different levels, parallel sensors at the same level, sensors with different heating arrangements and corresponding temperature and relative humidity values where available.
4.Development of a methodology for predicting long-term energy losses due to icing from pre-construction data		Use anemometer icing in pre-construction data to predict icing losses during wind park operation. Extrapolate historical icing events and inform a long-term adjustment from the matrices of relative humidity and temperature.

Table 2-6 SCADA analysis techniques

2.3.2.1 SCADA system for single wind turbine

When we focus on the SCADA data system, which is based on many single wind turbines, we need to understand the working steps as shown in figure 2-2 for monitoring and inspecting a single wind turbine [12].

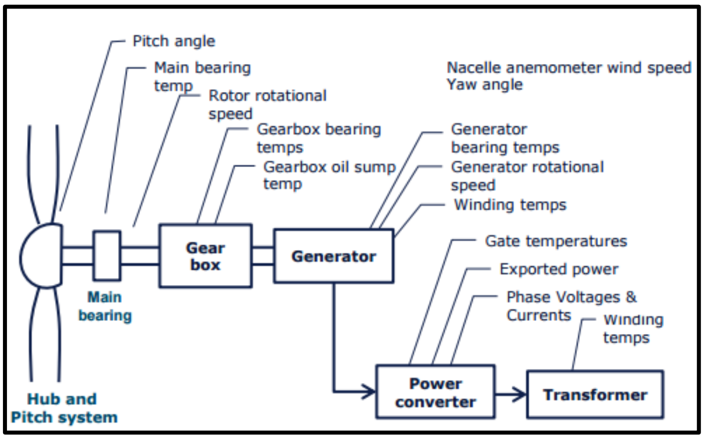


Figure 2-2 Single wind turbine work conditions [12]

2.3.2.2 SCADA data analysis for wind parks

For wind parks SCADA data analysis in cold regions, we need to know that inside the wind parks, there are many single wind turbines working together and outside the wind parks there are complex power grids connecting the wind parks with others or power users. In the cold climate regions, the performance of wind turbines probably decreases considerably because of ice accretion at turbine blades, and the loss of energy could be as high as around 50% in the wintertime, 10% annually [11]. Therefore, the ice accretion will be a big challenge for the wind energy development and operations under cold climate. DNV GL presented a study based on 20 operational wind parks in Scandinavia to find out the actual production losses due to icing [11]. Their methodology is summarized in Table 2-7:

Methodology		
1	Analysis of the production data.	Identification of ice-induced downtime
		Identification of ice-induced power curve degradation
		Quantification of ice-induced energy loss
2	Investigations of ice-induced energy loss with production data.	
3	Analysis of pre-construction meteorological data.	
4	Development of a methodology for predicting long-term energy losses due to icing from pre-construction data.	

Table 2-7 DNV GL methodology

Following are the conclusions of this study:

1. Wind turbines could continuously work during ice accretion period, so as to minimize the loss of energy caused by icing.
2. Polynomial relationship exists between icing production loss and altitudes of the sites in Sweden;
3. The icing problems have high variability, and the resulted energy loss decreases with an increase in the mean icing loss;
4. Fully heated cup anemometers outperform the unheated or partially heated ones in ice reduction;
5. A method is proposed and validated for predicting annual energy loss due to icing from the occurrences of anemometer icing;
6. A method based on temperature and humility data is developed for studying icing losses in a long-term context.

However, the problem of this method is that:

1. They didn't consider safety issues, noise problem and turbine life cycle;
2. Need to conduct more SCADA data analysis and find the correlation between the slope and shape with the ice loss and different altitudes;
3. There may be some difference in the energy loss and average of annual history;
4. The effects of ice on the sensors, such as the heated sensors, on SCADA data analysis vary across different icing conditions.

Based on the above description, we can use the method DNV GL proposed, but need to add more performance comparisons in our work.

2.4 Wind resource assessment in cold climate regions

2.4.1 Scope of wind resource assessment

The wind resource assessment in cold climate regions not only directly affects the site access, the working conditions and the production of the wind energy, but also affects the chosen techniques, wind noise, working loads and public safety. Many CC regions could offer great wind power potential but need to overcome the atmospheric icing problems and the difficult working conditions under low temperature [4]. We did not fully recognize these special challenges and had no way to solve the technical and financial problems until a few years ago. IEA report published in 2011 also points out the wind measuring methods to solve these problems, as stated in Table 2-8: [4]

Methods	Techniques
Site assessment	a. Adoptable equipment of site measurement; b. At least one year icing measurement data collection; c. The procedure of the measuring program needs to consider the location, parameters and working conditions.

Instrument and turbine manufacturers	a. Some partly sensors under the level of prototype; b. The devices for anti-icing and de-icing; c. Heated involving and so on.
High safety standards	a. High risks should be considered for planning, operating, insuring and investments and so on; b. Some additional costs will occur on the working condition, construction and site access. Therefore, we need to make plans to cut it.

Table 2-8 The way to solve the problem under wind assessment

The wind resource terms can be classified as following table 2-9 shows: [4]

Term	Definition	Comments
Atlas	Large area dataset of regional wind climates.	Scope: 100~10000km Scale: O (50km)
Regional climate	Statistics of wind, the temporal and spatial variation, and the standard conditions reduced.	Scope: regional validity Scale : O (50 km)
Resource	Long-term kinetic actual energy of the wind, which has a special location and height of the wind content.	Scale: O (1 m)

Table 2-9 Wind resource assessment estimation

Table 2-10 shows the eight approaches of wind assessment estimation [13]:

Components method	1	2	3	4	5	6	7	8
Measurements		☺	☺		☺	☺		☺
Database geostrophic winds				☺			☺	☺
Database land-use							☺	☺
Database orography							☺	☺
WASP terrain					☺	☺		☺
Mesoscale model							☺	☺
CFD					☺	☺		☺
Microscale model					☺	☺		☺
Geostrophic drag law				☺				
Statistical models			☺					
'Folklore'	☺							

Table 2-10 Wind resource assessment estimation

2.4.2 Numerical methods of wind resource assessment

Numerical methods of wind resource assessment can be classified according to three scales, *a) large, b) medium, c) small*; as shown in figure 2-3:

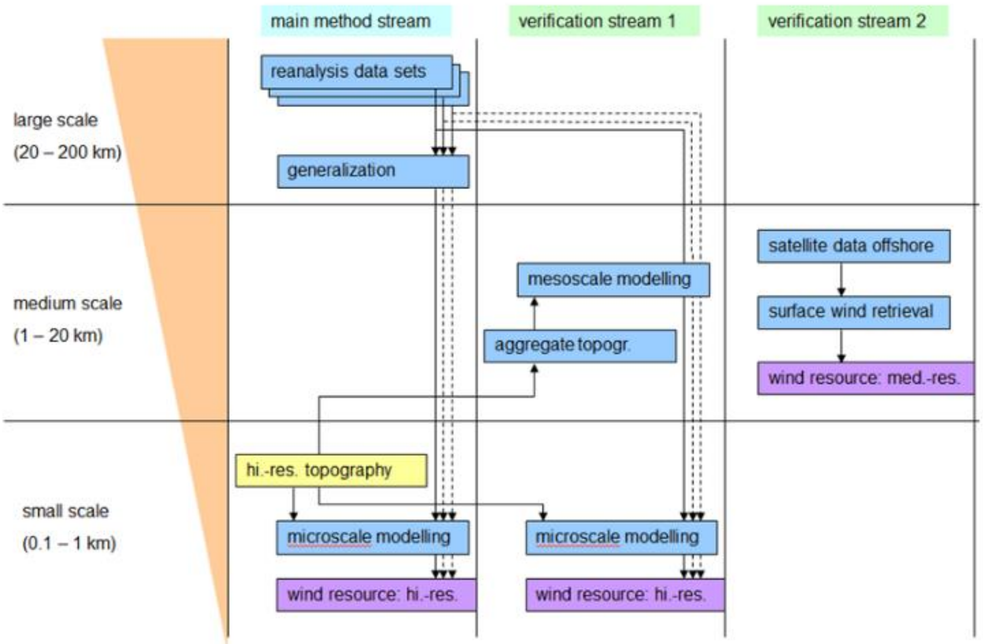


Figure 2-3 Processing of the scale of wind resource assessment [14]

From figure 2-3, we can see that the numerical methods include generalization part, mesoscale modelling part, wind data retrieval part, microscale-modelling part and so on in different streams. There are two main numerical methods: *a) mesoscale modelling method, b) microscale modelling method*.

- ***For mesoscale***, by modeling and measurement verification, it makes wind resource assessment better with uncertainties in the estimate of wind speed. In addition, mesoscale modeling could be used in verified assessment for precise national planning which is the basis for the private developers' activities.
- ***For microscale***, the input is from the mesoscale modeling output and the analysis of developer's measurements.

We review the mesoscale and microscale approaches as follows and compare the advantages and disadvantages to find a better solution to wind resource assessment.

2.4.2.1 Mesoscale approach

The report published in 2014 by World Wind Energy Association (WWEA), shows three approaches for the mesoscale wind resource assessment [15].

i. The first approach is Weather Research and Forecasting (WRF). This approach has metrological investigations and real-time Numerical Weather Prediction (NWP). It could conduct atmospheric simulations and data assimilation studies. Moreover, it could couple with other numerical models. By using WPS to define the grid of WRF, make the generate map, evaluation and condition information from WRF, also can make some model to analysis data and make a forecast, and interpolate the data to the grid of WRF.

ii. The second approach is PSU/NCAR mesoscale model, which can also be called MM5. It is from Penn State University and built on NCAR community model, and has all the capabilities of WRF. The model is a limited-area, non- hydrostatic one which can simulate mesoscale atmosphere conditions. It also can be used to make a latitude and longitude grid in an interpolated form and make a higher variable resolution in this area. It can forecast the weather and measure climate forecasting.

iii. The third approach is Boundary layer model (BLM), which is developed by “Wind Force”. It creates a region of interest (Rol), and could make outside urban area masked out of the wind assessment. It not only has long-term average data region, but also considers reasons which are not suitable for wind power development.

2.4.2.2 Microscale approach

The wind analysts must consider the accuracy of the numerical models. To use the computational fluid dynamics (CFD), we must think about whether it is sufficient as a linear model or not. Microscale methods based on CFD in wind resource assessment [16] are shown in Table 2-11.

Microscale list	Traditional approach	Tools	Advanced approach	Tools
Horizontal extrapolation	Linear model, near-neutral conditions	Wind Atlas Methodology (WAsP)	Non-linear model, different stabilities, built-in forest model	CFD solvers, turbulence model calibrated with sonic measurements
Vertical extrapolation	Define most likely wind shear based on lower measurements and experience	Linear model, near-neutral and/or experience	Profile calibration based on remote sensing and CFD modelling	Remote sensing + CFD

Table 2-11 Approaches of microscale analysis

From the above discussion, we see that both mesoscale and microscale approaches have their own limitations in wind resource assessment. We need to consider different methods for different wind resource assessment problems. It turns out that combining these two methods together can do a better job for wind resource assessment.

2.4.2.3 Coupling meso-micro scales approach

DTU wind energy department has pointed out that if we combine mesoscale and microscale together, the mean power density will expand by 50% [13]. The combination of mesoscale and microscale approaches has big advantages for the assessment of wind resources, especially for complex terrains of cold climate regions.

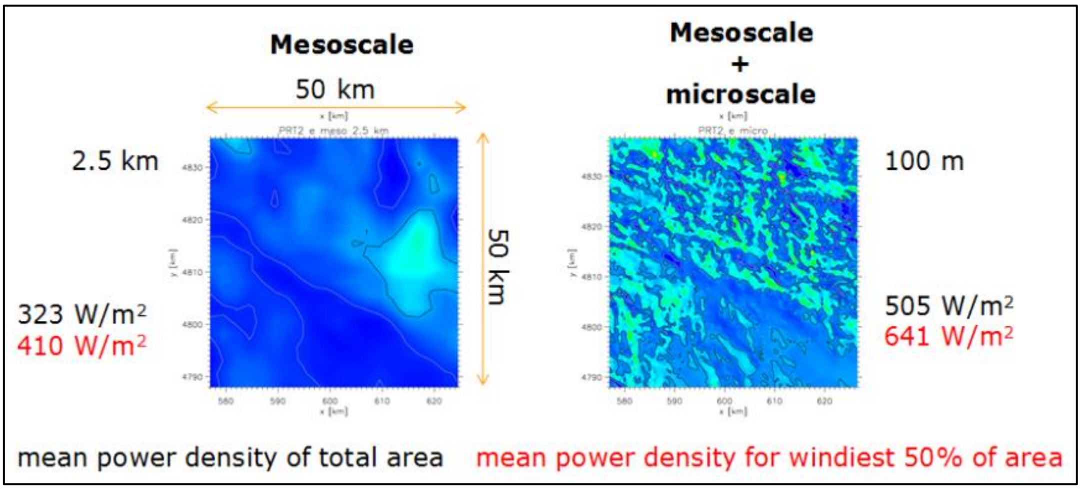


Figure 2-4 Comparison of mean power density [13]

2.4.3 Terrain roughness effects

The first thing we need to do before assessing terrain roughness data is to separate the topography, as shown in table 2-12 [17]:

Topography	Surface description	Resolution
Elevation	Shuttle Radar Topography Mission (SRTM)	Resolution 90-30 m
	Viewfinder, compiles SRTM and other datasets	Resolution 90-30 m
	ASTER Global Digital Elevation Model (ASTER GDEM)	Resolution 30 m
Land cover	ESA GlobCover	Resolution 300 m
	Modis, land cover classification	Resolution 500 m

Table 2-12 Topography separation [17]

2.4.4 Effects from climate change

Nowadays, the climate change not only affects the agriculture, forestry, animal husbandry and so on, but also influences the icing conditions. For example, when the weather becomes warmer, the Baltic Sea area's temperature increases and there is more rainfall [18]. The symptoms are shown as follows:

1. More rain and less sea ice;
2. Increased nutrient flows in the rivers and sea.

The results of the climate change, such as low temperature, ice detection and snow have influence on the normal operation of wind turbines, especially in cold climate regions. Ireland government published the report: *Connecting How Much with How To*, showing the vision for Ireland in 2050 facing climate change problems, and proposing one pragmatic approach and three tracks, as shown in Table 2-13. [19]. According to this report, climate change not only influences agriculture, transport and so on, but also influences energy and natural resources, like wind energy, which is the main topic in this master thesis.

Step	Approach	Explanation
Vision	A carbon-neutral Ireland society will be built by 2050. It is socially and environmentally sustainable economic development.	
Approach	Three Ideas	Climate-change is not a loop policy;
		How to achieve decarbonisation is critical;
		Involve more and more companies, public organizations and communities in decarbonisation.
Track	Track 1	Strategic and institutional
	Track 2	Exploration and Experimentation
	Track 3	Design and implementation

Table 2-13 Ireland and the climate change challenge

3 Design of Experiment

3.1 Wind park site description

Nygårdsfjellet wind park is located near Narvik Norway (68.506 ^{0}N 17,8943 ^{0}E) and comprises 14 wind turbines at an average elevation of 400 m a.s.l with a total production capacity of 32.2 MW and annual production of 104.2 GWh [20]. This wind park is prone to icing conditions, which makes it suitable for the objective of this master thesis work. All 14 turbines' SCADA data from Nygårdfjellet wind park has been used to further study the wind flow characterization over complex terrain and resultant power production from each wind turbine for three years (2013- 2015). Detailed analytical analysis of SCADA data has been carried out in this regard. Later computational fluid dynamics (CFD) based numerical simulations are carried out to better understand the wind flow physics and wake rotational effects on neighbouring wind turbines and its resultant effects on power production during summer and winter periods. Figure 3-1 shows the real pictures of Nygårdsfjellet wind park during summer and winter periods.

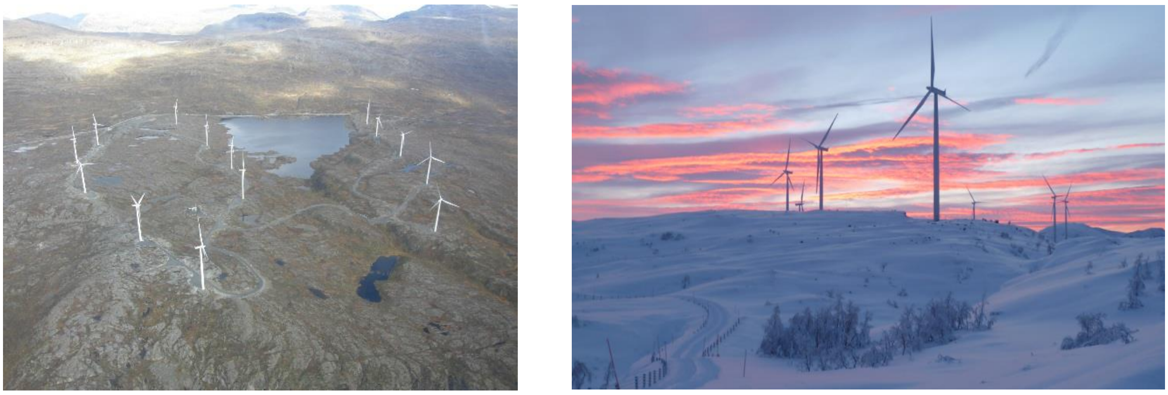


Figure 3-1 Nygårdsfjellet wind park during summer and winter periods

3.2 Design of experiment

The work presented in this thesis is carried out in following five main steps.

1) Literature review to better understand the previous work and nature of study
2) SCADA Data collection from Nygårdsfjellet wind park
3) SCADA Data sorting
4) Analytical analysis of SCADA data
5) CFD based numerical analysis

Figure 3-2 shows a schematic overview of design of experiments used for this study.

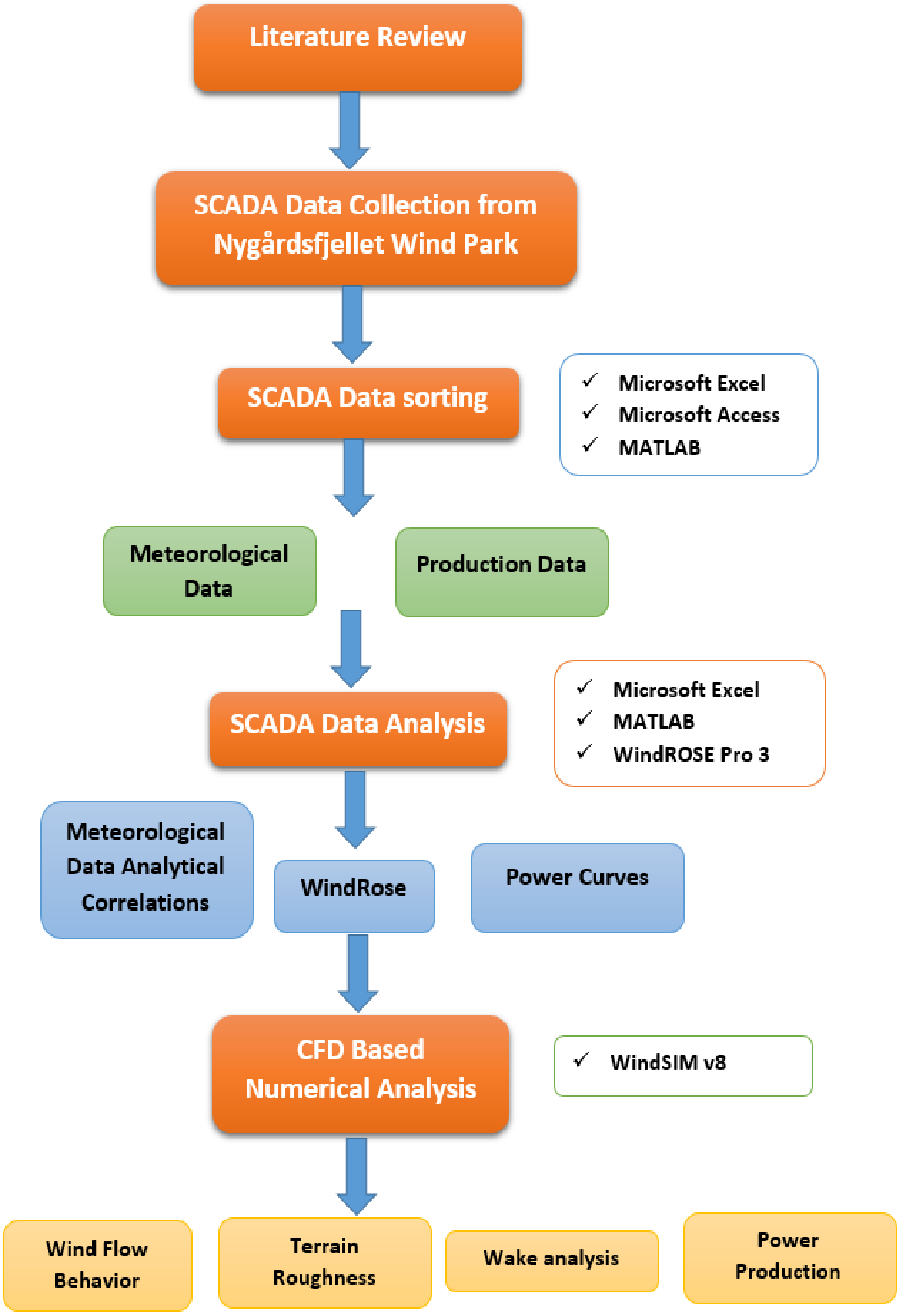


Figure 3-2 Schematic overview of design of experiment used for this study

3.3 Software overview- used for this study

3.3.1 Microsoft Access 2016

Microsoft Access 2016 is a Windows-based desktop relational database management software that Microsoft Company released in the end of 2015. It provides a variety of wizards, generators, templates, data storage, data query, interface design, report generation and other operational standardization to establish a fully functional database management system. Its user-friendly functionality also allows facilitating the basic/ordinary users. In this thesis, Microsoft access was used for data sorting as the original SCADA database provided by NordkraftVind was also in access database format.

3.3.2 Microsoft Excel 2016

Microsoft Excel 2016 has the background with Access 2016. Moreover, Excel is not only a data storage tool, but also a simple data analysis tool. Through Excel, we can easily get the format which can be imported to MATLAB, Wind Rose software and so on to do further analysis. In this master thesis Microsoft Excel was used for both SCADA data sorting and analysis. One Simple plugin was used to split Excel '.csv' format to Excel '.xlsx'. Because one-year database combination is too big to export to '.xlsx' Excel format, so we try to export to '.csv' format first, and then use the split tool to export to '.xlsx' format.

3.3.3 MATLAB R2016b

MATLAB is widely used by researchers for big data set analyses. Built-in plots and graphics make it easy to visualize data. Compared with previous versions, MATLAB R2016b working interface is more concise and the mathematic and graphic tools are easier to use. In this master thesis, MATLAB is mainly used for curve fitting analysis and SCADA database analysis. Several small subroutines programs were written for this purpose.

3.3.4 WindRose PRO3

WindRose PRO3 is a software for analysing and plotting wind direction and velocity from original database based on the Windows system. Moreover, time series can be chosen when customers have some other needs. For this purpose, WindRose PRO3 was used for making wind rose from SCADA data.

3.3.5 WindSim v8

WindSim is a computational fluid dynamics based software, developed by WindSim AS. Compared with WAsP, which is good for linear simulations, WindSim is one popular numerical modelling tool for wind energy sectors and can do advanced computational fluid dynamics based numerical simulation in non-linear ways. WindSim v8.0.0 includes many new features and is a clear way towards cloud computing. In this master thesis, WindSim v8 was used for the CFD based numerical simulations of flow over complex terrain of Nygårdsfjellet wind park. An extension of WindSim 8.0, WindSim Express 8.0, was used to input the elevation and roughness data map.

Based upon the features of each above-mentioned software, a careful comparison was made for the selection of most suitable tools for this study. Following Table 3-1 highlights this selection.

	Name	**Software Selection**
Data Analysis	Excel	
	MATLAB	√
WindRose Analysis	Excel	
	MATLAB	
	WindRose PRO	√
CFD Simulations	WAsP	
	WindSim	√

Table 3-1 Software Selection

4 SCADA Data Analysis

Three years' (*2013-2015*) SCADA data from all 14-wind turbines of Nygårdsfjellet Wind Park is collected for this study that contain meteorological, wind turbine operational and production data for each 10 minute time interval. The main parameters of this SCADA dataset are:

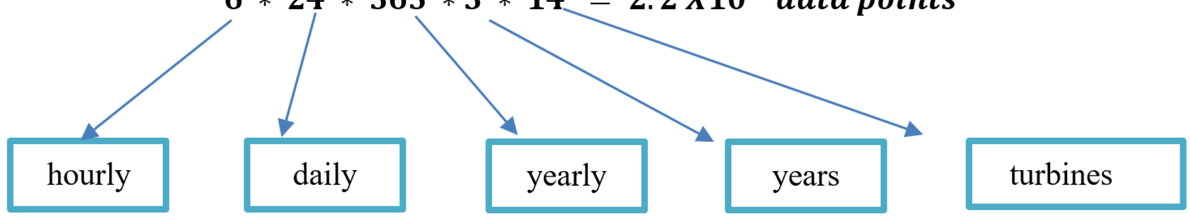
(1) Average wind velocity (m/s)
(2) Average atmospheric temperature (ºC)
(3) Wind power production (kW)
(4) Time series (10 min)

Interpolation methods have been used to do SCADA data analysis for:

(1) Time & Average wind velocity
(2) Time & Average temperature
(3) Time & Wind power production
(4) Average wind velocity & Wind power production
(5) Average wind velocity & Average temperature
(6) Average temperature & Wind power production

This SCADA dataset was sorted using Microsoft EXCEL & Access. The overall dataset size used for this study is around 70GB, where around 2.2 million data points were sorted and analysed.

$$\mathbf{6 * 24 * 365 * 3 * 14 = 2.2\,X10^{6}\ \textit{data points}}$$



.

Number	SCADA data File Number	Wind Turbine Size（MW）	Wind Turbine Manufacturer	Wind Turbine Coordinates
01	0575	2.3	Siemens 2.3-93VS	617113, 7602557
02	0574	2.3	Siemens 2.3-93VS	617083, 7602303
03	0573	2.3	Siemens 2.3-93VS	617132, 7602020
04	4531	2.3	Siemens 2.3-93VS	617433, 7602865
05	4532	2.3	Siemens 2.3-93VS	617531, 7602548
06	4533	2.3	Siemens 2.3-93VS	617570, 7602223
07	4534	2.3	Siemens 2.3-93VS	617534, 7601910
08	4535	2.3	Siemens 2.3-93VS	617393, 7601483
09	4536	2.3	Siemens 2.3-93VS	617285, 7601695
10	4537	2.3	Siemens 2.3-93VS	617950, 7601635
11	4538	2.3	Siemens 2.3-93VS	618084, 7601877
12	4539	2.3	Siemens 2.3-93VS	618174, 7602185
13	4549	2.3	Siemens 2.3-93VS	618244, 7602485
14	4541	2.3	Siemens 2.3-93VS	618358, 7602797

Table 4-1 Location and SCADA data file number for each wind turbine used

Figure 4-1 shows the design layout and terrain model of the Nygårdsfjellet wind park.

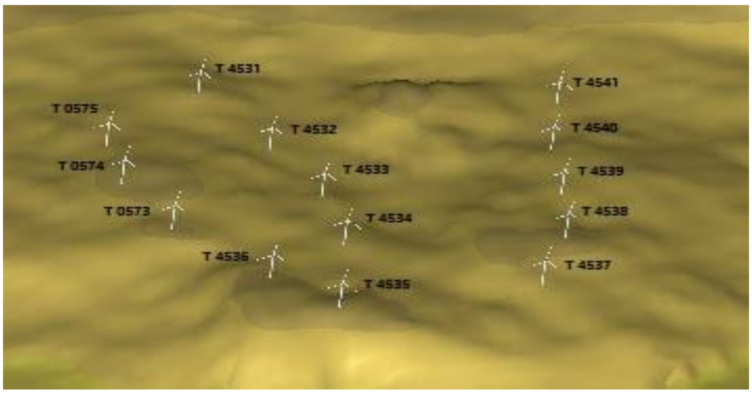


Figure 4-1 Nygårdsfjellet wind park design layout

Figure 4-2 shows the methodology used for SCADA data sorting and analysis in this master thesis work.

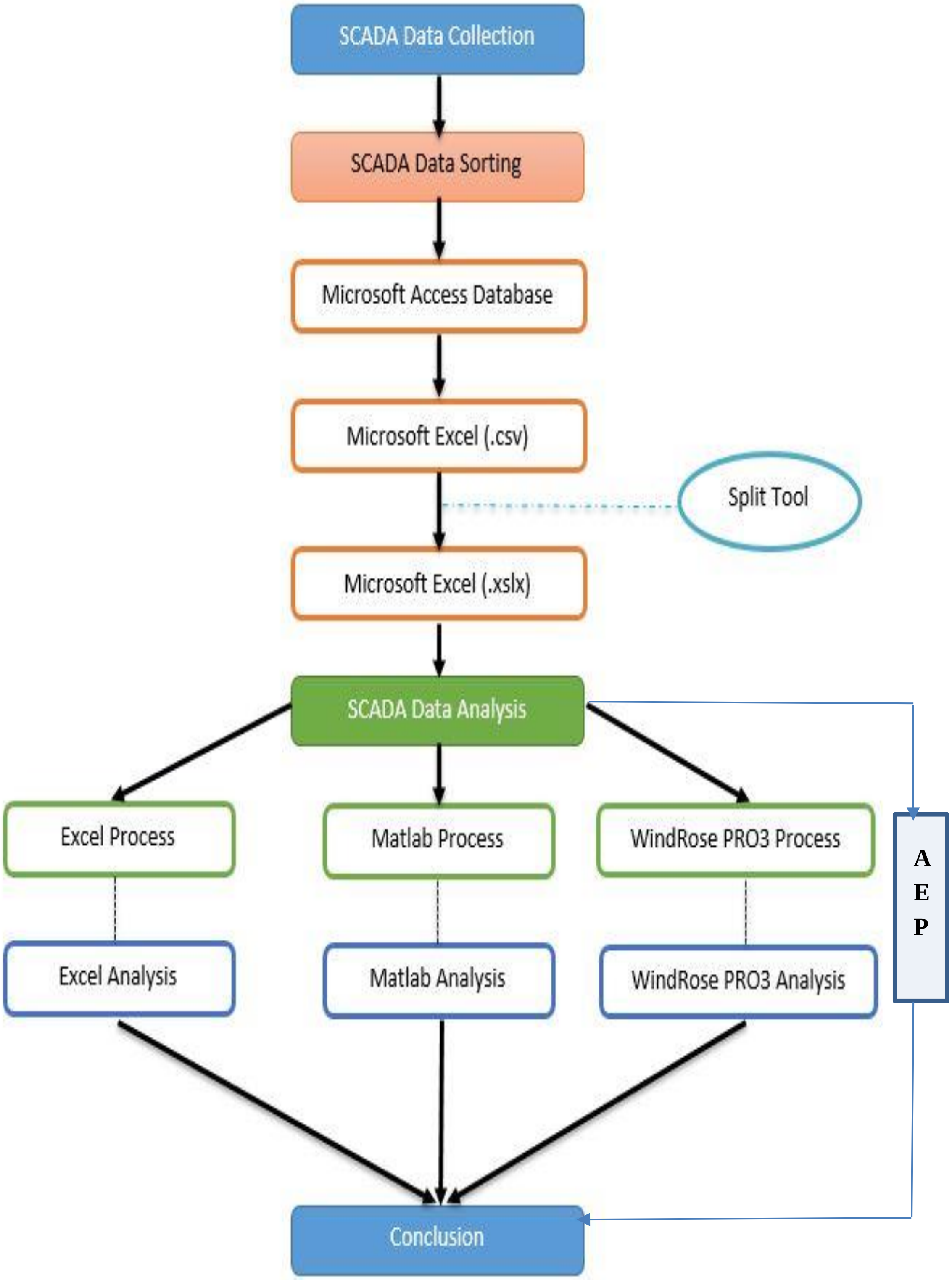


Figure 4-2 SCADA Data Analysis Structure

4.1 SCADA data sorting

Different software's have been used for SCADA data sorting and analysis in this work. Following sections explain the procedure used for the sorting of SCADA data.

4.1.1 Microsoft Access to Excel (.csv)

1. Downloaded the following two files
   a. Year-month-tur (e.g. 2014-12-tur)
   b. Year-month-grd (e.g. 2014-12-grd)

2. Created a Microsoft Access Database (2014-12.accdb)

3. Imported the files from step 1 into the database
   a. External data
   b. Access
   c. Browse and select the file
   d. In the "Import items" Select All, OK Close

4. Created a union query for the files as follows.
   a. Create
   b. Query designers
   c. Select both tables
   d. Select Time stamp, Station Id from tblSCTurbine
   e. UNION
   f. Select Timestamp, StationIdFrom tblSCTurGrid;

5. Saved this relation as **TimeId** (or some other convenient name)
6. Created a new query.
7. Go to SQL viewing.
8. Paste in the text below. Modify the highlighted table name to the current year and month.
9. Save the query as, "qry2014x01"

   SELECT TimeId.Timestamp, TimeId.StationId, tblSCTurbine.wtc_PitchRef_BladeA_max, tblSCTurGrid.wtc_ActPower_mean, tblSCTurbine.wtc_PeWindSp_mean, tblSCTurbine.wtc_SeWindSp_mean, tblSCTurbine.wtc_AeWindSp_mean, tblSCTurbine.wtc_NacelPos_mean, tblSCTurbine.wtc_ScYawPos_mean, Day([TimeId]![Timestamp]) AS [Day], Month([TimeId]![Timestamp]) AS [Month], Year([TimeId]![Timestamp]) AS [Year], Hour([TimeId]![Timestamp]) AS [Hour], Minute([TimeId]![Timestamp]) AS [Minute] INTO tbl2014x01

   FROM (TimeId LEFT JOIN tblSCTurbine ON (TimeId.StationId = tblSCTurbine.StationId) AND (TimeId.Timestamp = tblSCTurbine.TimeStamp)) INNER JOIN tblSCTurGrid ON (TimeId.StationId = tblSCTurGrid.StationId) AND (TimeId.Timestamp = tblSCTurGrid.TimeStamp);

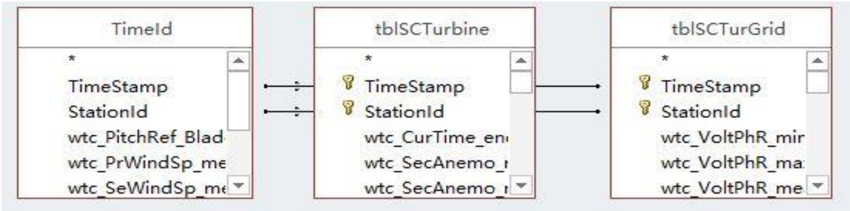


Figure 4-3 SQL Query structure

10. Create the table by double-clicking the query. The 13 columns should be in the same order or the program will not work or generate invalid results (*Unless you modify the program*).

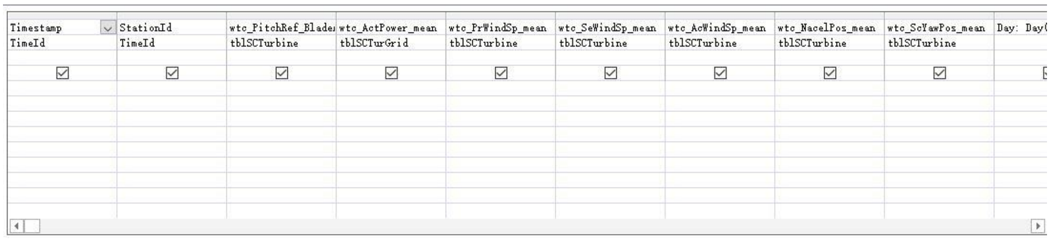


Figure 4-4 Data table sorting -1

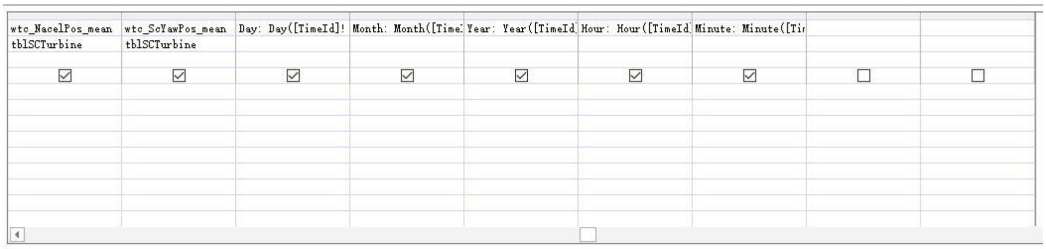


Figure 4-5 Data table sorting -2

Test of data columns from turbine T04 in 2013 to see which ones should be included.

- TimeStamp – **ok**
- StationId – **ok**
- PitchRef_BladeA_max – this show when the turbine is stopped. **Keep.**
- ActPower_mean – this shows the power production. **Keep**.
- wtc_PeWindSp_mean – this shows a separate speed. **Keep**.
- wtc_SeWindSp_mean – this shows a separate speed. **Keep**.
- wtc_AeWindSp_mean – this show either PrWindSp or SeWindSp. **Keep.**
- wtc_NacelPos_mean – this shows a separate direction. **Keep.**
- wtc_ScYawPos_mean – this shows a separate direction, and goes from -380 to + 480. Perhaps it is the absolute direction, to make sure it does not over twist. **Keep.**
- wtc_PriAnemo_mean – this always shows 1.2 . **Do not use**.
- wtc_SecAnemo_mean – this shows the same as SeWindSp_mean. **Do not use**
- wtc_YawPos_mean – this shows the same as NacelPos_mean. **Do not use**
- wtc_AmbieTmp_mean – **not included.**

11. Open the table produced from this relation.
12. Export this table into Excel
13. External data -> Export to Excel
14. Change filename to include the turbine, which is selected.
15. Choose option 1, (Exporter data with formatting and layout).
16. Finished export from Access to Excel (.csv).
    Do the same processing of wind temp. files, and added the two Excel files into one. Saved it.

4.1.2 Excel (.csv) to Excel (.xlsx)

A plugin has been used to split Excel '.csv' format to Excel '.xlsx' as shown in figure 4-6. Because databases' time arranges are different, e.g., January and February have different time lengths, and there may be some data missing, we need to do some data (filtering) fine-tuning before carrying them out of '.xlsx' files.

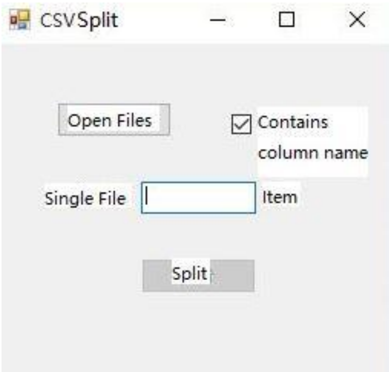


Figure 4-6 CSV split

4.1.3 Microsoft Excel to MATLAB

1. Repeat the above process for wind temp. files, and pool the two Excel files into one. Saved it. Prepare and named Excel(.xlsx) database.
2. Open MATLAB software, click 'Import data' button on the toolbar, as figure4-7 shows.

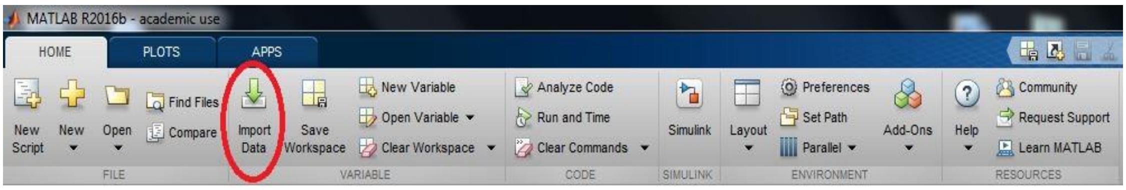


Figure 4-7 Import data to MATLAB

3. In the pop-up dialog box, open '.xlsx' files that saved before.
4. In the pop-up dialog box choose 'Numeric Matrix' in the top, and then 'Import Selection' to import the database in workspace, saved it. As figure 4-8 shows.

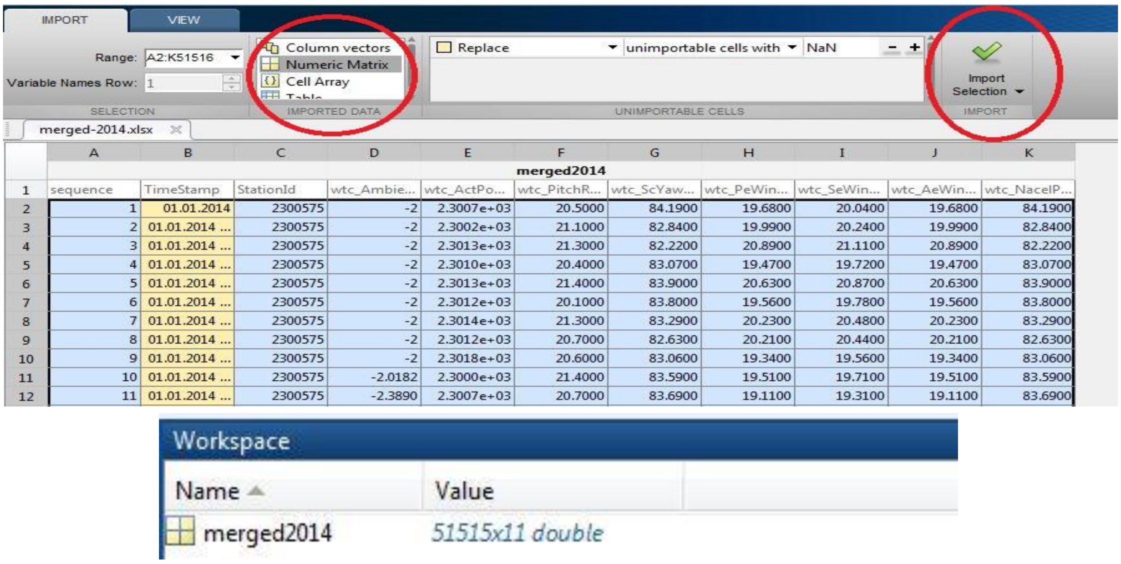


Figure 4-8 Import Selection & save workspace

5. Close 'Import' window, click the workspace that you choose, then you can analysis it as you want.

NOTE:

There are some issues that may result in data importing failure:

a) When you choose the data in 'Import data' window, there may be columns or rows missing because of data missing;
   Solution: single click the top cell, then press 'Ctrl +Shift+↓', then you can choose the whole datasheet.
b) Close MATLAB by mistake, and the workspace might be missing;
   Solution: save workspace before your analysis, then you can open workspace anytime.

4.1.4 Microsoft Excel to WindRose PRO3

1. Open WindRose PRO3 and choose 'File'—'load data' then renew it.

   a. Select the worksheet which you want;
   b. Choose 'Column with directions'—'wtc_ScYawPos_mean', which is the variable of wind direction.
   c. Choose 'Column with data'—'wtc_SeWinSp_mean', which is the variable of wind speed.
   d. Choose 'Data time'—'use data'
      --'Column with data and time'—'TimeStamp', which shows time series;
      --'Date/time format'—'mm/dd/yyyy hh:mm:ss', which shows the format of time series.
   e. Leave 'Third Variable'.
   f. Choose 'Action for non-numerical values'—'assign this value to non-numerical'—'0'.
      Run this as figure 4-9 shows.

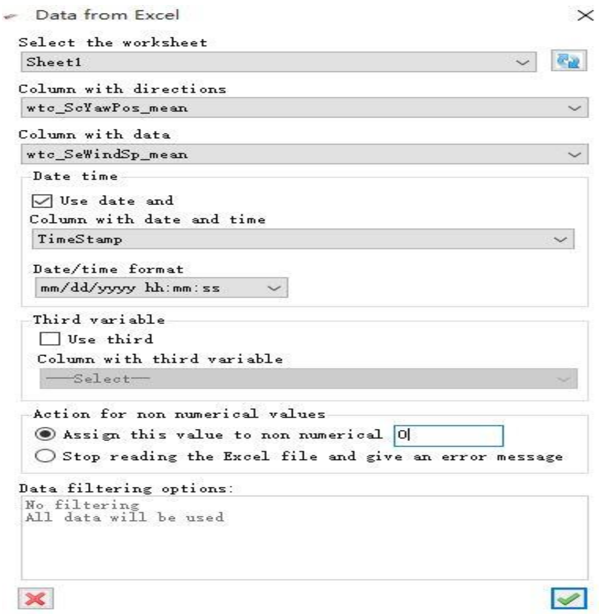


Figure 4-9 Wind Rose data load

2. Choose ‘Analysis and Draw’ to start WindRose PRO3 analysis.
3. Change some details by choosing ‘Options’.
   a. Intervals
      Chose different speed range and different colours, as figure 4-10 shows.

Figure 4-10 Intervals

   b. Add title and subtitle
      As figure 4-11 shows, change the size of letter and background colour.

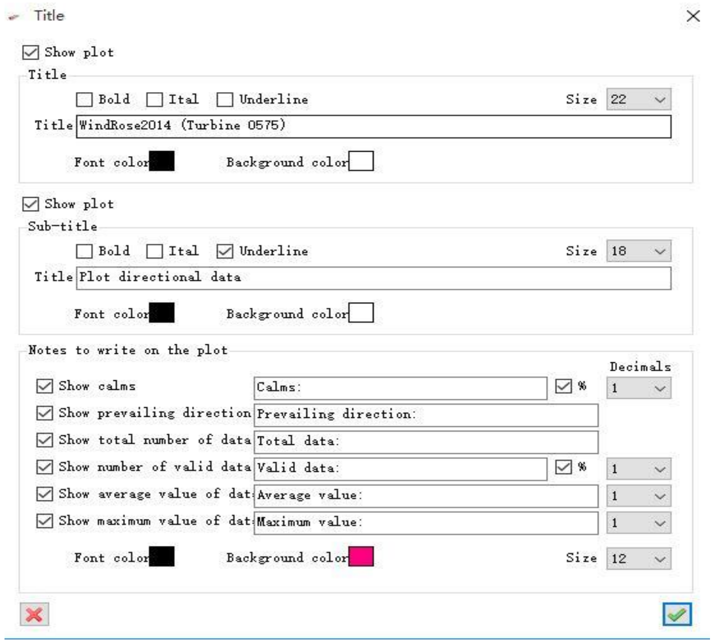


Figure 4-11 Title

c. Choose ‘Legend’ and draw the legend as figure 4-12 shows.

Figure 4-12 Legend

d. Change ‘Type’ as ‘wind rose’ and direction chosoe ‘16’. Shows as figure 4-13.

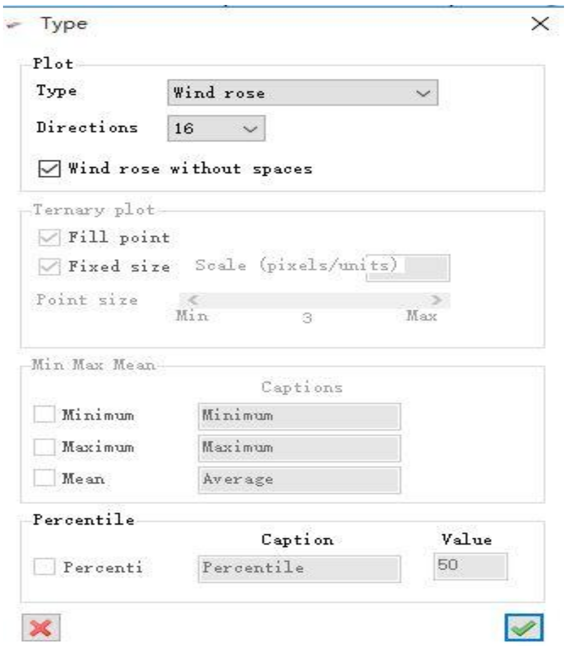


Figure 4-13 Type

e. Change details into 'Circles' as figure 4-14 shows.

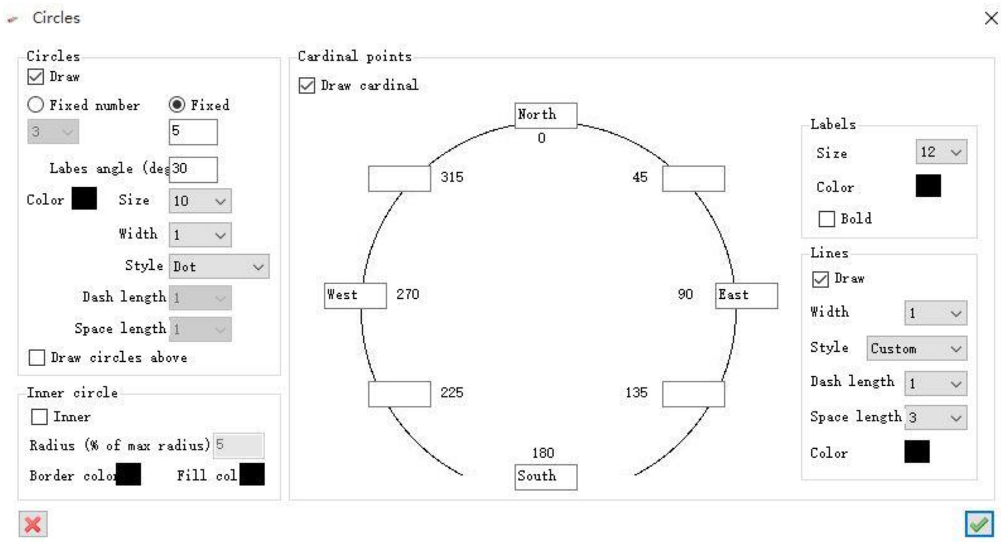


Figure 4-14 Circles

f. Leave 'Logo', 'Calms' and other options unless some analysis need it.

4. Output figure or database

   Choose 'Action' –'Batch processing'—'Monthly plot' to export wind rose monthly.
   Choose 'Output folder'—'Image height (pixels)', 'Image format' and so on to export.

4.2 SCADA data analysis

This section will present the results of SCADA data analysis, which has been done using the following methodology:

(1) Comprehensive analysis
   a. *Vertical interpolation*
   b. *Horizontal interpolation*
(2) Specific analysis
   a. *Vertical analysis*
   b. *Horizontal analysis*
(3) Wind rose analysis

- ***Comprehensive Vertical Interpolation analysis*** shows 3 years data (2013-15) for 14 turbines, with comparison between different polynomial curves (4^{th} to 9^{th} degree) including linear analysis as reference. We choose the best polynomial curve for further analysis.

- ***Comprehensive Horizontal Interpolation analysis*** shows 1 year data (2014) for 14 wind turbines. Six functions (*4 variables combination*) are used for comparison and we choose the best correlations for further analysis.

- ***Wind rose analysis*** shows graphical comparison of wind direction & wind speed between turbines for the year 2014.

Specific vertical and horizontal analyses show 3 years' data (2013-15) for each turbine. Best polynomial curve (with linear reference) fitting was carried out to make the detailed comparison between turbines.

4.2.1 Comprehensive analysis

4.2.1.1 Vertical interpolation

In this section, 3 years database has been used in different polynomial curves' fitting comparison. First, I use Microsoft Excel to make the R-Square table. After that I use 'Curve Fitting' APPS in MATLAB R2016b to select different variables in the curve fitting comparison, then copy the table into Excel 2016 and use 'transpose' and filter to complete database. It turns out that 7^{th} to 9^{th} polynomial curves fit better than 4^{th} to 6^{th} ones in general (*linear be as reference*), as shown in tables 4-2 & 4-3.

Table 4-2 Power production & wind speed (R-square) for 3 years' data and 14 turbines SCADA data

Turbine	4th-2013	4th-2014	4th-2015	5th-2013	5th-2014	5th-2015	6th-2013	6th-2014	6th-2015	7th-2013	7th-2014	7th-2015	8th-2013	8th-2014	8th-2015	9th-2013	9th-2014	9th-2015	Linear 2013	Linear 2014	Linear 2015
0575	82.42%	92.05%	38.29%	82.43%	92.05%	38.29%	82.81%	92.83%	38.36%	83.24%	93.24%	38.57%	83.25%	93.39%	38.58%	83.48%	93.66%	38.72%	70.81%	77.37%	33.43%
0574	59.16%	88.77%	45.08%	60.25%	88.77%	45.79%	60.25%	89.19%	45.80%	60.27%	89.71%	46.25%	60.57%	89.77%	46.32%	61.40%	90.06%	46.33%	37.61%	74.95%	33.42%
0573	62.94%	89.89%	71.61%	63.07%	89.89%	71.63%	63.45%	90.33%	71.86%	63.91%	90.91%	71.97%	63.91%	90.96%	72.06%	64.07%	91.32%	72.51%	51.90%	75.15%	54.96%
4531	91.00%	74.05%	50.38%	91.02%	75.67%	50.38%	91.56%	75.70%	50.39%	91.86%	75.70%	50.82%	91.94%	75.85%	51.24%	92.20%	76.05%	51.29%	80.23%	50.38%	32.91%
4532	93.71%	95.95%	79.23%	93.90%	96.51%	79.53%	94.52%	97.00%	79.80%	94.59%	97.03%	79.94%	94.76%	97.27%	80.13%	94.87%	97.27%	80.14%	83.64%	85.51%	70.51%
4533	93.76%	93.53%	82.18%	94.04%	94.23%	82.42%	94.72%	94.75%	82.42%	94.72%	94.76%	82.96%	94.92%	94.97%	83.43%	94.95%	94.97%	83.43%	84.42%	84.15%	71.63%
4534	92.43%	93.06%	85.09%	92.46%	93.51%	85.44%	92.95%	93.94%	85.61%	93.04%	93.94%	85.80%	93.26%	94.16%	85.93%	82.45%	94.16%	85.93%	82.45%	82.99%	77.01%
4535	91.70%	90.87%	80.46%	91.74%	90.89%	80.59%	92.06%	91.57%	80.75%	92.52%	91.78%	80.75%	92.53%	91.91%	80.83%	92.71%	92.09%	80.91%	78.53%	75.83%	69.01%
4536	90.08%	92.04%	78.24%	90.15%	92.06%	78.32%	90.47%	93.03%	78.59%	91.00%	93.23%	78.59%	91.02%	93.60%	78.80%	91.21%	93.70%	78.97%	75.85%	75.37%	66.79%
4537	100.0%	94.91%	80.05%	91.29%	95.23%	80.46%	91.62%	95.77%	80.80%	92.10%	95.78%	80.94%	92.10%	95.95%	81.08%	92.45%	96.02%	81.08%	79.60%	82.12%	70.69%
4538	89.54%	95.61%	80.85%	89.55%	95.80%	80.94%	90.14%	96.37%	81.28%	90.48%	96.38%	81.39%	90.54%	96.63%	81.52%	90.85%	96.64%	81.88%	77.86%	81.75%	69.87%
4539	88.90%	94.90%	74.65%	88.90%	95.27%	75.13%	89.35%	95.74%	76.00%	89.73%	95.76%	76.03%	89.76%	96.12%	76.20%	90.14%	96.12%	76.20%	78.47%	82.79%	65.84%
4549	85.19%	60.53%	74.05%	85.23%	60.56%	74.11%	85.58%	61.08%	74.59%	85.91%	61.21%	74.67%	85.94%	61.35%	75.25%	86.21%	61.49%	75.26%	74.26%	51.62%	64.23%
4541	93.28%	94.20%	45.78%	93.41%	94.54%	45.82%	93.65%	95.24%	46.05%	94.42%	95.24%	46.05%	94.42%	95.65%	46.09%	94.77%	95.65%	46.09%	82.18%	82.22%	42.58%

Table 4-3 Average temperature and time series (R-square) for 3 years' data and 14 turbines SCADA data

Turbine	4th-2013	4th-2014	4th-2015	5th-2013	5th-2014	5th-2015	6th-2013	6th-2014	6th-2015	7th-2013	7th-2014	7th-2015	8th-2013	8th-2014	8th-2015	9th-2013	9th-2014	9th-2015	Linear 2013	Linear 2014	Linear 2015
0575	78.64%	69.20%	70.86%	78.71%	70.26%	73.61%	78.72%	71.09%	74.24%	78.90%	75.37%	77.93%	79.18%	77.77%	78.41%	79.22%	77.85%	78.94%	3.41%	5.76%	12.73%
0574	74.96%	69.14%	70.77%	75.14%	70.23%	73.37%	75.14%	71.09%	73.89%	75.18%	75.20%	77.09%	75.61%	77.63%	77.59%	75.87%	77.69%	78.30%	0.53%	5.61%	11.93%
0573	78.42%	69.07%	70.89%	78.43%	70.15%	73.50%	78.43%	71.11%	73.86%	78.62%	75.29%	77.04%	78.96%	77.66%	77.73%	78.96%	77.72%	78.47%	2.58%	5.69%	12.03%
4531	78.79%	68.91%	71.72%	78.86%	69.15%	74.41%	78.86%	73.38%	74.93%	79.08%	73.63%	78.31%	79.38%	74.17%	78.81%	79.44%	74.24%	79.40%	3.56%	0.34%	12.52%
4532	79.17%	69.54%	72.28%	79.22%	70.54%	74.82%	79.23%	71.27%	75.37%	79.46%	75.66%	78.70%	79.75%	78.15%	79.17%	79.78%	78.27%	79.79%	3.63%	5.73%	13.04%
4533	78.99%	69.51%	71.32%	79.09%	70.52%	74.01%	79.09%	71.29%	74.62%	79.31%	75.54%	78.20%	79.52%	78.07%	78.65%	79.60%	78.16%	79.21%	3.90%	5.53%	12.55%
4534	78.65%	69.28%	70.86%	78.83%	70.33%	73.64%	78.84%	71.23%	74.26%	79.13%	75.40%	77.76%	79.41%	77.80%	78.24%	3.98%	77.89%	78.82%	3.98%	5.57%	12.71%
4535	78.21%	68.82%	70.08%	78.41%	69.96%	73.04%	78.41%	70.92%	73.69%	78.70%	74.88%	77.19%	78.97%	77.38%	77.66%	79.06%	77.46%	78.20%	3.87%	5.47%	12.30%
4536	78.36%	68.92%	70.53%	78.56%	69.99%	73.49%	78.56%	70.95%	74.13%	78.86%	75.06%	77.68%	79.15%	77.50%	78.14%	79.24%	77.59%	78.66%	3.84%	5.70%	12.34%
4537	78.05%	69.29%	70.32%	78.57%	70.32%	73.55%	78.75%	71.18%	75.37%	79.96%	75.41%	78.34%	79.96%	77.87%	78.54%	80.44%	77.98%	79.60%	9.14%	5.64%	14.59%
4538	78.70%	69.12%	70.71%	78.87%	70.17%	73.49%	78.88%	71.06%	74.10%	79.18%	75.28%	77.59%	79.43%	77.73%	78.12%	79.49%	77.82%	78.71%	3.91%	5.65%	12.33%
4539	78.79%	69.39%	72.46%	79.08%	70.45%	74.33%	79.08%	71.27%	74.50%	79.31%	75.51%	77.98%	79.61%	77.95%	79.00%	79.70%	78.05%	79.49%	4.24%	5.55%	10.73%
4549	78.17%	70.09%	71.32%	78.48%	70.96%	73.82%	78.53%	71.59%	74.46%	78.65%	75.95%	77.85%	78.88%	78.39%	78.34%	78.88%	78.50%	79.00%	3.89%	6.11%	12.54%
4541	79.09%	69.18%	71.80%	79.18%	70.15%	74.47%	79.18%	70.91%	75.07%	79.41%	75.33%	78.56%	79.66%	77.93%	79.00%	79.73%	78.07%	79.56%	3.90%	6.48%	12.64%

4.2.1.2 Horizontal interpolation

In this section, I used one year SCADA data (2014) for each turbine, and compare 6 functional forms (4 variables combination) to choose the best correlations for further analytical analysis. Based on the curve fitting in MATLAB, '*average wind speed & wind power production* and *time & average temperature* fit the data better than other alternatives by more than 50% in terms of R-square. The results are shown in Table 4-4.

2014	7^{th} - time&power	7^{th} - time&speed	7^{th} - time&temp	7^{th} - temp&speed	7^{th} - power&temp	7^{th}- speed&power
Turbine 01	22.51%	20.31%	75.37%	20.30%	24.39%	93.24%
Turbine 02	23.50%	19.98%	75.20%	19.44%	22.01%	89.71%
Turbine 03	20.20%	17.84%	75.29%	18.88%	22.49%	90.91%
Turbine 04	17.57%	43.23%	73.63%	29.87%	16.65%	75.70%
Turbine 05	23.49%	21.83%	75.66%	19.94%	23.11%	97.03%
Turbine 06	21.01%	18.35%	75.54%	16.95%	18.57%	94.76%
Turbine 07	18.11%	16.59%	75.40%	15.10%	19.48%	93.94%
Turbine 08	17.07%	13.24%	74.88%	13.28%	17.20%	91.78%
Turbine 09	17.27%	15.63%	75.06%	15.73%	19.06%	93.23%
Turbine 10	17.00%	14.13%	75.41%	12.50%	16.76%	95.78%
Turbine 11	17.28%	16.13%	75.28%	15.12%	17.54%	96.38%
Turbine 12	19.47%	15.69%	75.51%	14.93%	19.62%	95.76%
Turbine 13	14.26%	16.32%	75.95%	16.31%	6.22%	61.21%
Turbine 14	22.33%	21.39%	75.33%	19.11%	21.39%	95.24%

Table 4-4 Six relationship comparison for year 2014 (R-square)

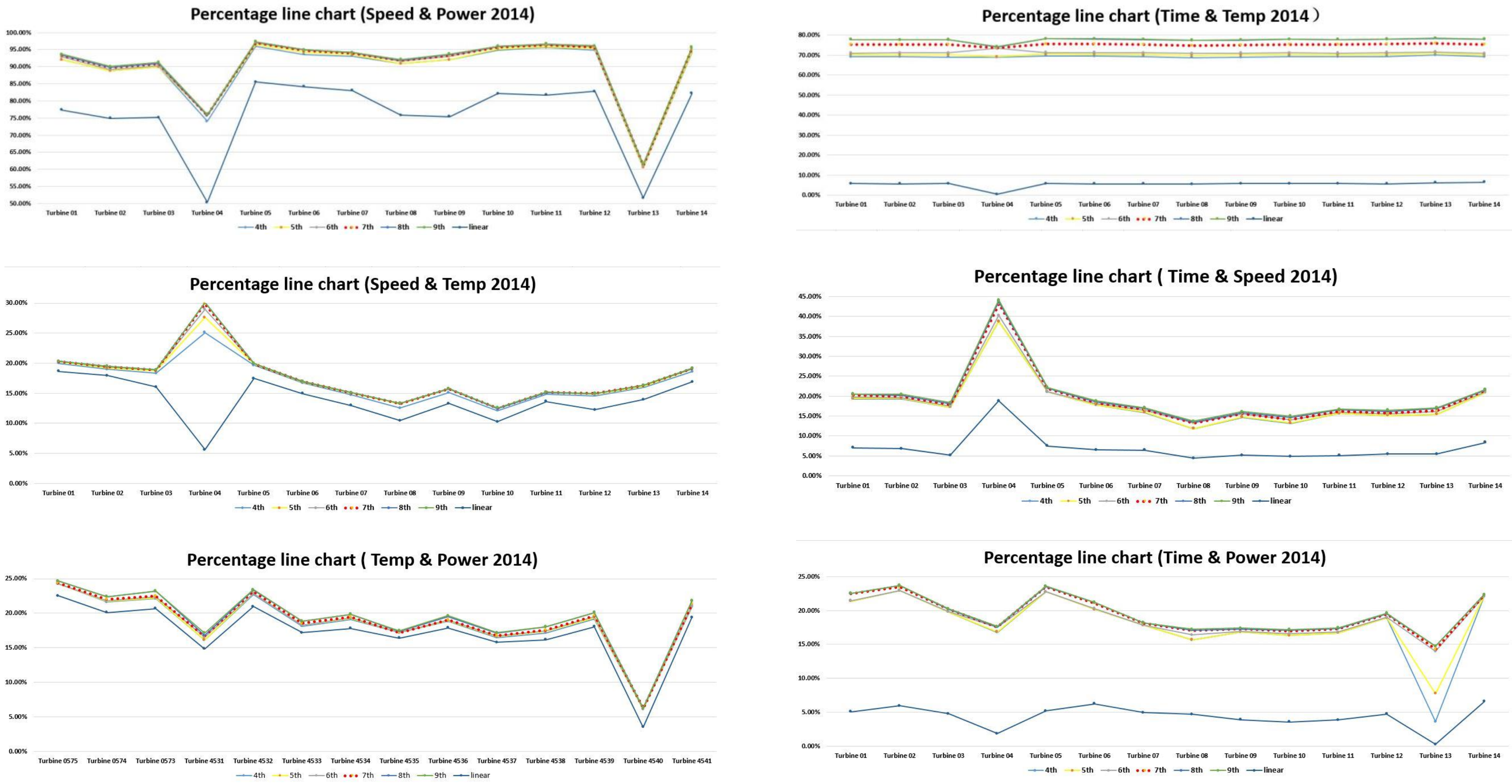
The most suitable correlations found from above mentioned analysis are:

a. Average wind speed & wind power production
b. Time & average temperature

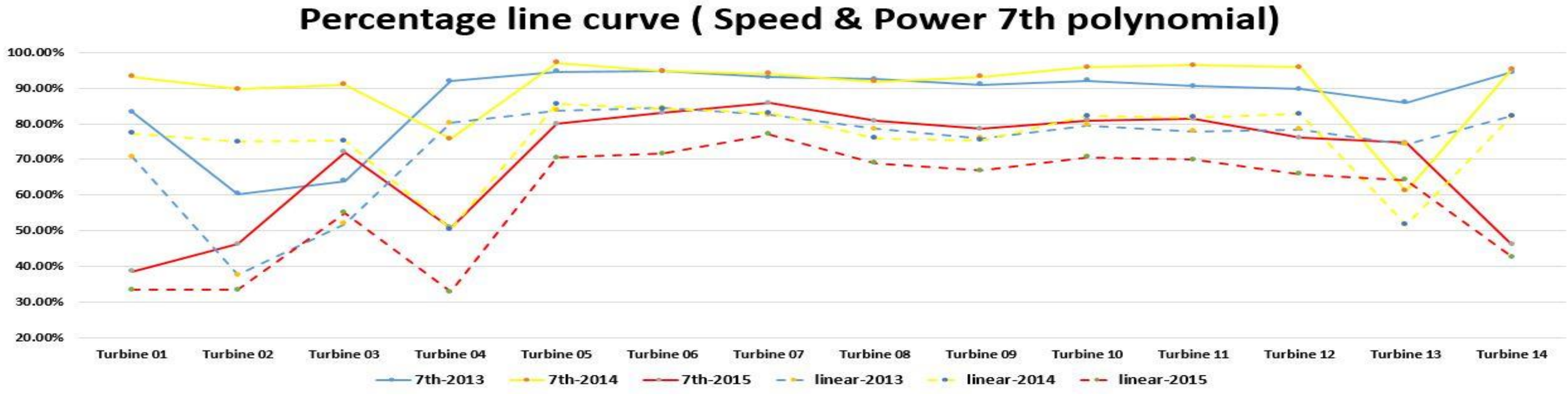
4.2.1.3 Analysis

One year SCADA data (2014) is used to do comprehensive verification analysis. Figure 4-15 shows 6 different functions with 4th to 9th polynomial curve fitting (linear as reference) for 14 turbines. Ignoring errors within 1%, 4th and 5th are similar, and 6th to 9th are similar. Considering actual wind production and application, I choose the simplest equation—7th polynomial curve for further work. Analysis of Average Wind Speed & Wind Power Production and Time & Average Temperature from 2013 to 2015 are shown in Figure 4-16 for 14 turbines, with a comparison between 2 different functions, 7th polynomial and linear. From Figure 4-16, we can see that for most of the time 7th polynomial curves fit the relationship between Average Wind Speed & Wind Power Production and that between Time & Average Temperature very well.

Figure 4-15 Different polynomial and linear curve fitting yearly comparison (2014)



1. Wind Power Production and Wind Average Velocity fitting for different wind turbines



2. Wind Average Temperature and Time fitting into different wind turbines

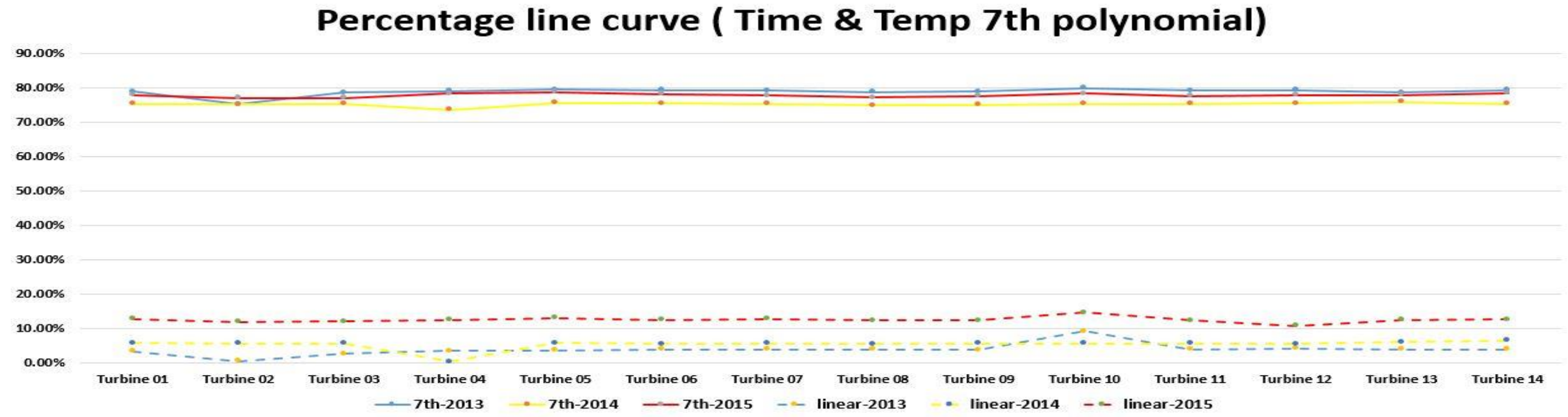


Figure 4-16 Three years, 7^{th} polynomial and linear curve fitting comparison (2013—2015)

4.2.2 Specific analysis

In this section, I use 7th degree polynomial (linear as reference) to fit the relationship between Average Wind Speed & Wind Power Production and that between Time & Average Temperature in specific vertical and horizontal comparison.

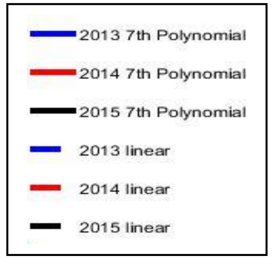
4.2.2.1 Vertical analysis

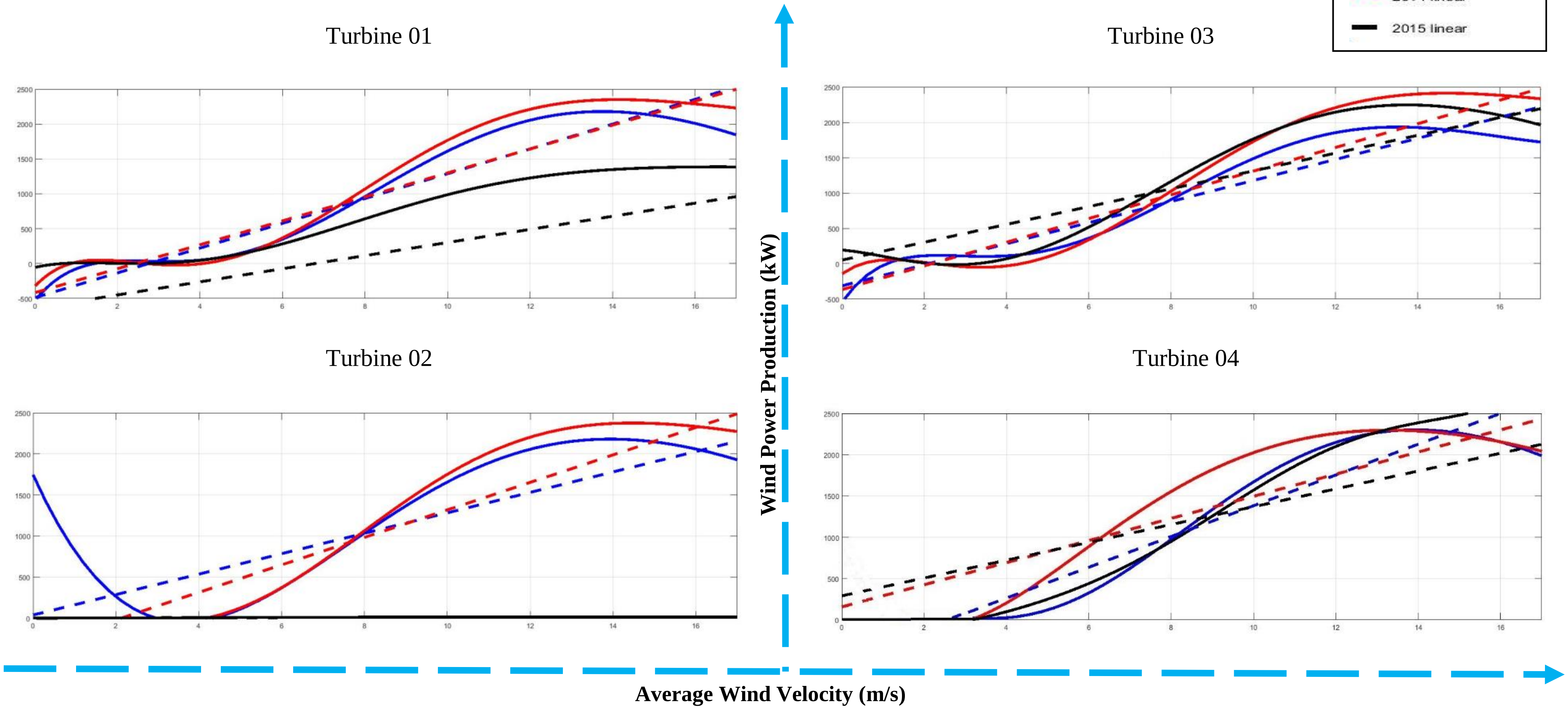
This section presents two-part analysis for 14 turbines of 3 years data with 7th degree polynomial curve fitting (linear as reference), as shown in Figures 4-17 & 4-18.

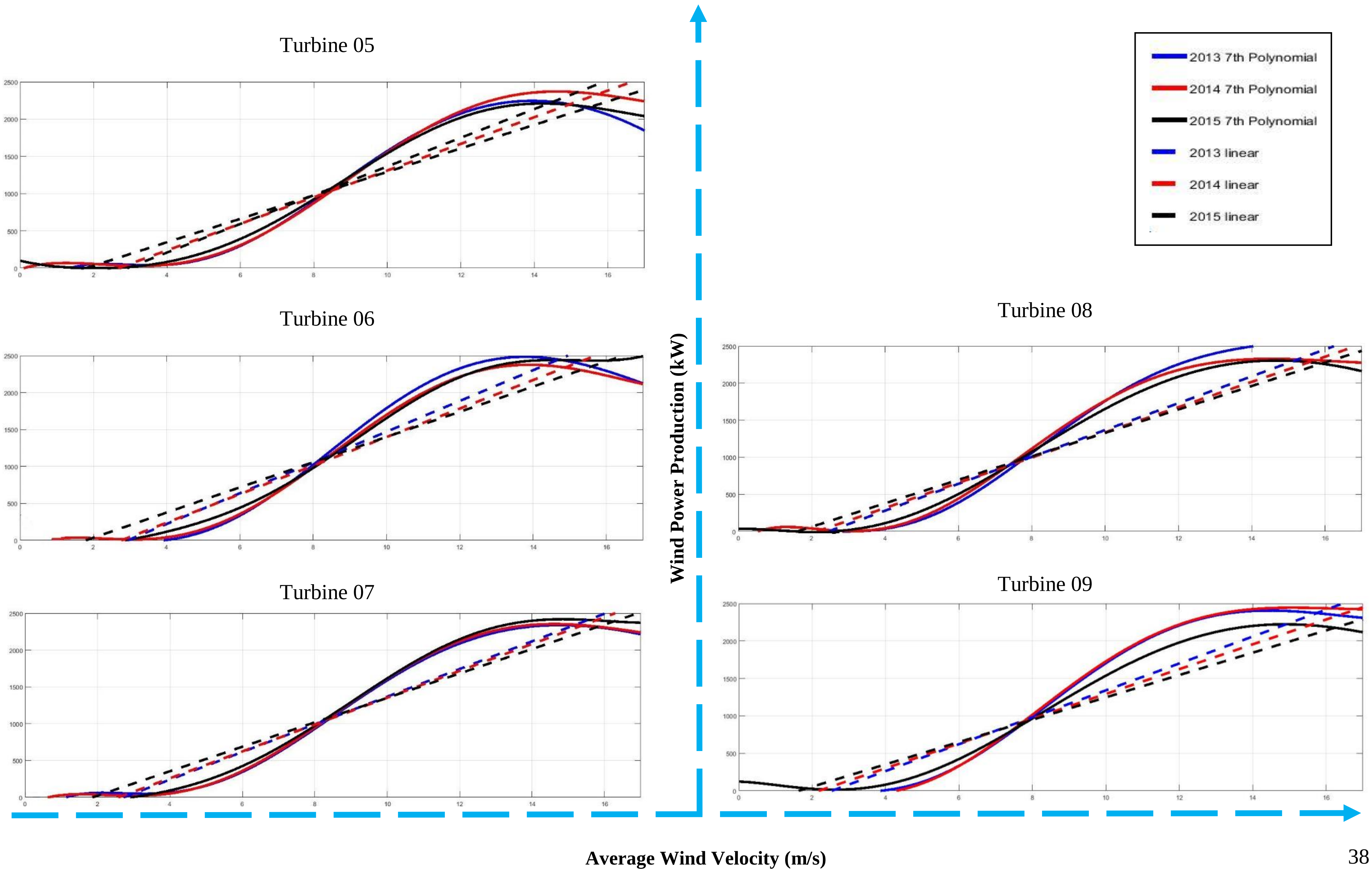
a. In Average Wind Speed & Wind Power Production figures, it is observed that 3 years' curves have the same trend (positive correlation), except turbine 02 (0574) in 2015.

b. In Time & Wind Average Temperature figures, the 3 years' curves in different turbines show roughly Normal Distribution. In addition, they all have the same trend (positive correlation).

Figure 4-17 Wind Power Production & Wind Average Velocity






Turbine 05
Turbine 06
Turbine 07
Turbine 08
Turbine 09
2013 7th Polynomial
2014 7th Polynomial
2015 7th Polynomial
2013 linear
2014 linear
2015 linear
Wind Power Production (kW)
Average Wind Velocity (m/s)

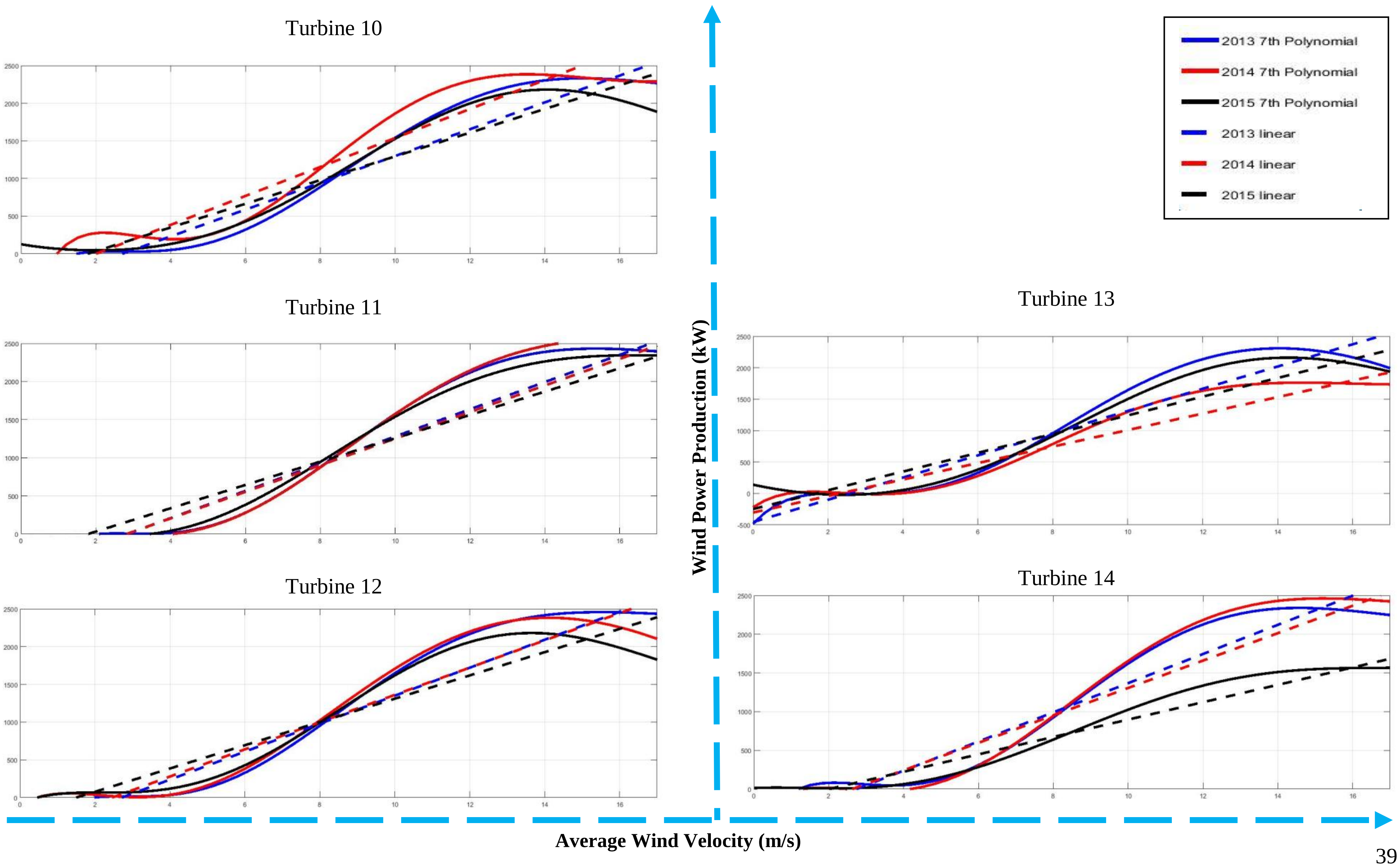
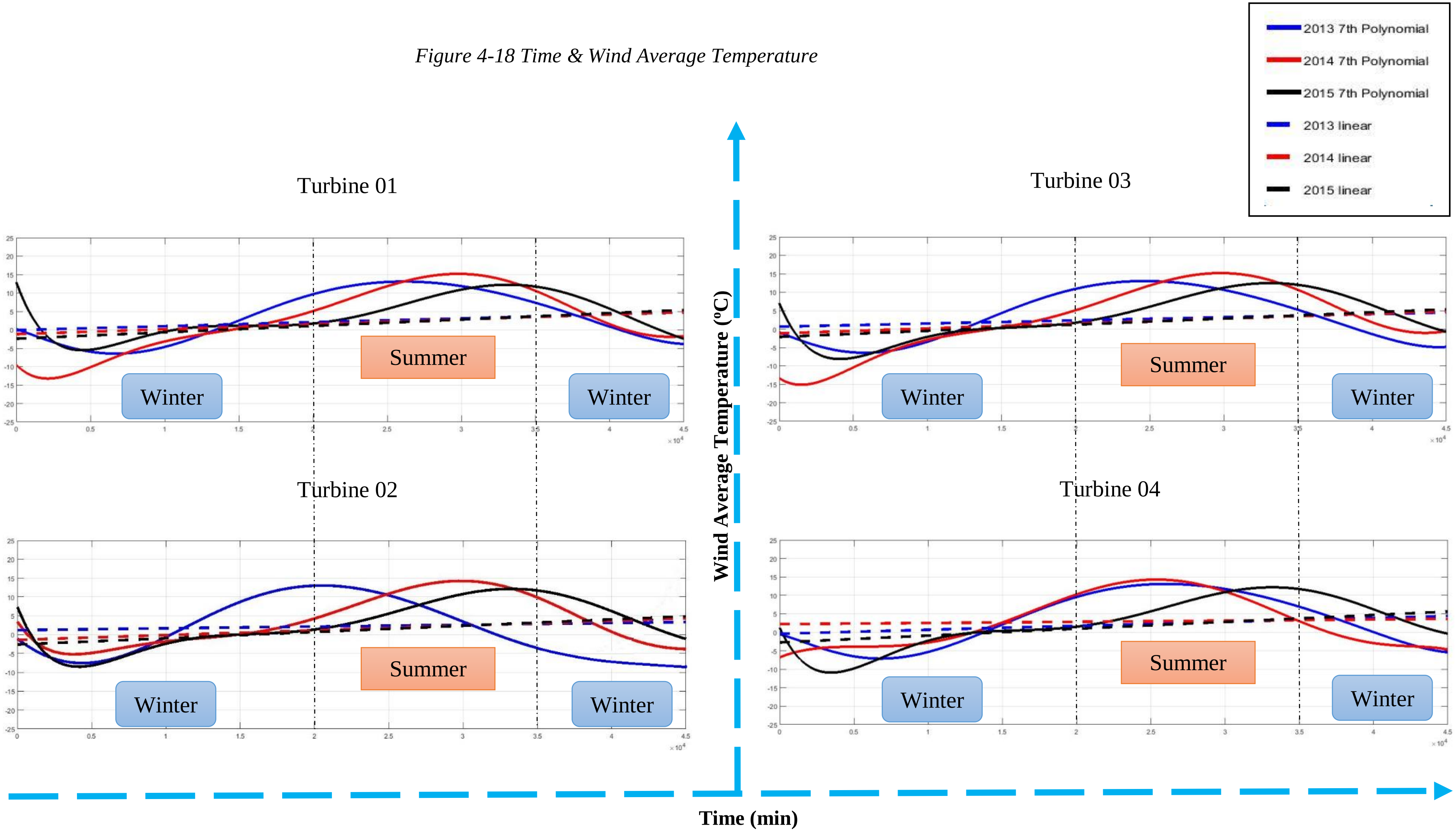
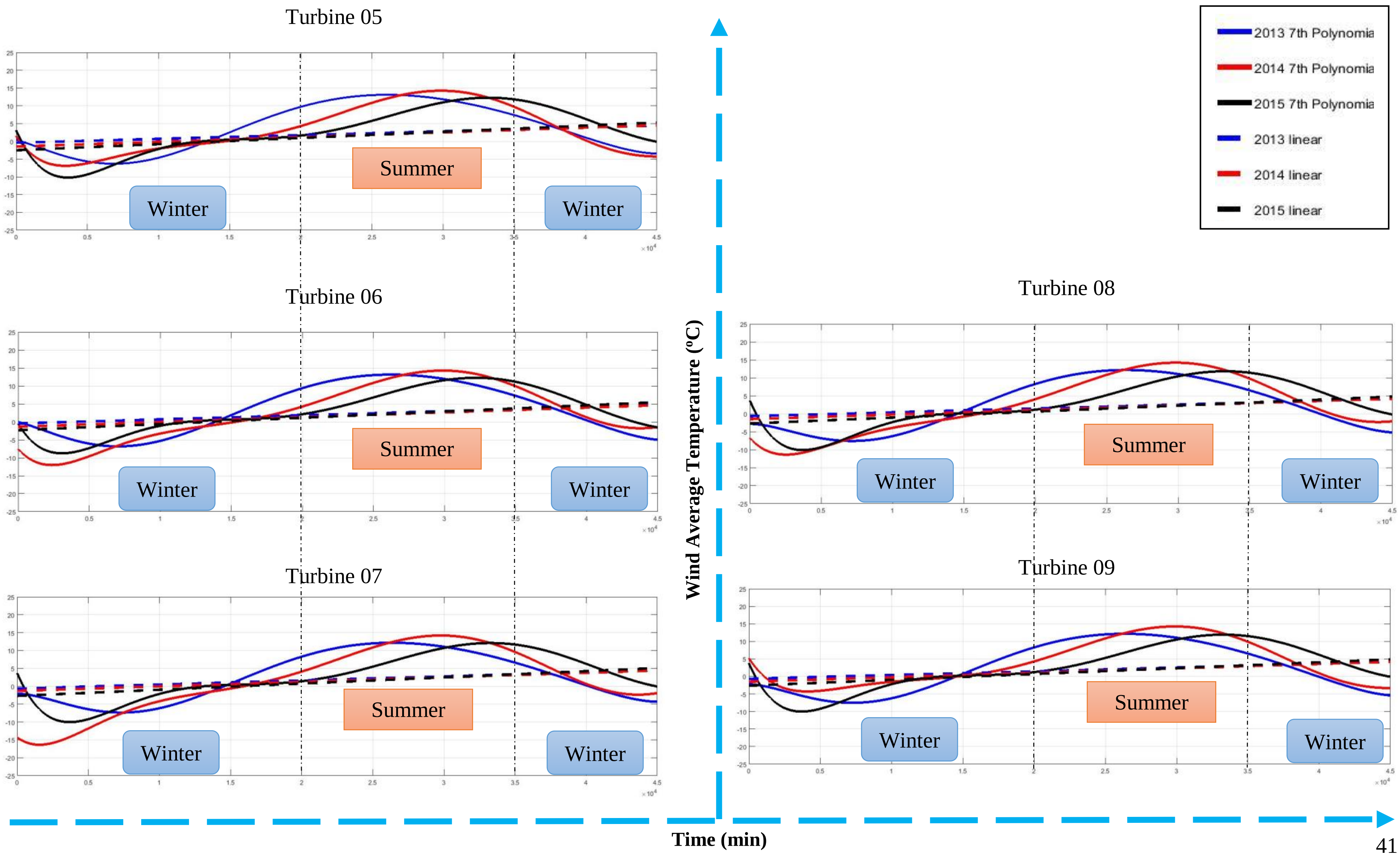
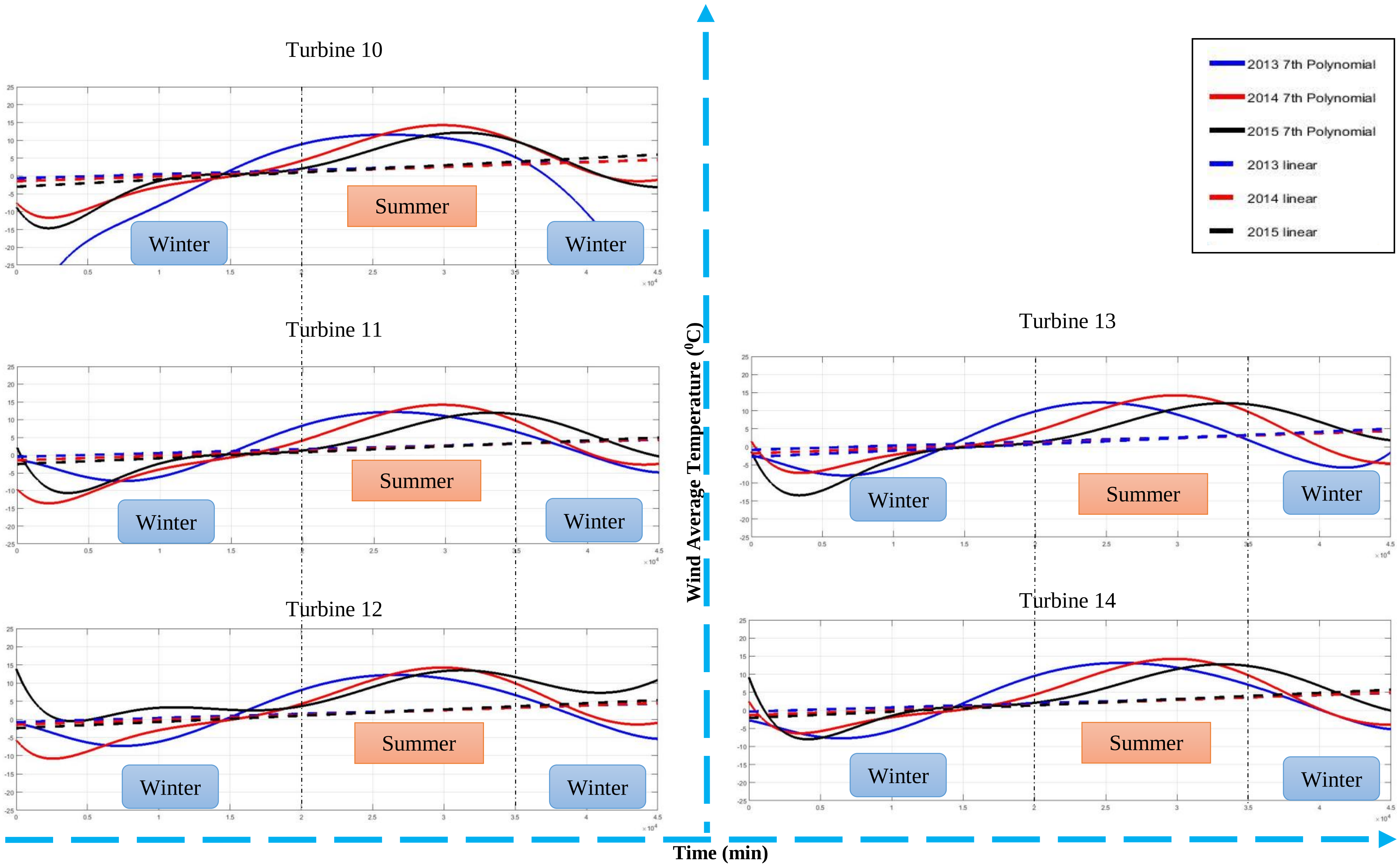

Turbine 10
Turbine 11
Turbine 12
Turbine 13
Turbine 14
2013 7th Polynomial
2014 7th Polynomial
2015 7th Polynomial
2013 linear
2014 linear
2015 linear
Wind Power Production (kW)
Average Wind Velocity (m/s)

Figure 4-18 Time & Wind Average Temperature




Turbine 05
Summer
Winter
Winter
Turbine 06
Summer
Winter
Winter
Turbine 07
Summer
Winter
Winter
Turbine 08
Summer
Winter
Winter
Turbine 09
Summer
Winter
Winter
2013 7th Polynomia
2014 7th Polynomia
2015 7th Polynomia
2013 linear
2014 linear
2015 linear
Wind Average Temperature (ºC)
Time (min)


Turbine 10
Turbine 11
Turbine 12
Turbine 13
Turbine 14
Winter
Summer
Winter
2013 7th Polynomial
2014 7th Polynomial
2015 7th Polynomial
2013 linear
2014 linear
2015 linear
Wind Average Temperature (⁰C)
Time (min)

4.2.2.2 Horizontal analysis

We conduct horizontal analysis for each wind turbine for the year 2014. 7th degree polynomial curve (with linear reference) fitting is used for comparison as shown in Figures 4-19 & 20. In addition, 6 different functions are plotted together for 14 wind turbines for a detailed comparison as shown in Figure 4-21. Below are the main observations:

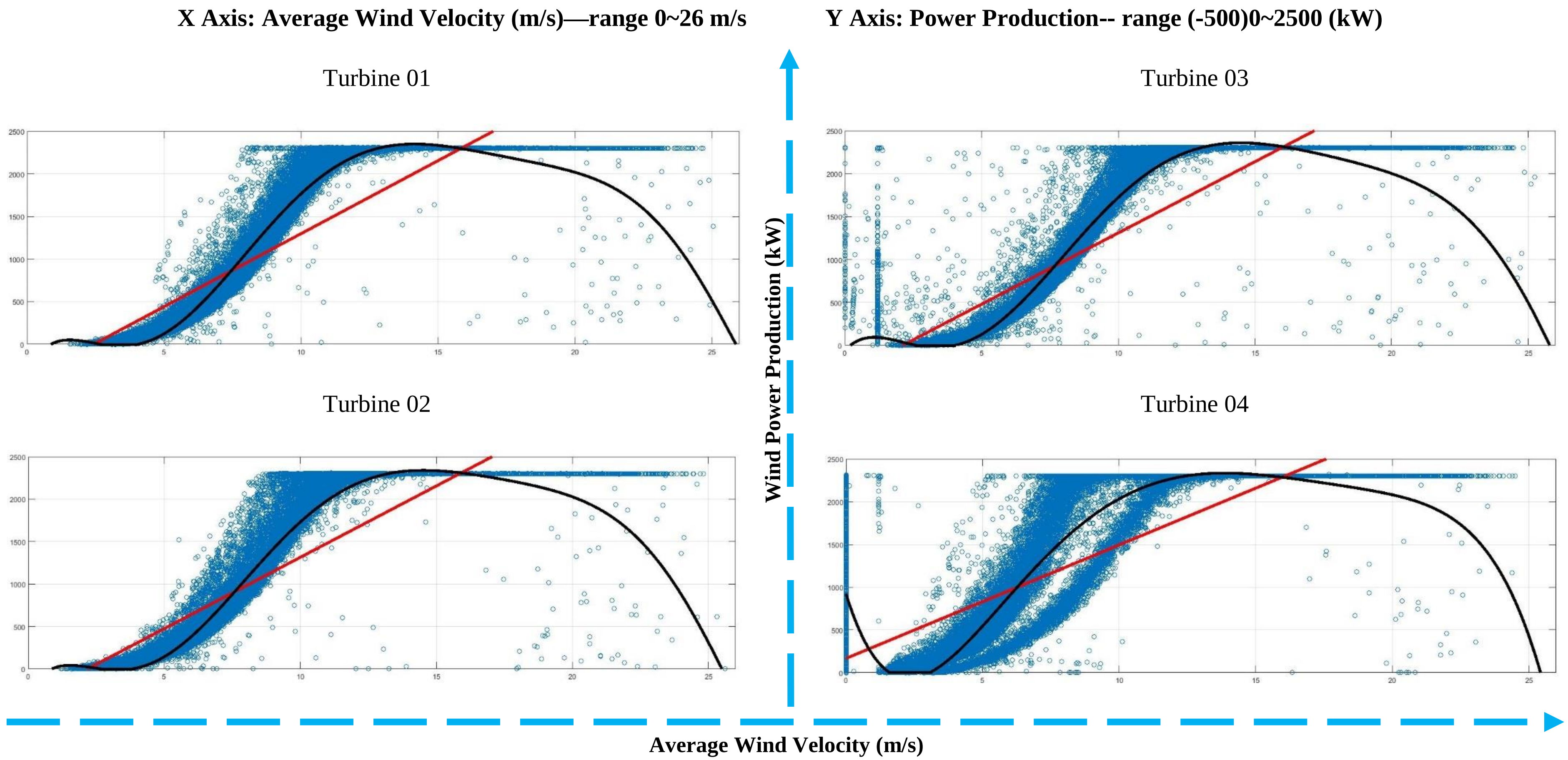
a. From Figure 4-19:

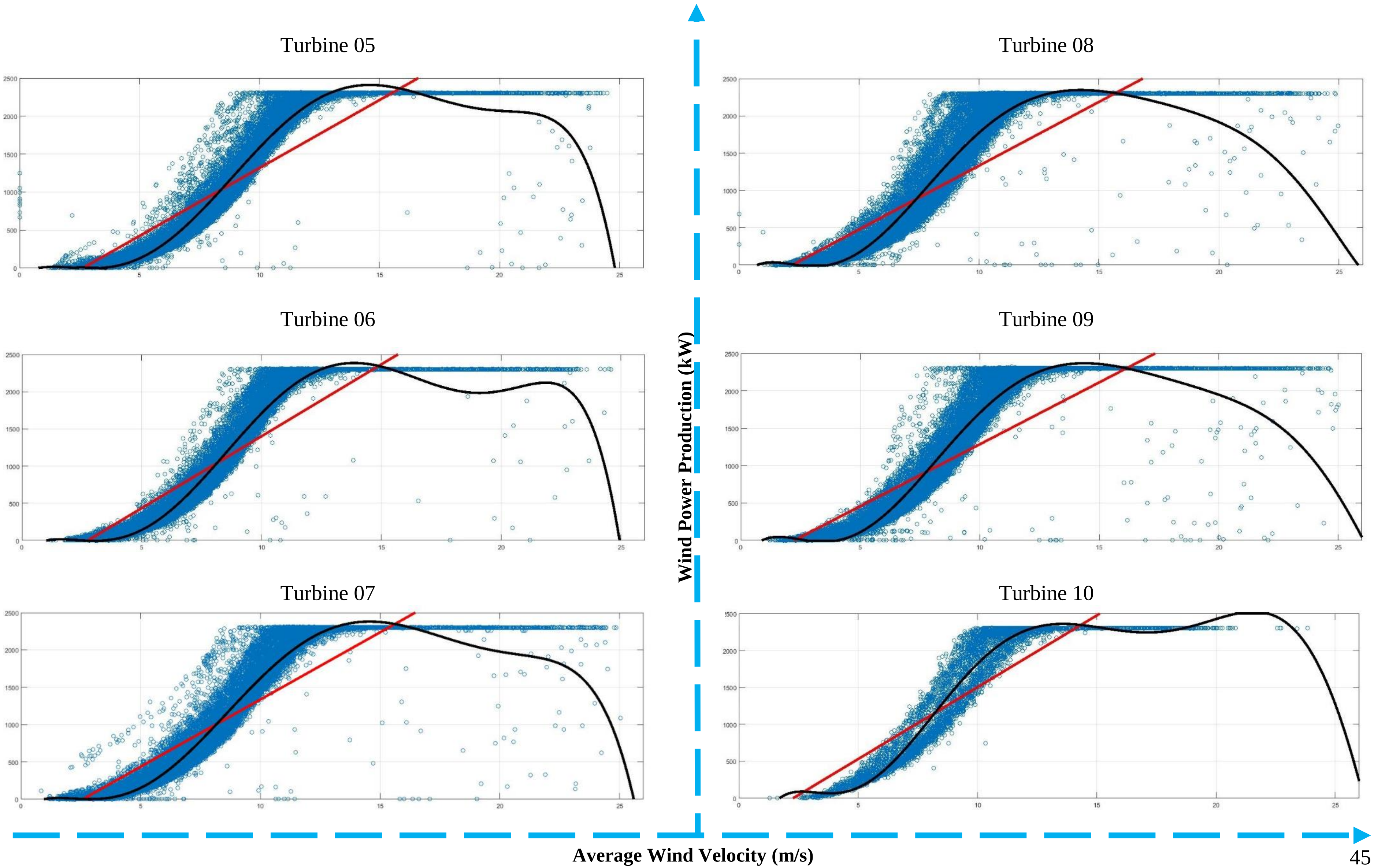
i. As wind velocity increases, wind power production also increases (positive correlation);
ii. Maximal power production is 2290 kW. In general, wind power production stays the same after reaching its peak, even when wind velocity increases further;
iii. Some points show a different trend after reaching maximal power production --the power production decreases as average wind velocity increases. This feature needs further consideration in the future work;
iv. As the time series expand, temperature has the trends: increasing –decreasing-increasing a little bit;
v. Turbine 04 (4531) has some special features in speed &power plot: The data points can be divided into two groups, one of which go to the maximal power production faster than the other.

b. From Figure 4-20:

i. Average Wind Velocity and Wind Power Production have similar trends over time (positive correlation), but the Average Temperature has the opposite trend (negative correlation).We need to note this in wind power production problems;
ii. Average Wind Velocity and Wind Power Production do not correlate with average temperature.

Figure 4-19 Average Wind Velocity & Power Production (2014 whole year—14 turbines)





Turbine 05
Turbine 06
Turbine 07
Turbine 08
Turbine 09
Turbine 10
Wind Power Production (kW)
Average Wind Velocity (m/s)

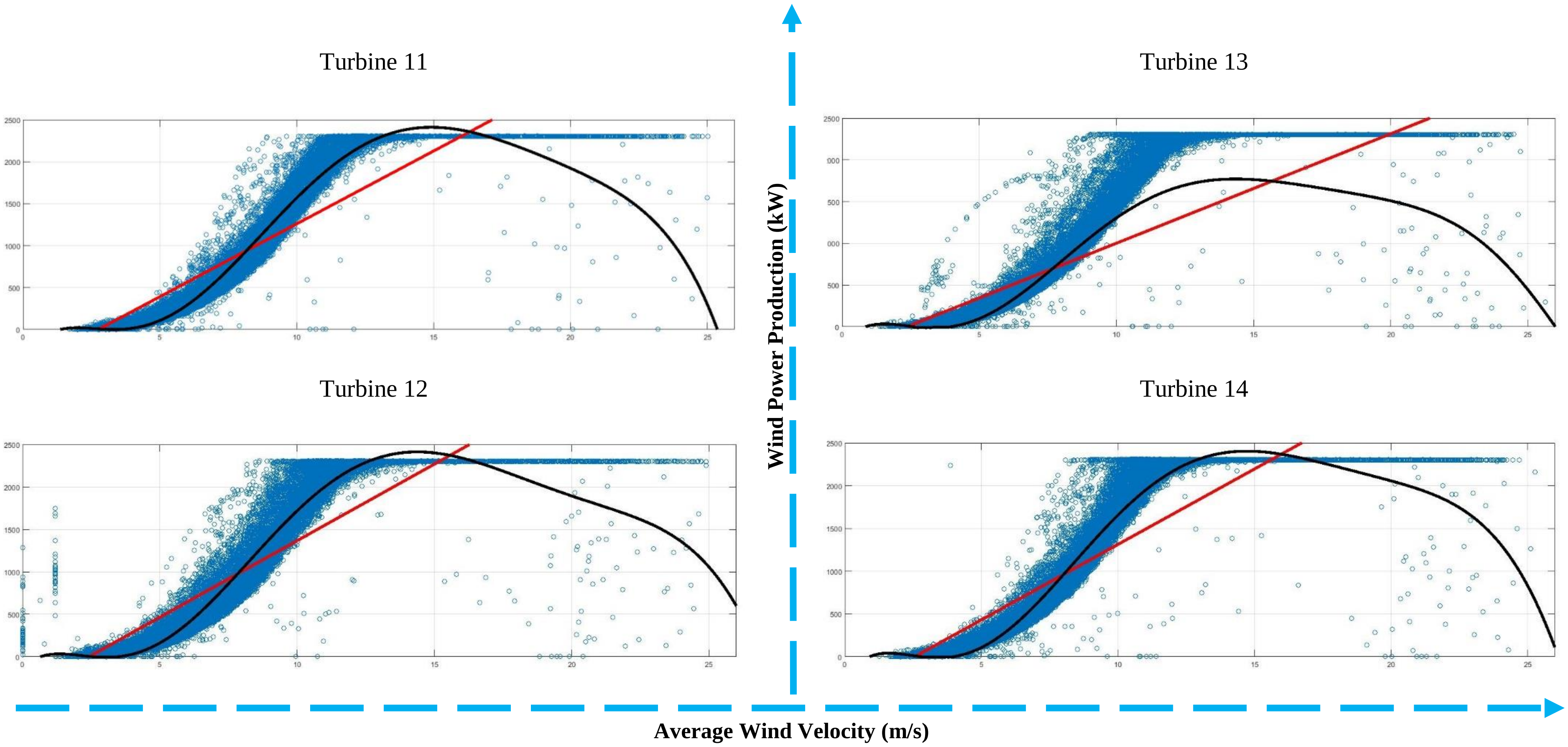
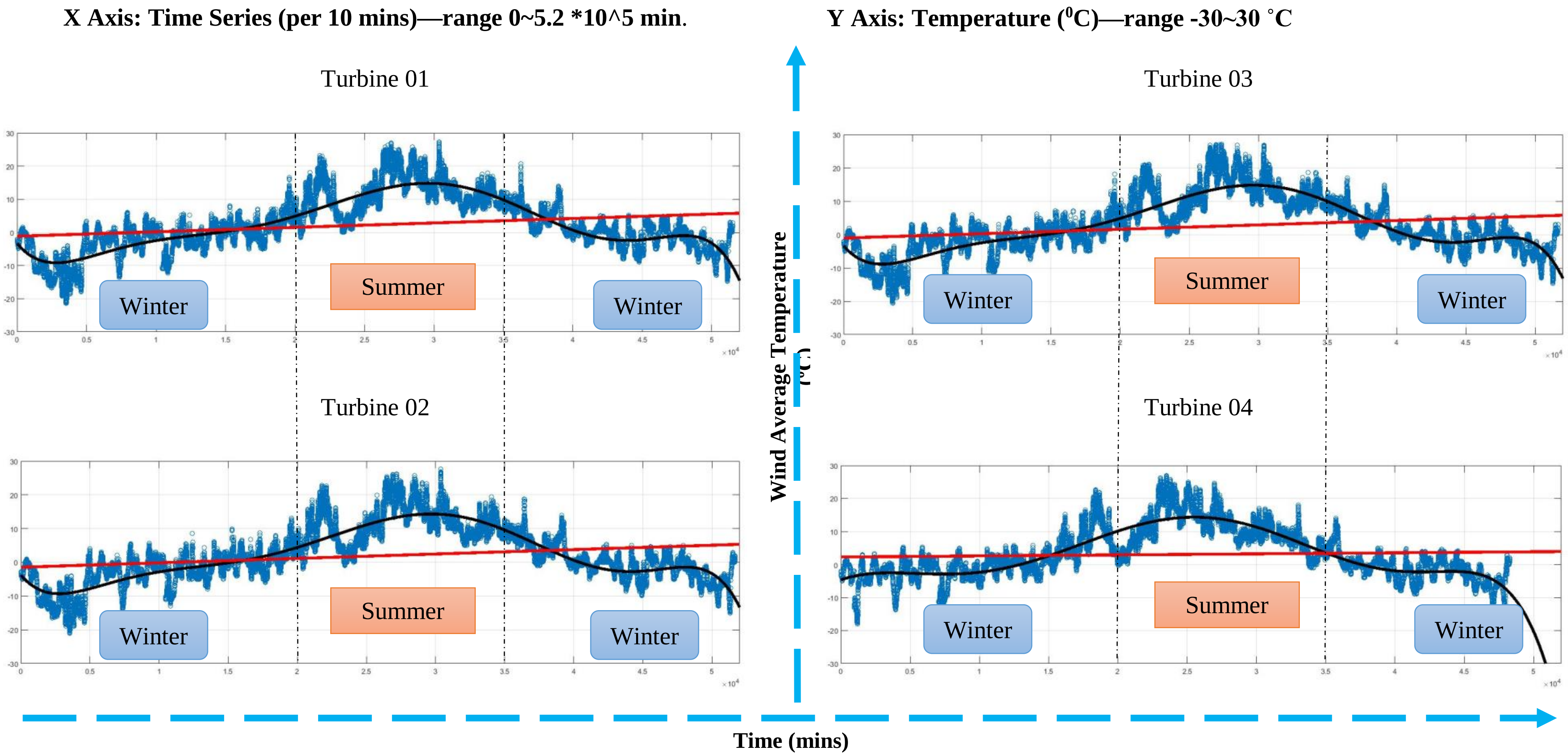
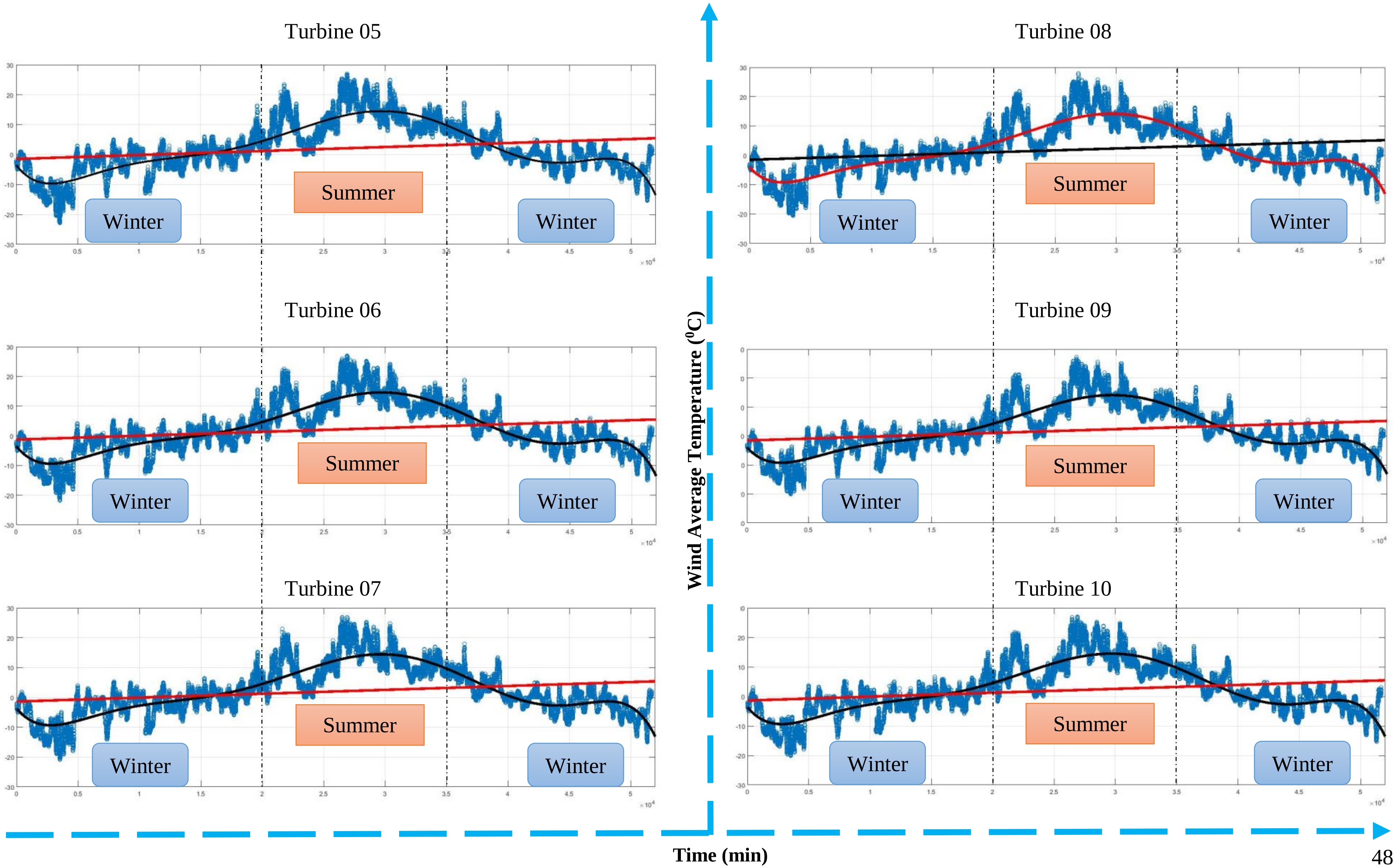

Turbine 11
Turbine 13
Turbine 12
Turbine 14
Wind Power Production (kW)
Average Wind Velocity (m/s)

Figure 4-20 Wind Temperature & Time (2014 whole year—14 turbines)




Turbine 05
Summer
Winter
Winter
Turbine 06
Summer
Winter
Winter
Turbine 07
Summer
Winter
Winter
Turbine 08
Summer
Winter
Winter
Turbine 09
Summer
Winter
Winter
Turbine 10
Summer
Winter
Winter
Wind Average Temperature (^{0}C)
Time (min)

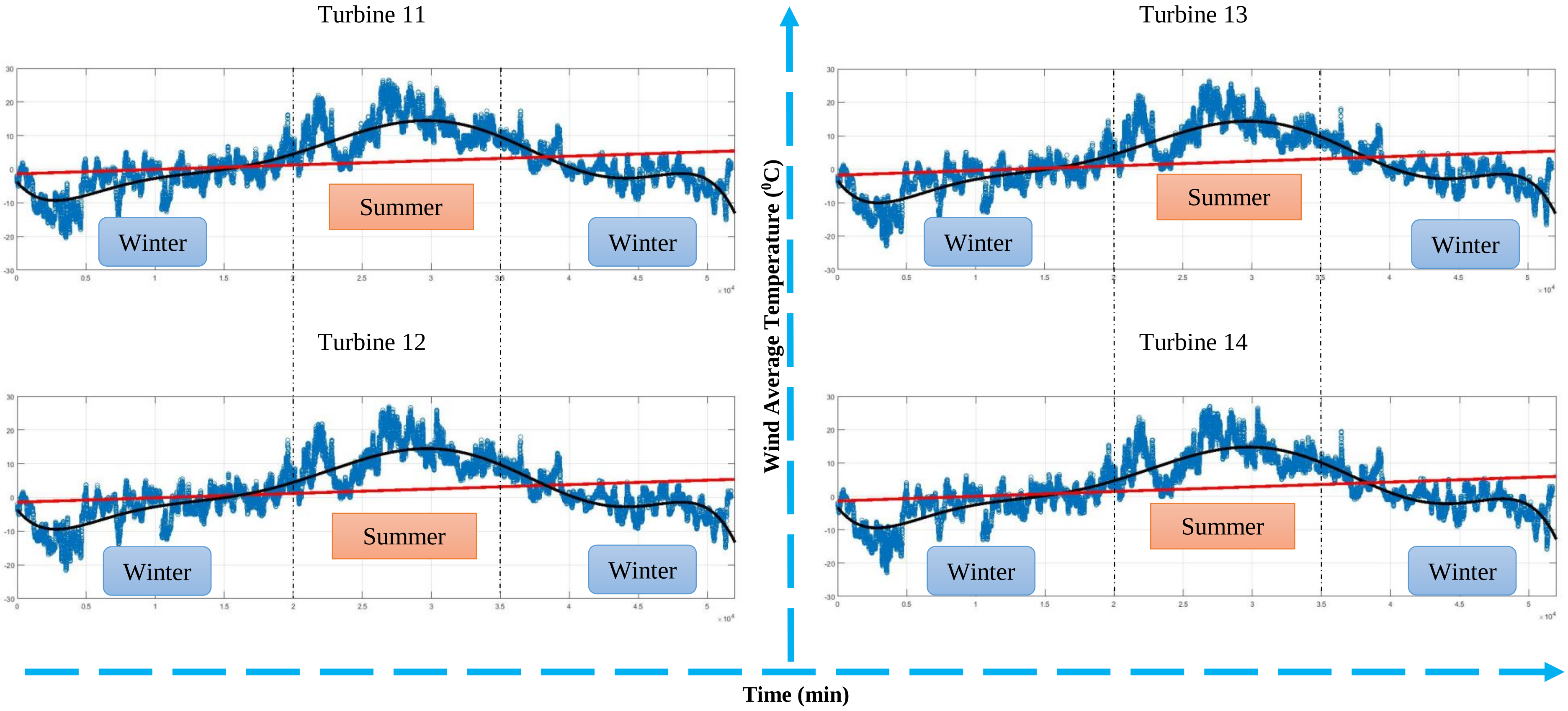
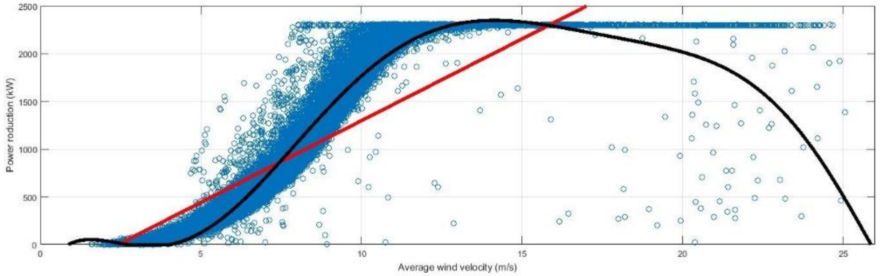


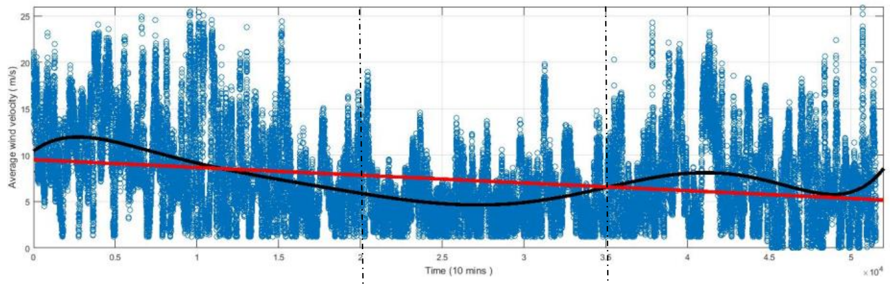
Figure 4-21 Power Production & wind velocity

Turbine - 1

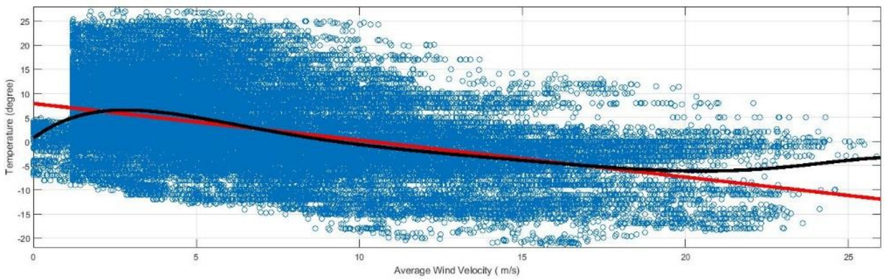
Average Wind Velocity & Power Production



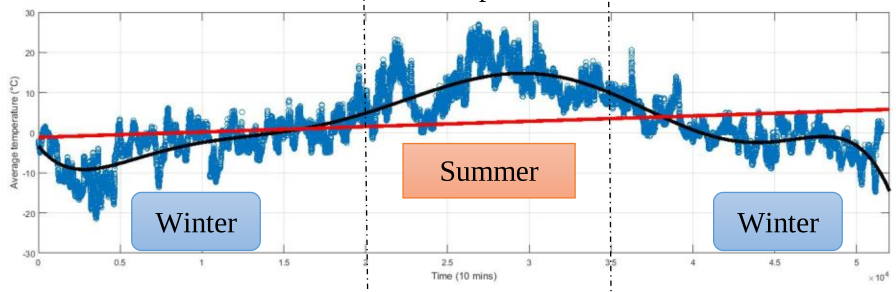
Time & Average Wind Velocity



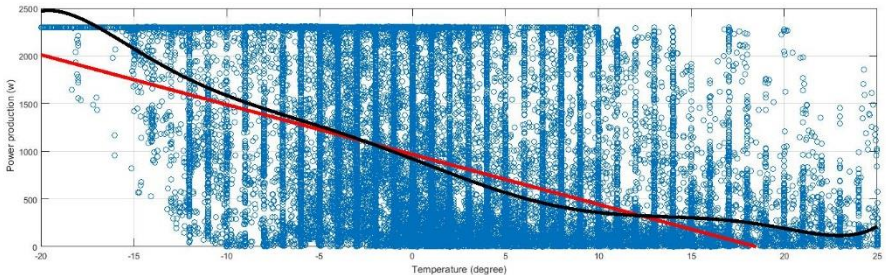
Average Wind Velocity & Temperature



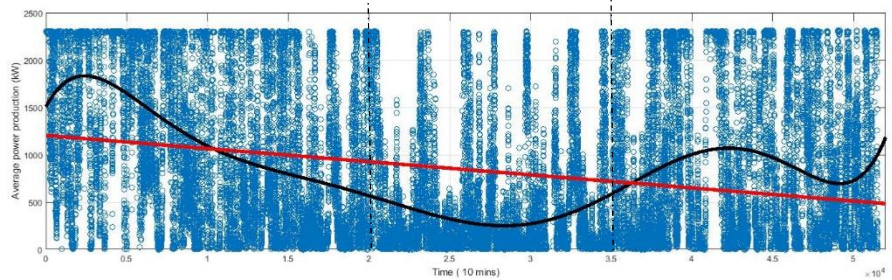
Time & Temperature



Temperature & Power Production

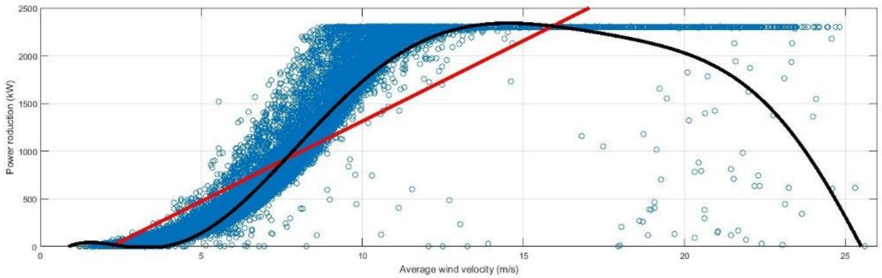


Time & Power Production

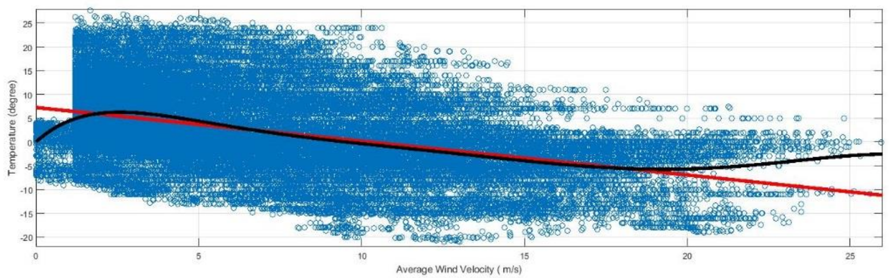


Turbine - 2

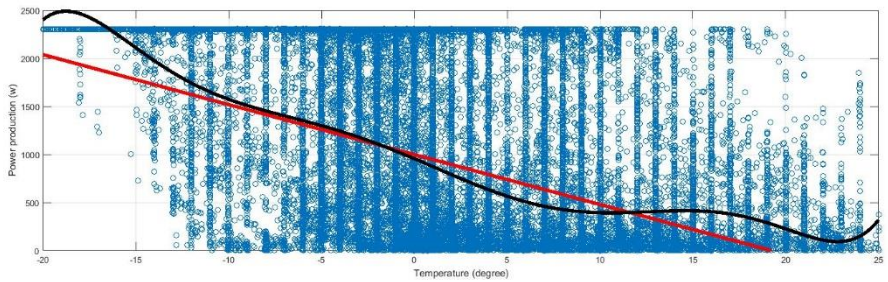
Average Wind Velocity & Power Production



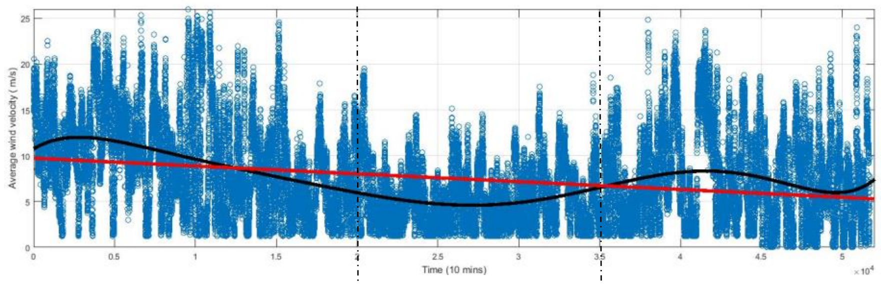
Average Wind Velocity & Temperature



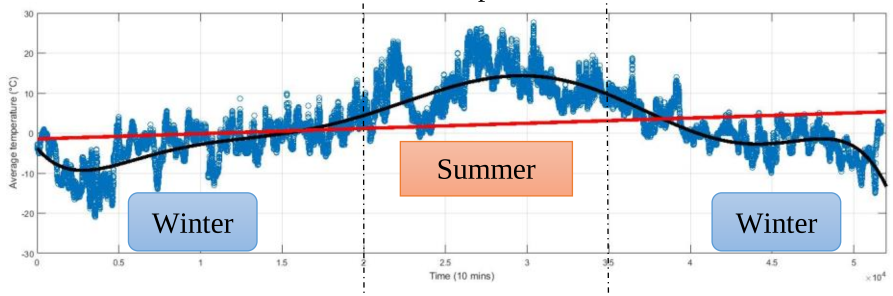
Temperature & Power Production



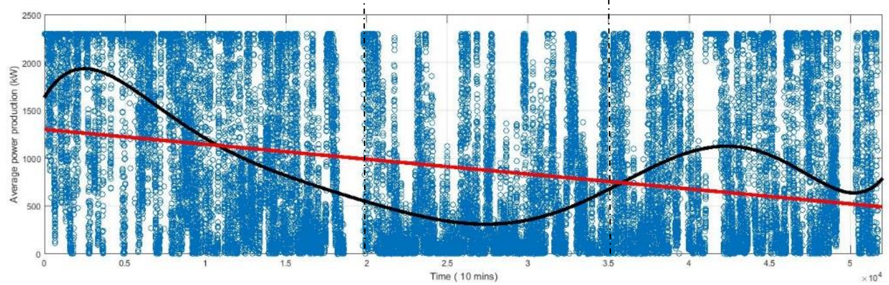
Time & Average Wind Velocity



Time & Temperature

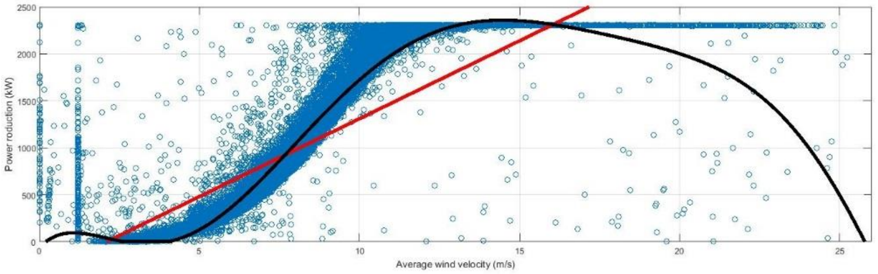


Time & Power Production

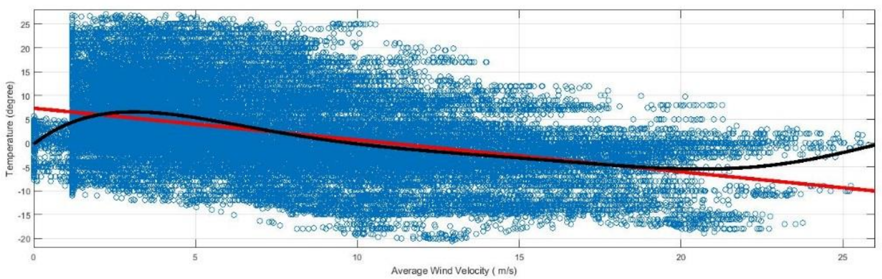


Turbine - 3

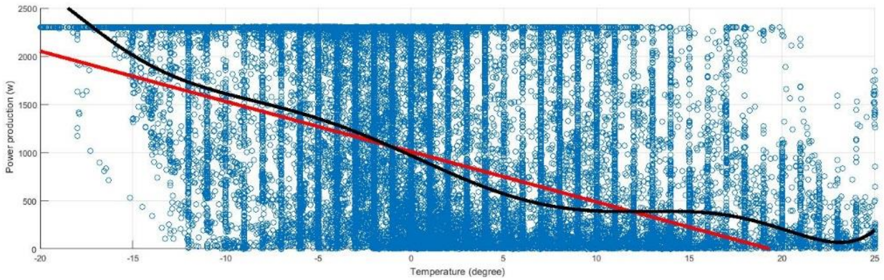
Average Wind Velocity & Power Production



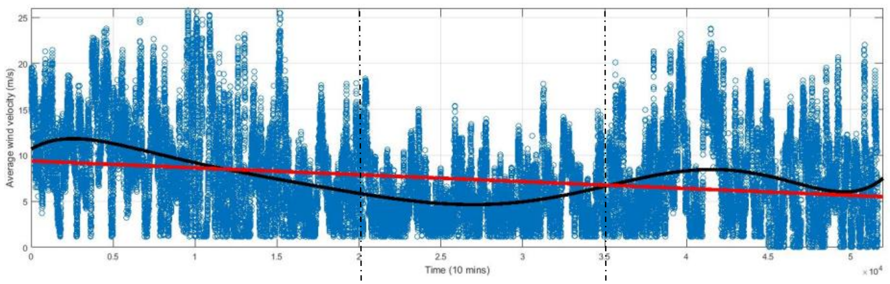
Average Wind Velocity & Temperature



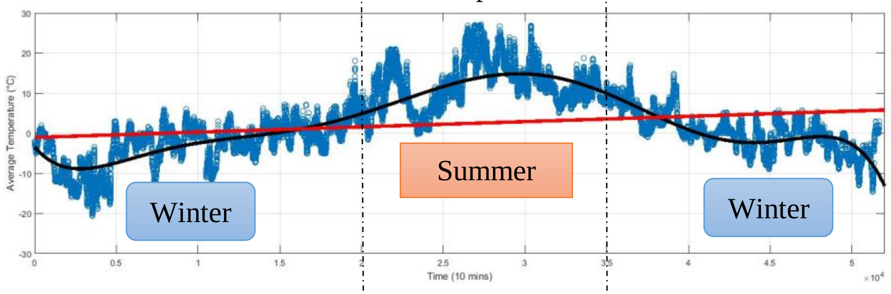
Temperature & Power Production



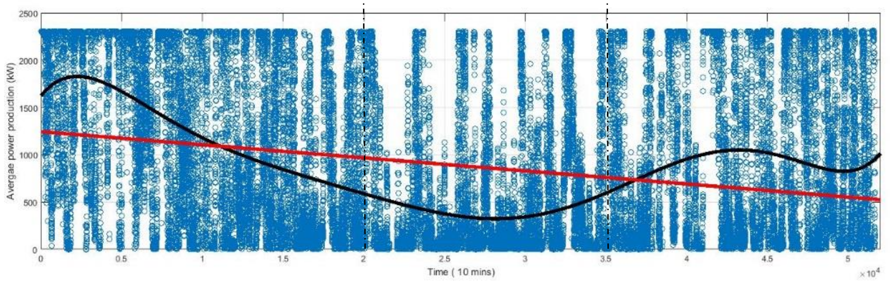
Time & Average Wind Velocity



Time & Temperature

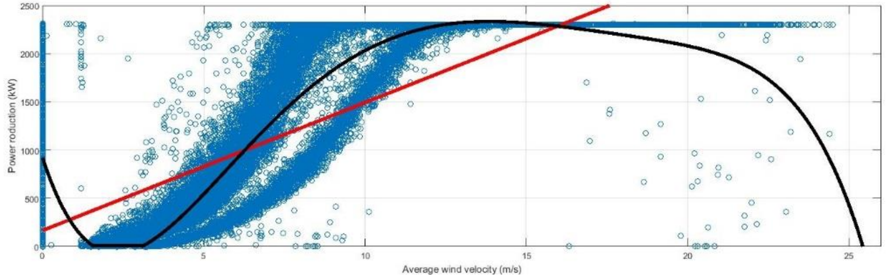


Time & Power Production

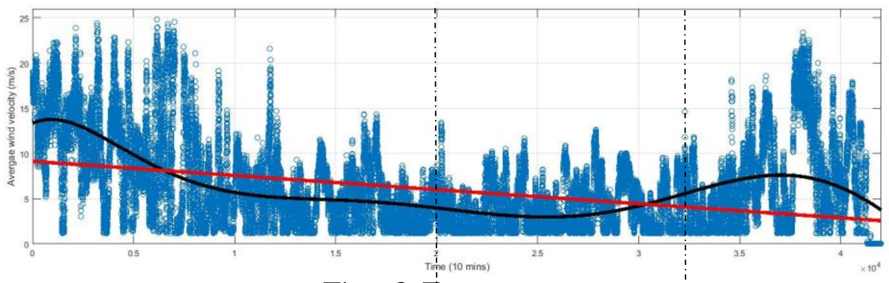


Turbine - 4

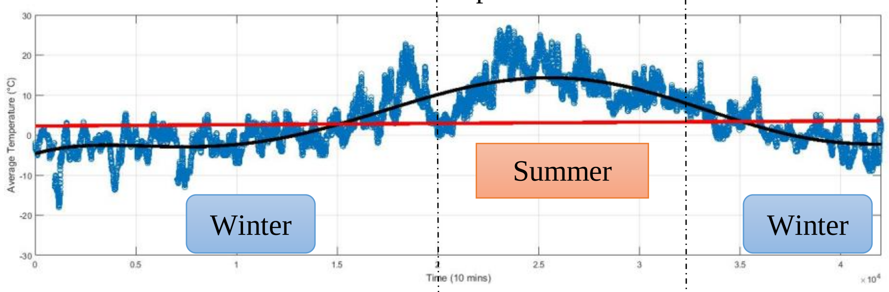
Average Wind Velocity & Power Production



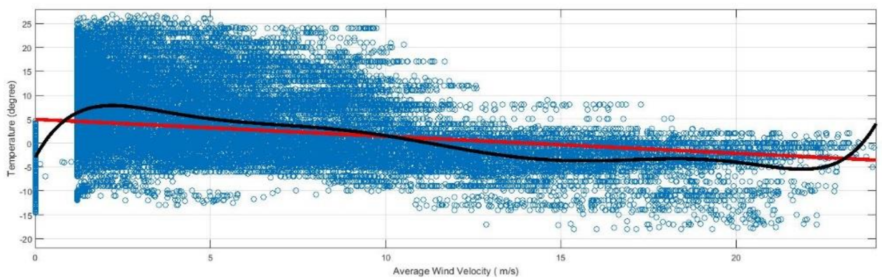
Time & Average Wind Velocity



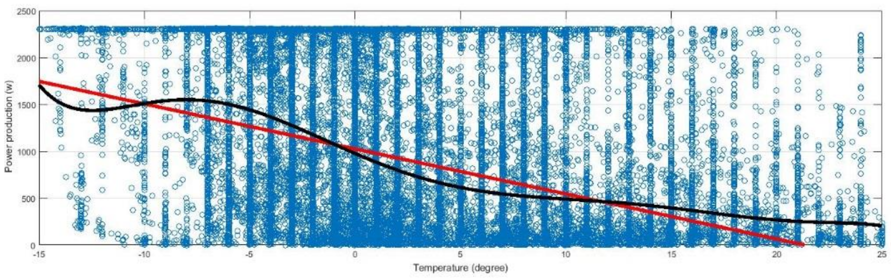
Time & Temperature



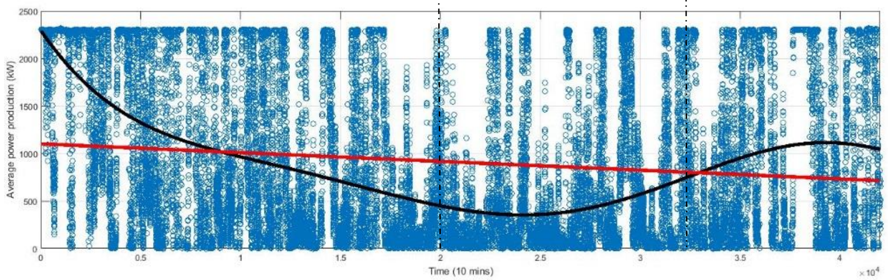
Average Wind Velocity & Temperature



Temperature & Power Production

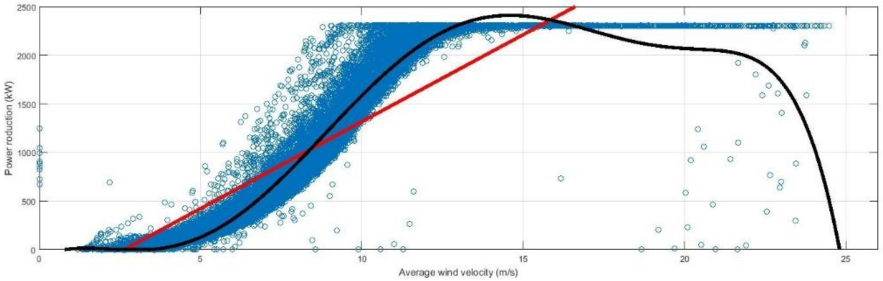


Time & Power Production

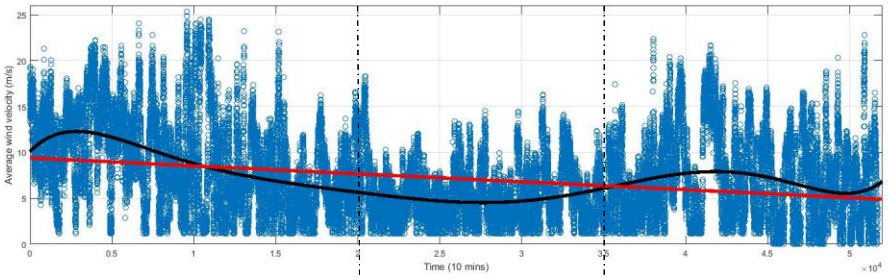


Turbine - 5

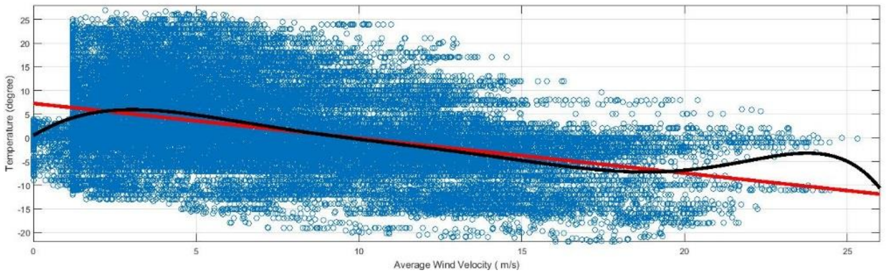
Average Wind Velocity & Power Production



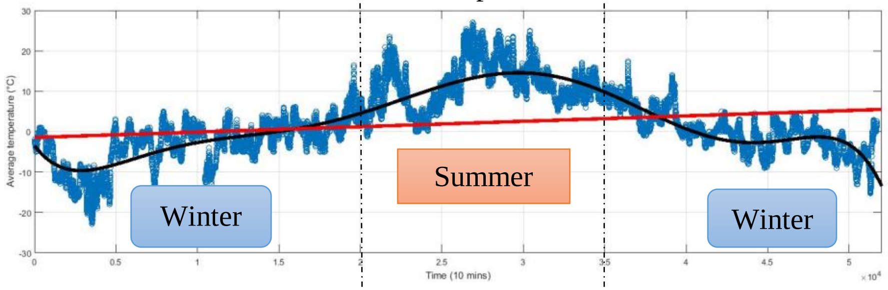
Time & Average Wind Velocity



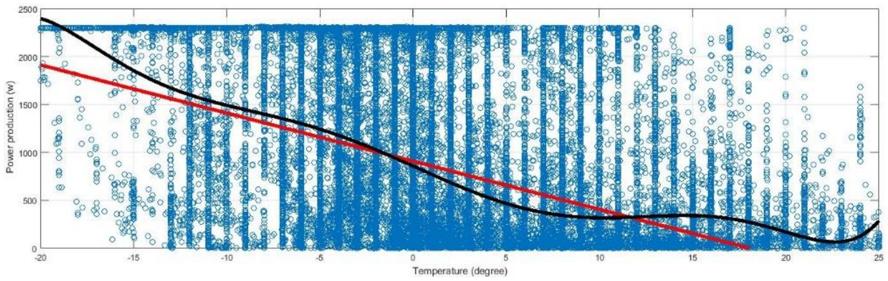
Average Wind Velocity & Temperature



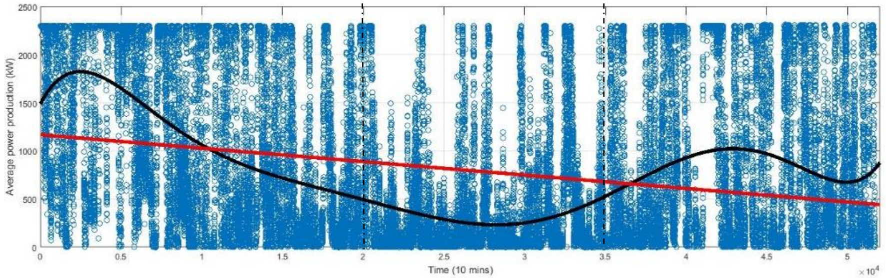
Time & Temperature



Temperature & Power Production

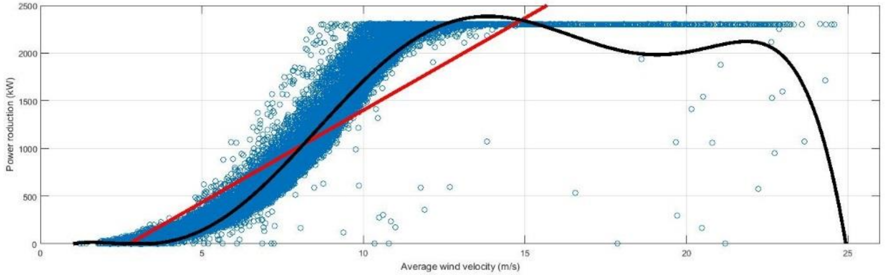


Time & Power Production

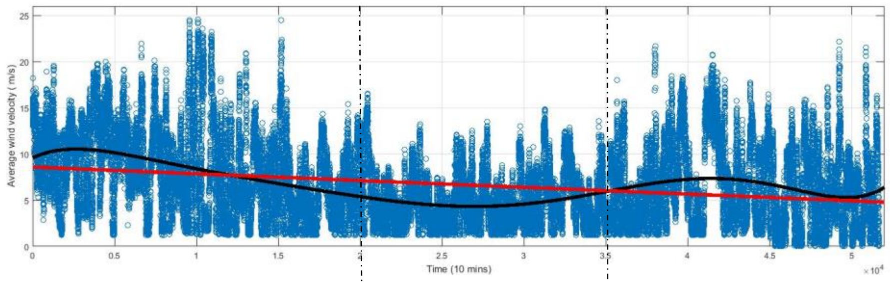


Turbine – 6

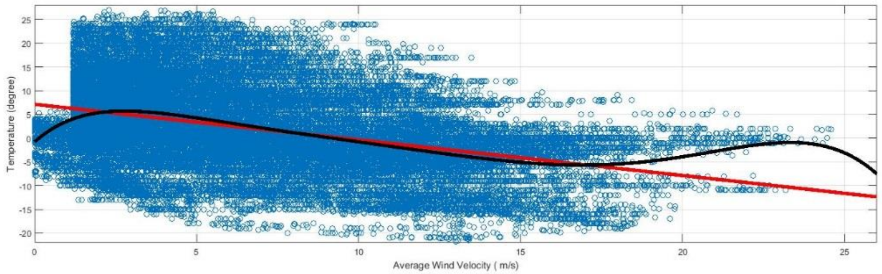
Average Wind Velocity & Power Production



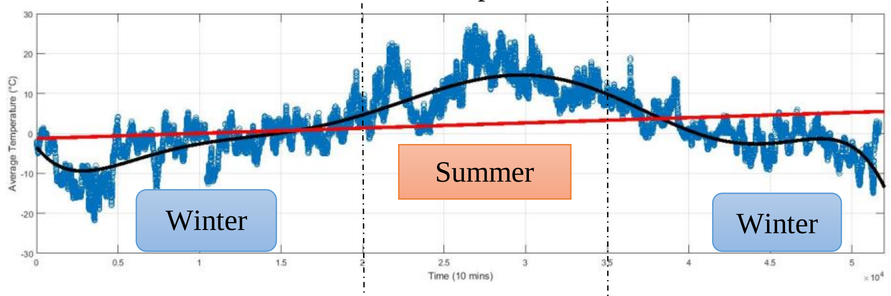
Time & Average Wind Velocity



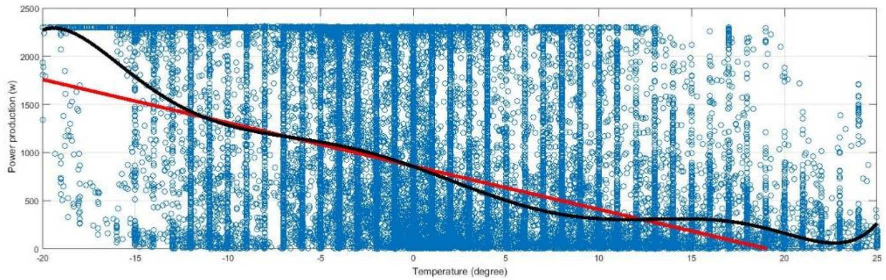
Average Wind Velocity & Temperature



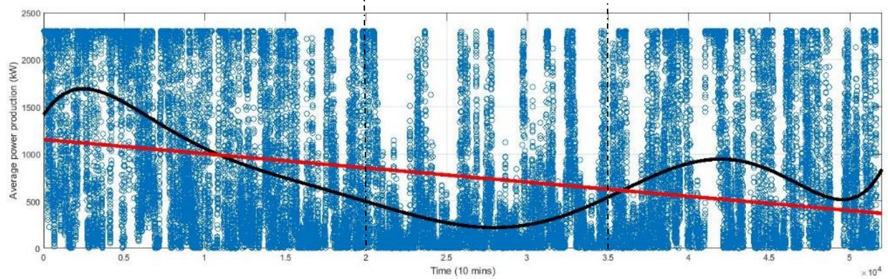
Time & Temperature



Temperature & Power Production

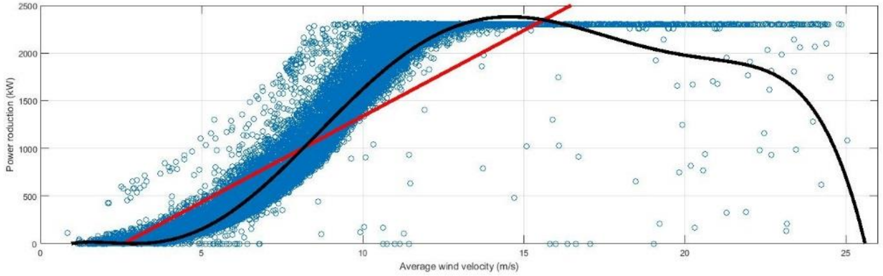


Time & Power Production

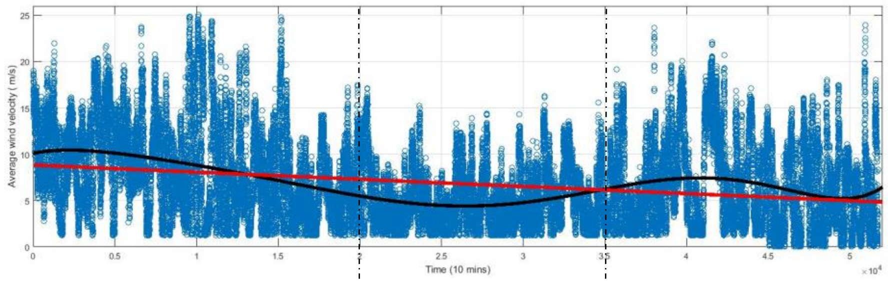


Turbine - 7

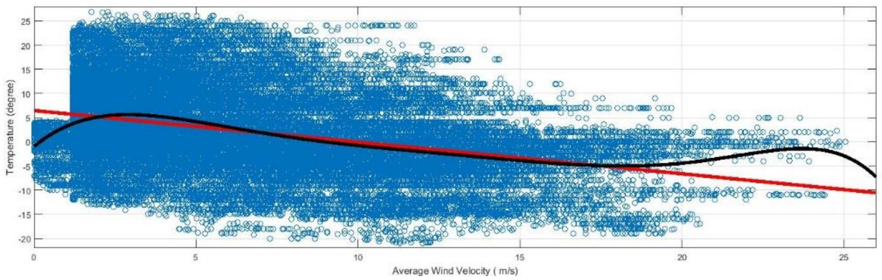
Average Wind Velocity & Power Production



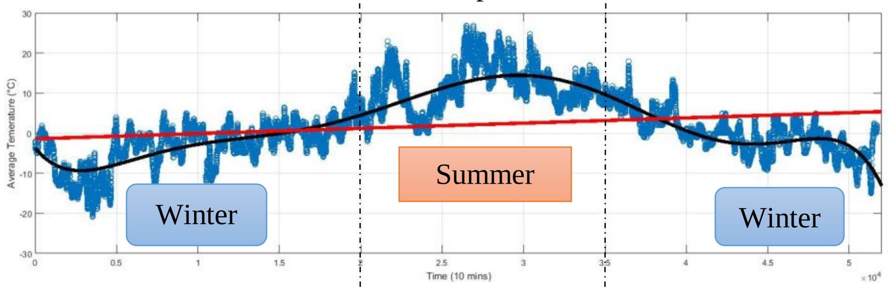
Time & Average Wind Velocity



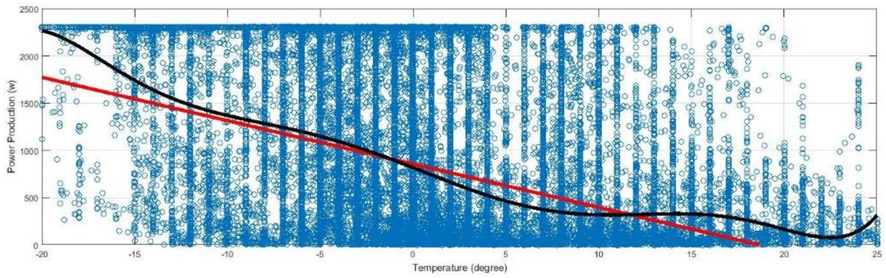
Average Wind Velocity & Temperature



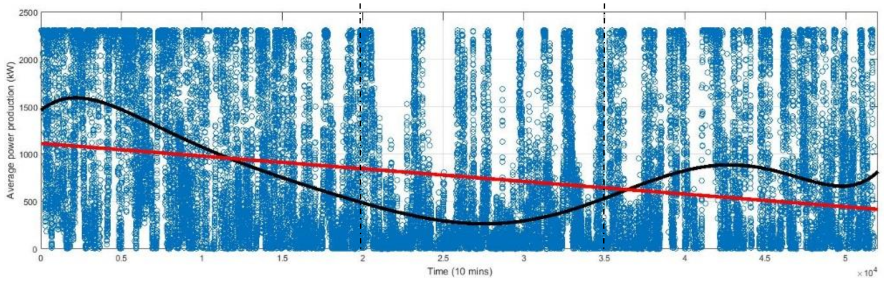
Time & Temperature



Temperature & Power Production

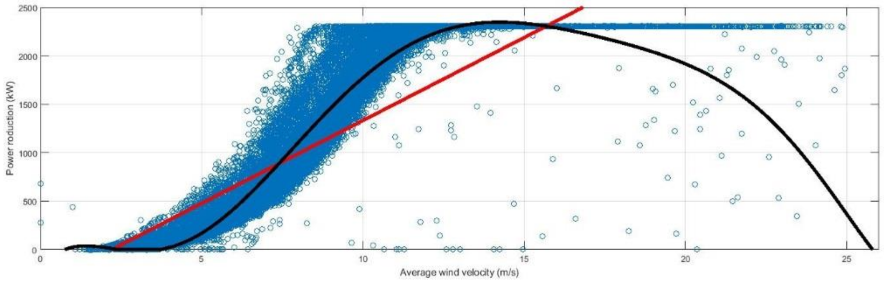


Time & Power Production

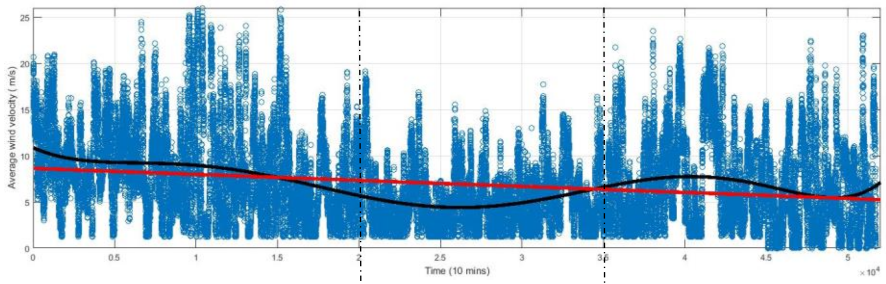


Turbine - 8

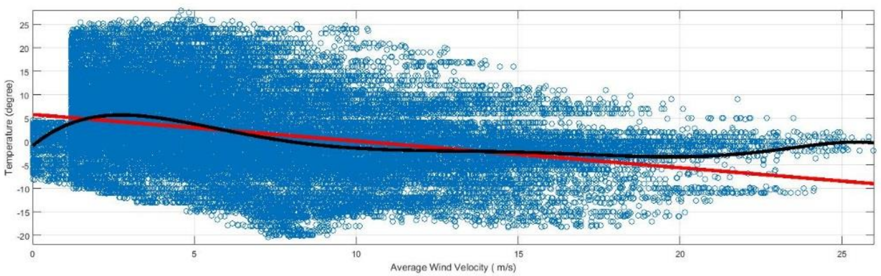
Average Wind Velocity & Power Production



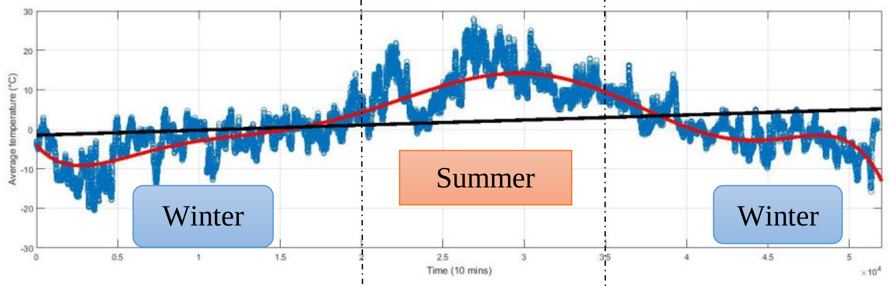
Time & Average Wind Velocity



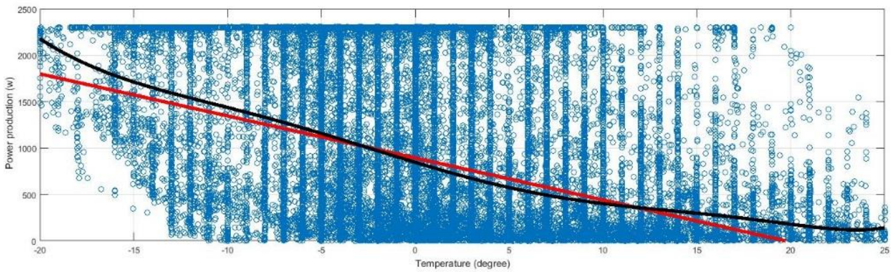
Average Wind Velocity & Temperature



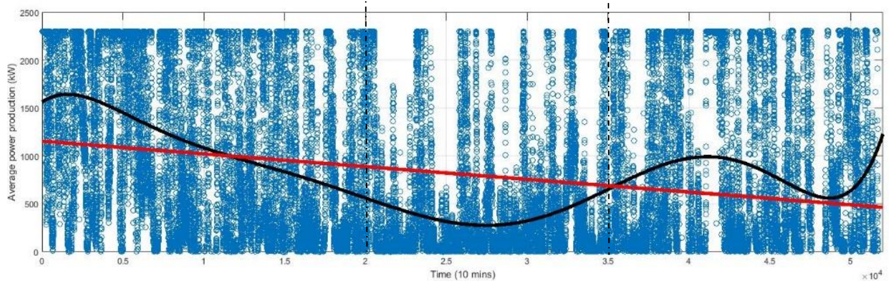
Time & Temperature



Temperature & Power Production

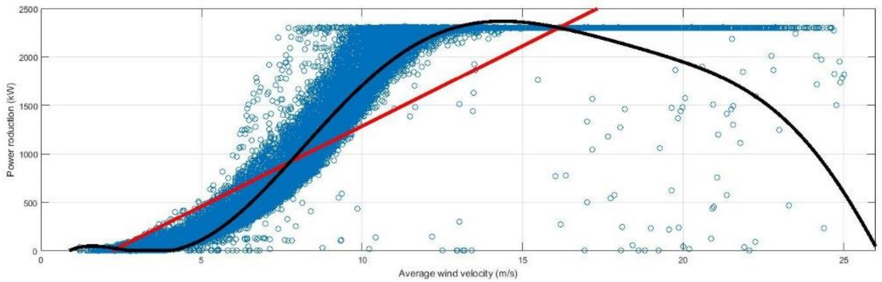


Time & Power Production

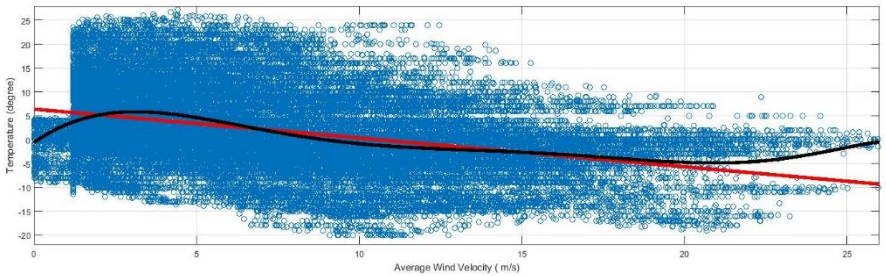


Turbine - 9

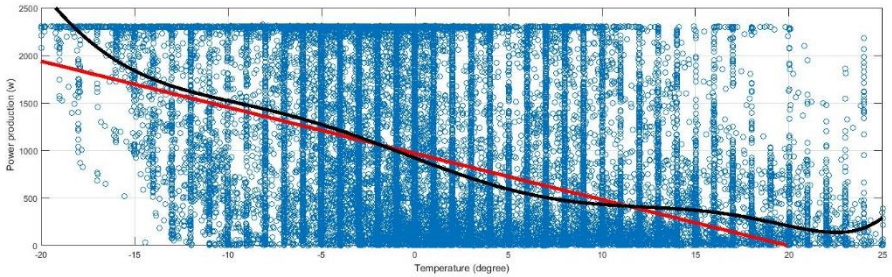
Average Wind Velocity & Power Production



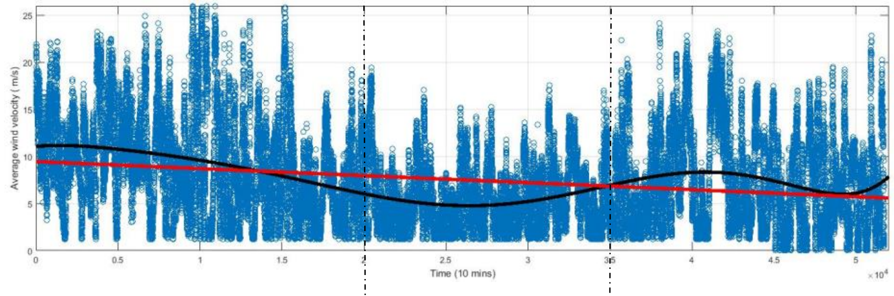
Average Wind Velocity & Temperature



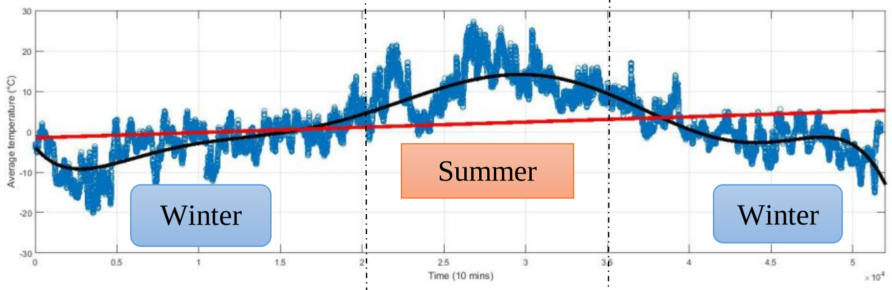
Temperature & Power Production



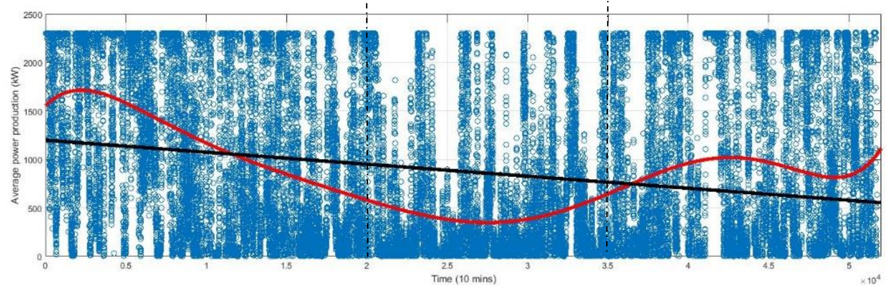
Time & Average Wind Velocity



Time & Temperature

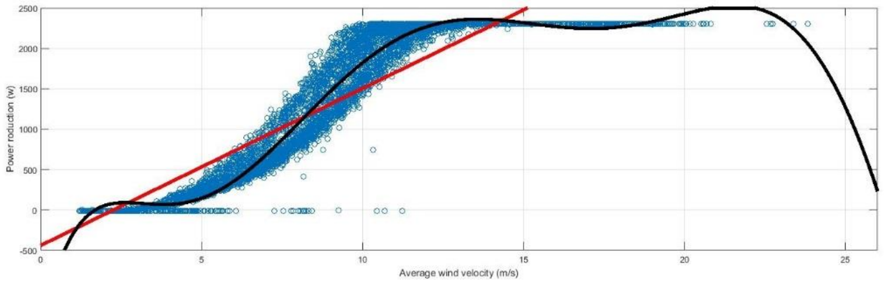


Time & Power Production

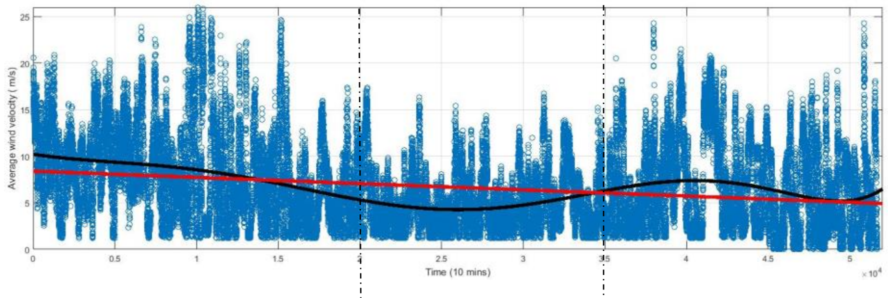


Turbine - 10

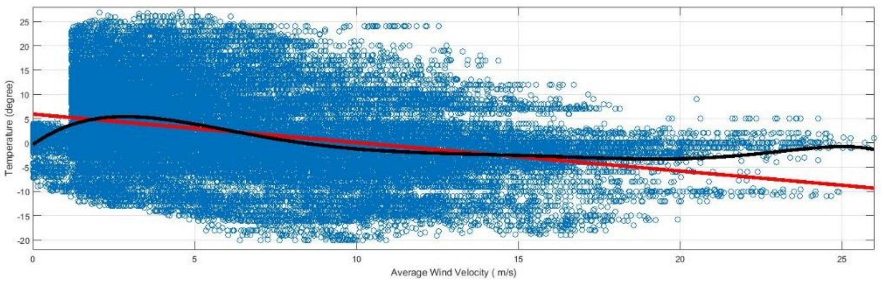
Average Wind Velocity & Power Production



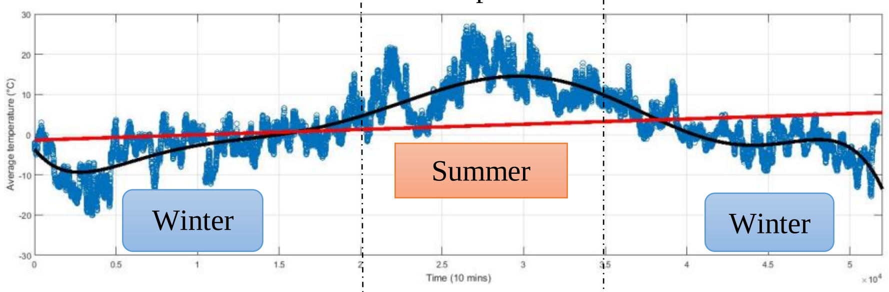
Time & Average Wind Velocity



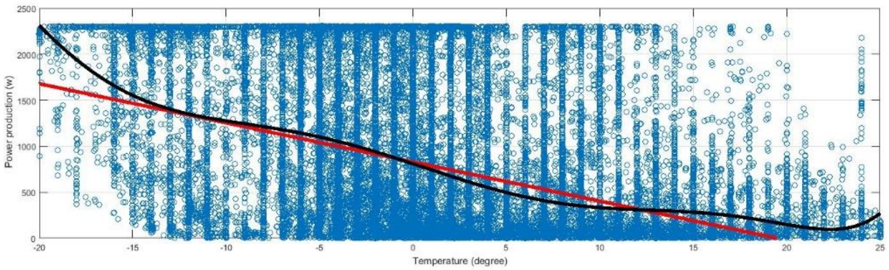
Average Wind Velocity & Temperature



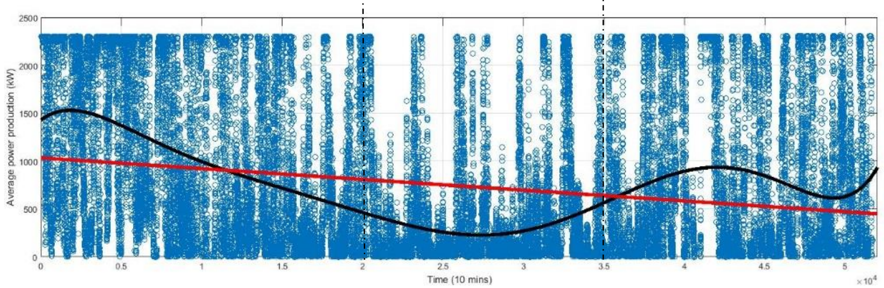
Time & Temperature



Temperature & Power Production

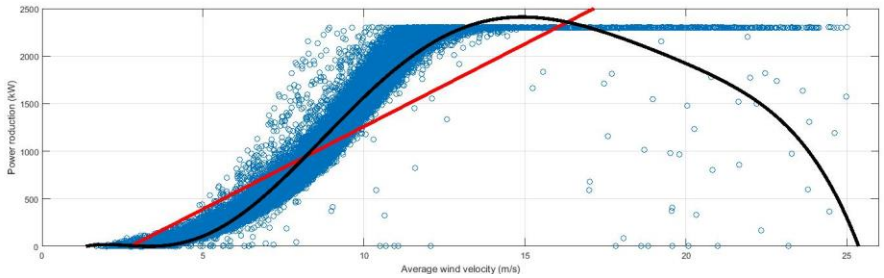


Time & Power Production

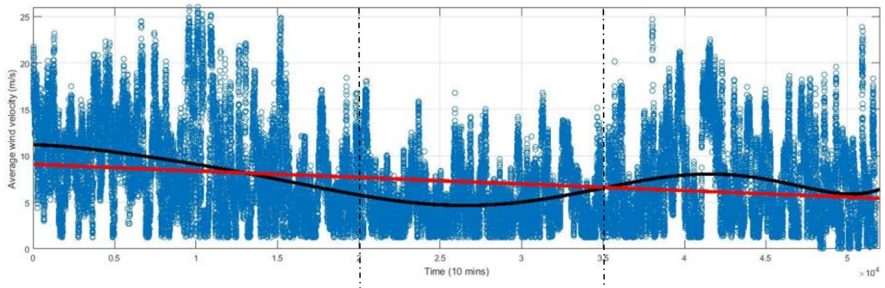


Turbine - 11

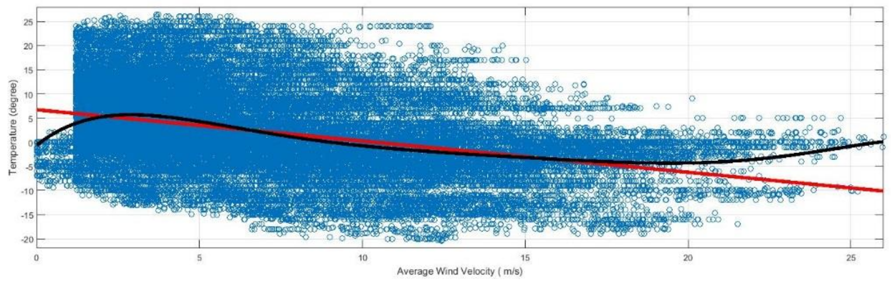
Average Wind Velocity & Power Production



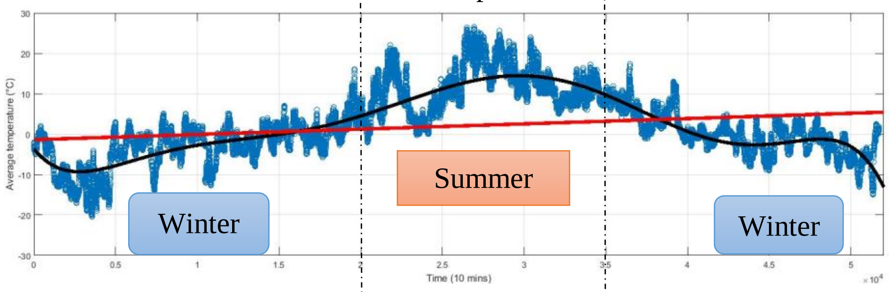
Time & Average Wind Velocity



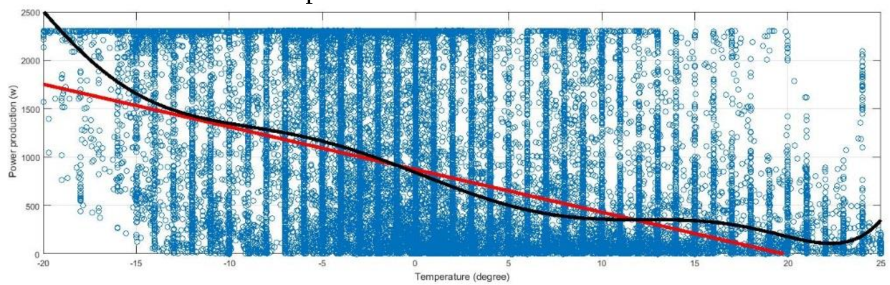
Average Wind Velocity & Temperature



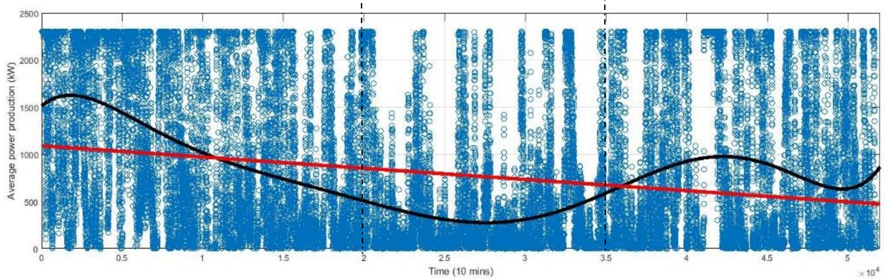
Time & Temperature



Temperature & Power Production

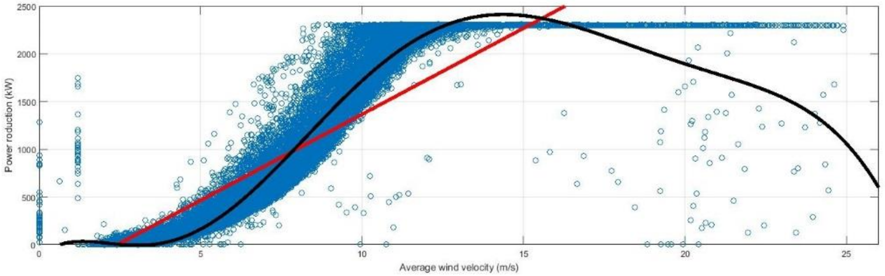


Time & Power Production

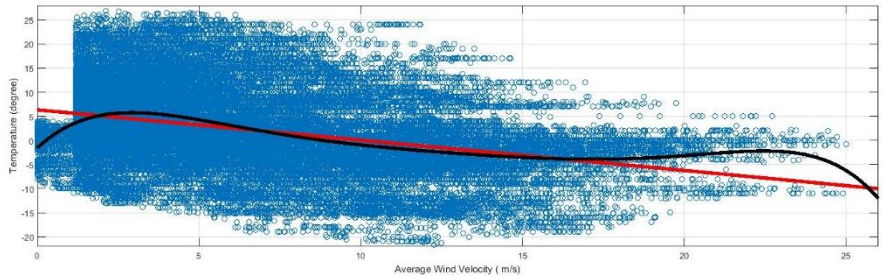


Turbine - 12

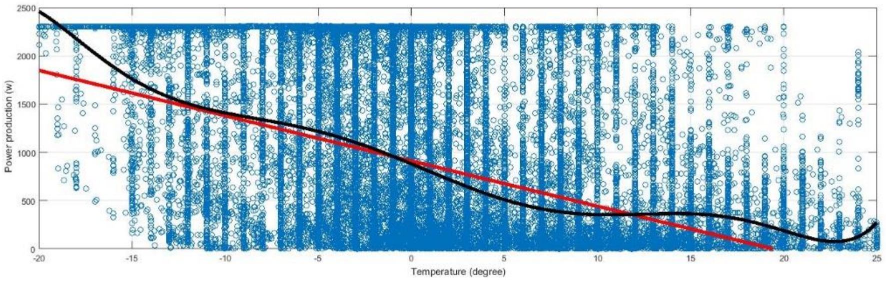
Average Wind Velocity & Power Production



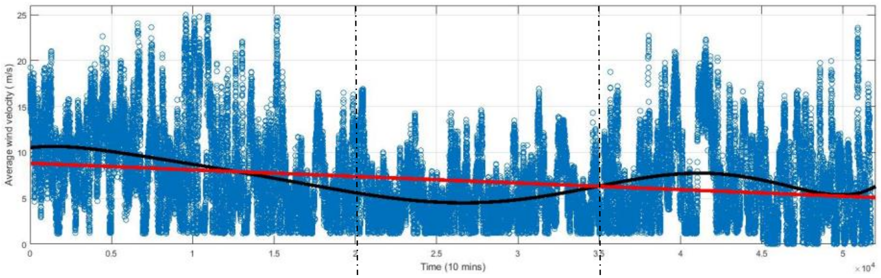
Average Wind Velocity & Temperature



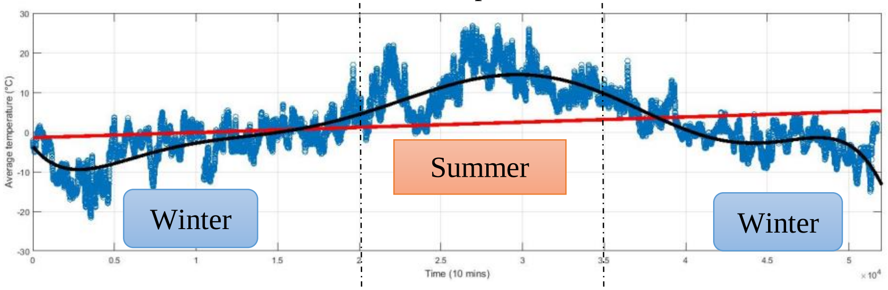
Temperature & Power Production



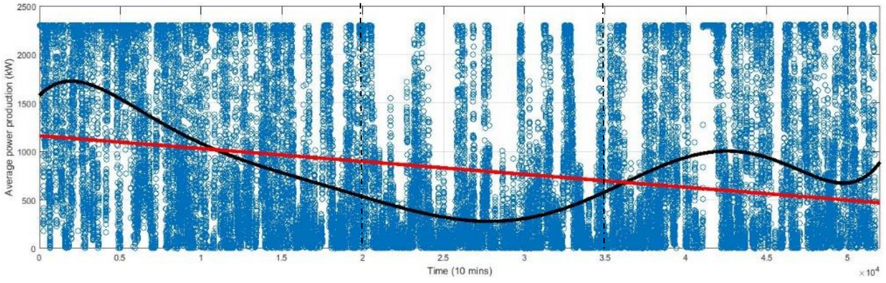
Time & Average Wind Velocity



Time & Temperature

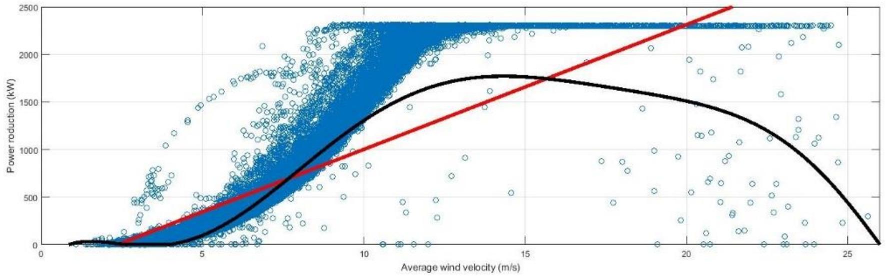


Time & Power Production

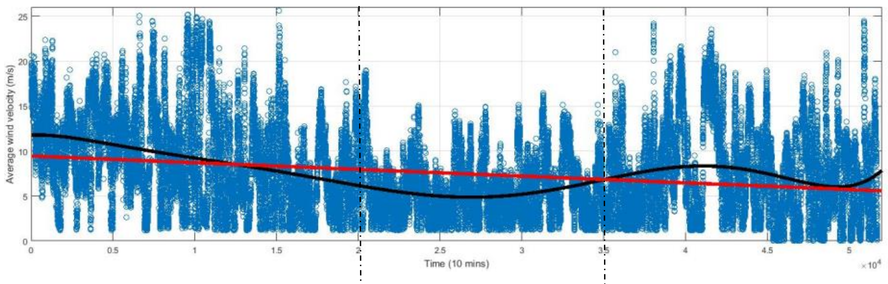


Turbine - 13

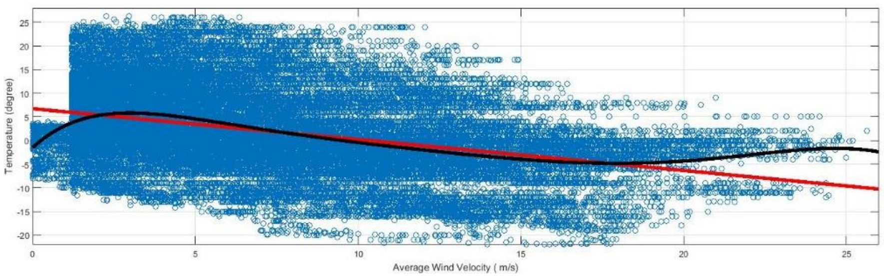
Average Wind Velocity & Power Production



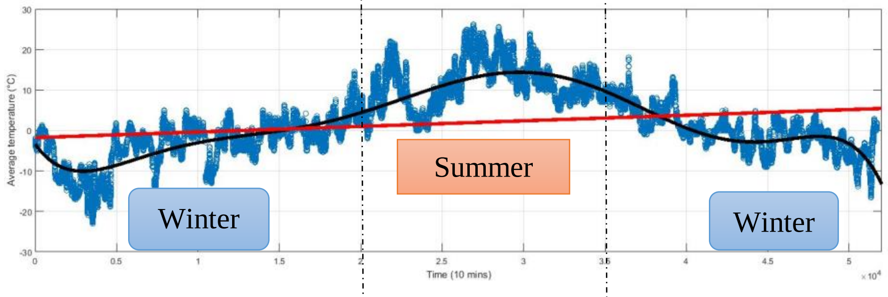
Time & Average Wind Velocity



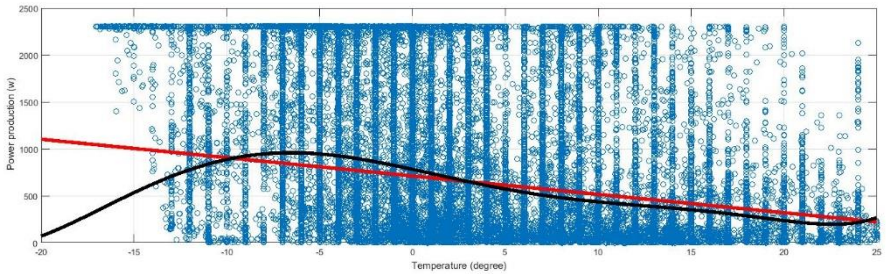
Average Wind Velocity & Temperature



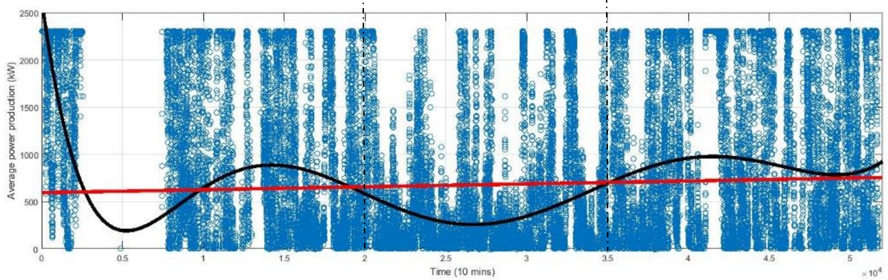
Time & Temperature



Temperature & Power Production

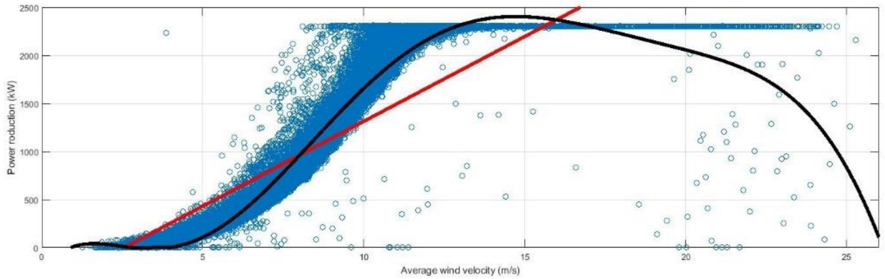


Time & Power Production

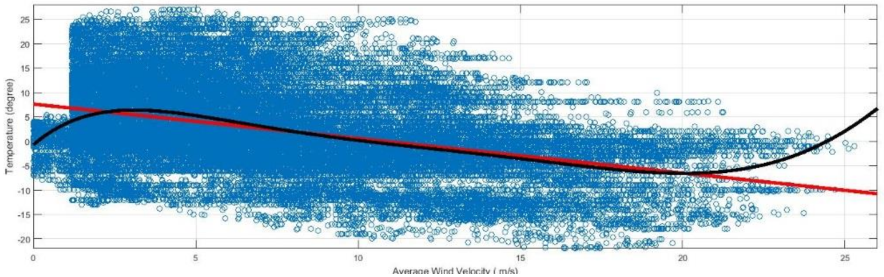


Turbine - 14

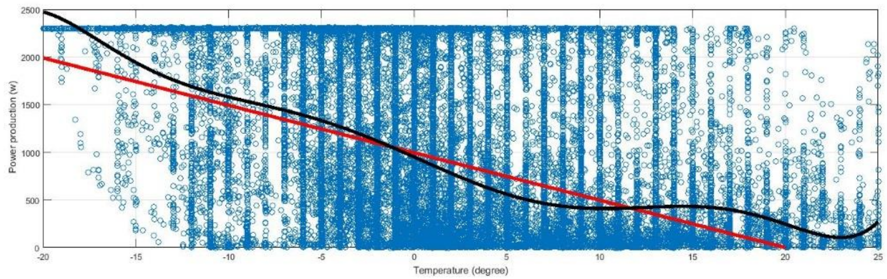
Average Wind Velocity & Power Production



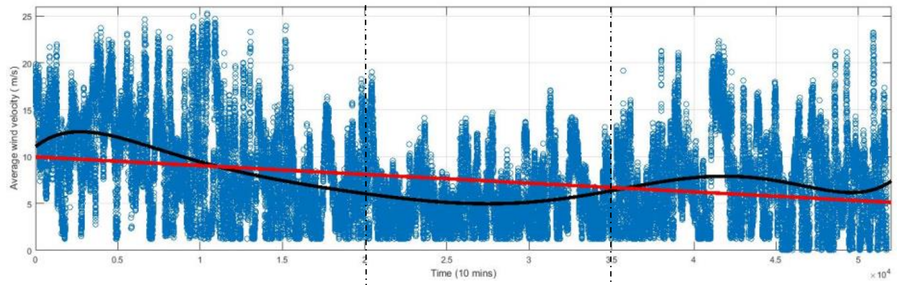
Average Wind Velocity & Temperature



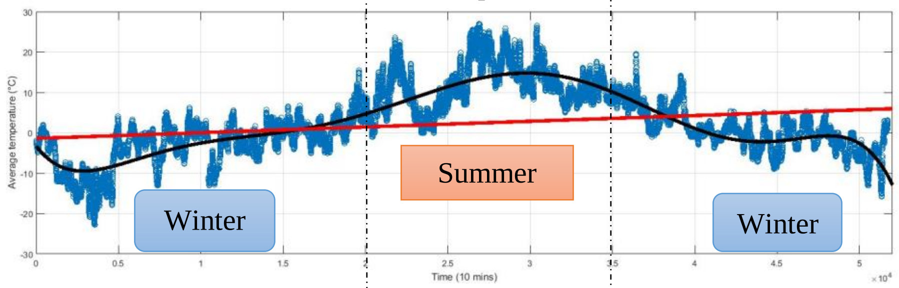
Temperature & Power Production



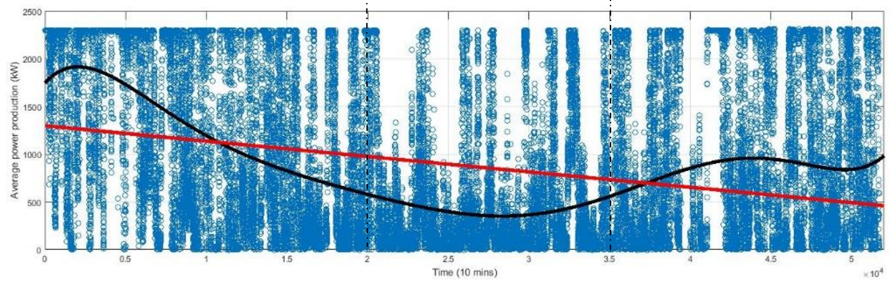
Time & Average Wind Velocity



Time & Temperature



Time & Power Production



4.3 Wind rose

Wind rose is the best way to show the typical distribution of wind velocity and direction in a particular region. This section shows wind rose analysis for one year data of each turbine's wind direction & wind speed. In order to be consistent with previous analysis, data from year 2014 have been used for wind rose analysis. WindRose PRO3 has been used to complete the wind rose analysis. The example below demonstrates the process:

Worksheet with data: Sheet1

Column with directions: wtc_ScYawPos_mean

Column with data: wtc_SeWindSp_mean

Column with 3rd variable: Not used

Column with dates: TimeStamp

Date/time format: mm/dd/yyyy hh:mm:ss

Total number of data in file: 51515

Number of valid data: 51515

Data filtering options: None

Number of data after date/time filtering: 51515

Minimum value: 0

5th percentile: 1.48

25th percentile: 3.76

50th percentile: 6.41

75th percentile: 9.95

95th percentile: 16.69

Maximum value: 29.13

Direction: 0 Angle: 0.000 Data (%): 1.314

Direction: 1 Angle: 22.500 Data (%): 0.503

Direction: 2 Angle: 45.000 Data (%): 0.526

Direction: 3 Angle: 67.500 Data (%): 3.873

Direction: 4 Angle: 90.000 Data (%): 50.983

Direction: 5 Angle: 112.500 Data (%): 1.468

Direction: 6 Angle: 135.000 Data (%): 0.316

Direction: 7 Angle: 157.500 Data (%): 0.369

Direction: 8 Angle: 180.000 Data (%): 0.268

Direction: 9 Angle: 202.500 Data (%): 0.580

Direction: 10 Angle: 225.000 Data (%): 1.308

Direction: 11 Angle: 247.500 Data (%): 8.167

Direction: 12 Angle: 270.000 Data (%): 19.672

Direction: 13 Angle: 292.500 Data (%): 7.590

Direction: 14 Angle: 315.000 Data (%): 1.770

Direction: 15 Angle: 337.500 Data (%): 1.103

Interval: 0 From: 0 To: 5 #Data: 19099 Data (%): 37.075

Interval: 1 From: 5 To: 10 #Data: 19564 Data (%): 37.977

Interval: 2 From: 10 To: 15 #Data: 8508 Data (%): 16.516

Interval: 3 From: 15 To: 20 #Data: 3473 Data (%): 6.742

Interval: 4 From: 20 To: 25 #Data: 762 Data (%): 1.479

Interval: 5 From: 25 To: 30 #Data: 11 Data (%): 0.021

EXCEEDING FREQUENCIES (Calculated using >)

Interval Counts Frequency(%) Value Exceeding counts Exceeding frequency(%)

0 - 5 19099 37.075 0 51417 99.810

5 - 10 19564 37.977 5 32318 62.735

10 - 15 8508 16.516 10 12754 24.758

15 - 20 3473 6.742 15 4246 8.242

20 - 25 762 1.479 20 773 1.501

25 - 30 11 0.021 25 11 0.021

Input directions rotated of 0 degree

Direction: 0 Angle: 0.000 Min: 0.110 Avg: 4.473 Max: 27.340

Direction: 1 Angle: 22.500 Min: 1.150 Avg: 4.275 Max: 9.120

Direction: 2 Angle: 45.000 Min: 0.005 Avg: 2.016 Max: 11.030

Direction: 3 Angle: 67.500 Min: 0.010 Avg: 6.766 Max: 22.400

Direction: 4 Angle: 90.000 Min: 0.001 Avg: 8.874 Max: 24.930

Direction: 5 Angle: 112.500 Min: 1.150 Avg: 5.333 Max: 19.080

Direction: 6 Angle: 135.000 Min: 1.200 Avg: 3.576 Max: 13.420

Direction: 7 Angle: 157.500 Min: 0.490 Avg: 2.898 Max: 10.580

Direction: 8 Angle: 180.000 Min: 0.270 Avg: 3.266 Max: 10.260

Direction: 9 Angle: 202.500 Min: 0.110 Avg: 4.986 Max: 12.750

Direction: 10 Angle: 225.000 Min: 0.640 Avg: 3.926 Max: 22.600

Direction: 11 Angle: 247.500 Min: 0.009 Avg: 5.641 Max: 25.500

Direction: 12 Angle: 270.000 Min: 0.005 Avg: 6.568 Max: 25.410

Direction: 13 Angle: 292.500 Min: 0.001 Avg: 5.289 Max: 22.450

Direction: 14 Angle: 315.000 Min: 0.300 Avg: 5.660 Max: 22.690

Direction: 15 Angle: 337.500 Min: 0.060 Avg: 3.823 Max: 29.130

CIRCULAR STATISTICS

Interval: 0 - 5

Counts: 19099

Scalar average of direction: 279.327

Scalar average of data: 3.039

Vector average of direction: 283.444

Vector average of data: 0.407

Persistence: 0.134

Standard deviation of direction: 92.581

Root mean square of data: 3.266

Variance of data: 1.430

Variance of the X component of data: 9.115

Variance of the Y component of data: 1.388

Covariance of the X and Y components of data: 0.329

Cross wind data variance: 1.954

Along wind data variance: 8.548

Interval: 5 - 10

Counts: 19564

Scalar average of direction: 75.819

Scalar average of data: 7.242

Vector average of direction: 77.137

Vector average of data: 2.721

Persistence: 0.376

Standard deviation of direction: 77.808

Root mean square of data: 7.373

Variance of data: 1.914

Variance of the X component of data: 44.252

Variance of the Y component of data: 2.701

Covariance of the X and Y components of data: -0.019

Cross wind data variance: 4.768

Along wind data variance: 42.184

Interval: 10 - 15

Counts: 8508

Scalar average of direction: 82.688

Scalar average of data: 12.191

Vector average of direction: 82.856

Vector average of data: 5.865

Persistence: 0.481

Standard deviation of direction: 68.108

Root mean square of data: 12.276

Variance of data: 2.072

Variance of the X component of data: 112.425

Variance of the Y component of data: 3.871

Covariance of the X and Y components of data: 4.669

Cross wind data variance: 4.398

Along wind data variance: 111.898

Interval: 15 - 20

Counts: 3473

Scalar average of direction: 85.712

Scalar average of data: 17.026

Vector average of direction: 85.760

Vector average of data: 10.777

Persistence: 0.633

Standard deviation of direction: 54.121

Root mean square of data: 17.087

Variance of data: 2.067

Variance of the X component of data: 169.300

Variance of the Y component of data: 6.515

Covariance of the X and Y components of data: 19.202

Cross wind data variance: 4.573

Along wind data variance: 171.242

Interval: 20 - 25

Counts: 762

Scalar average of direction: 90.261

Scalar average of data: 21.473

Vector average of direction: 90.854

Vector average of data: 5.496

Persistence: 0.256

Standard deviation of direction: 84.877

Root mean square of data: 21.513

Variance of data: 1.728

Variance of the X component of data: 412.674

Variance of the Y component of data: 19.934

Covariance of the X and Y components of data: 56.682

Cross wind data variance: 21.710

Along wind data variance: 410.898

Interval: 25 - 30

Counts: 11

Scalar average of direction: 297.845

Scalar average of data: 23.563

Vector average of direction: 292.250

Vector average of data: 15.956

Persistence: 0.677

Standard deviation of direction: 52.265

Root mean square of data: 24.742

Variance of data: 56.950

Variance of the X component of data: 110.706

Variance of the Y component of data: 246.837

Covariance of the X and Y components of data: 134.432

Cross wind data variance: 321.544

Along wind data variance: 36.000

Interval: All data

Counts: 51417

Scalar average of direction: 74.004

Scalar average of data: 7.377

Vector average of direction: 80.473

Vector average of data: 2.665

Persistence: 0.361

Standard deviation of direction: 89.560

Root mean square of data: 8.736

Variance of data: 21.906

Variance of the X component of data: 66.138

Variance of the Y component of data: 3.077

Covariance of the X and Y components of data: 3.741

Cross wind data variance: 3.583

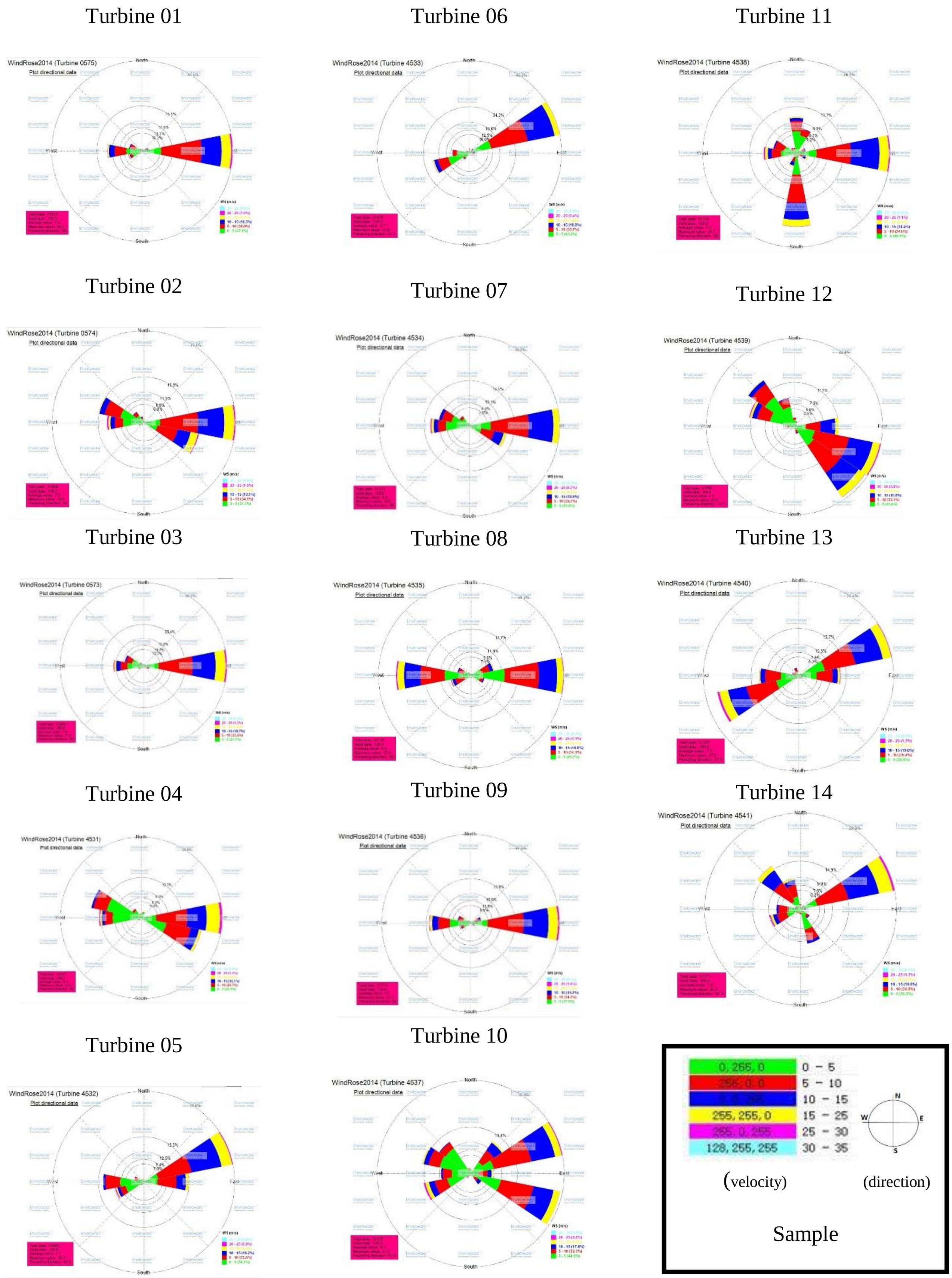
Along wind data variance: 65.632

AUTOCORRELATION AND STRUCTURE FUNCTION

Distance	Autocorrelation	Structure function
0	1.000E+000	0.000E+000
1	9.863E-001	6.028E-001
2	9.733E-001	1.172E+000
3	9.633E-001	1.612E+000
4	9.550E-001	1.975E+000
5	9.476E-001	2.303E+000
6	9.403E-001	2.624E+000
7	9.331E-001	2.939E+000
8	9.260E-001	3.250E+000
9	9.191E-001	3.554E+000
10	9.122E-001	3.856E+000
11	9.052E-001	4.161E+000
12	8.984E-001	4.459E+000
13	8.916E-001	4.759E+000
14	8.850E-001	5.049E+000
15	8.782E-001	5.346E+000
16	8.715E-001	5.638E+000
17	8.646E-001	5.942E+000
18	8.577E-001	6.244E+000
19	8.511E-001	6.535E+000
20	8.446E-001	6.817E+000
21	8.379E-001	7.114E+000
22	8.311E-001	7.408E+000
23	8.245E-001	7.701E+000
24	8.176E-001	7.999E+000

Figure 4-22 shows the wind rose analysis of each wind turbine for year 2014.

Figure 4-22 Wind rose analysis for year 2014 (14 turbines)



From Figure 4-22, we can see that for five turbines' wind rose plots show one main wind direction, eight turbines' show two main directions, and one turbine's shows three main directions, as specified in Table 4-5.

Table 4-5 Wind rose observations

Number of wind direction	Turbine	Direction
1 main direction	Turbine 01	West↔East
	Turbine 03	West↔East
	Turbine 06	Sourthwest↔Northeast
	Turbine 08	West↔East
	Turbine 09	West↔East
2nd main direction	Turbine 02	West↔East Northwest↔Sourthwest
	Turbine 04	West↔East Northwest↔Sourthwest
	Turbine 05	West↔East Sourthwest↔Northeast
	Turbine 07	West↔East Northwest↔Sourthwest
	Turbine 10	Sourthwest↔Northeast Northwest↔Sourthwest
	Turbine 11	West↔East North↔South
	Turbine 12	Northwest↔Sourthwest(*2)
	Turbine 13	Sourthwest↔Northeast
3rd main direction	Turbine 14	Sourthwest↔Northeast Northwest↔Sourthwest(*2)

4.4 Annual Energy Production (AEP)

Based on SCADA data sorting and analysis combined with real conditions of wind parks, the annual wind energy is one of the most significant factors in wind energy production. The database of 14 Turbines wind power production (GW) from 2013 to 2015 is shown in Table 4-6.

Table 4-6 3 years' wind power production comparison for 14 turbines

Wind power production (GW)		**2013**	**2014**	**2015**	**Total (GW)**
T01	**T0575**	35.791	43.749	25.395	104.934
T02	**T0574**	34.334	46.535	39.518	120.387
T03	**T0573**	35.609	45.920	37.644	119.173
T04	**T4531**	42.789	42.526	43.393	128.708
T05	**T4532**	35.116	41.869	36.975	113.961
T06	**T4533**	34.774	39.572	36.339	110.685
T07	**T4534**	35.881	39.704	37.296	112.881
T08	**T4535**	38.712	42.035	39.549	120.297
T09	**T4536**	41.087	45.476	41.570	128.133
T10	**T4537**	29.798	38.525	33.830	102.152
T11	**T4538**	34.575	40.594	36.360	111.529
T12	**T4539**	35.843	42.405	35.949	114.196
T13	**T4540**	37.533	35.101	40.117	112.751
T14	**T4541**	41.643	45.706	29.439	116.788
Total		513.486	589.719	513.372	1616.577

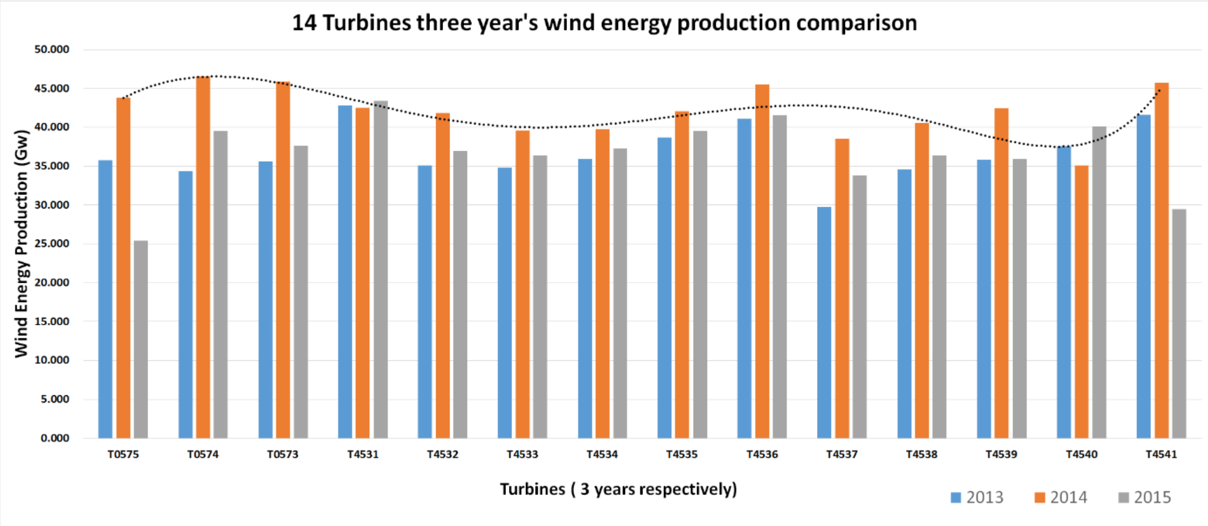


Figure 4-23 Wind energy production comparison

From Figure 4-23, we can see:

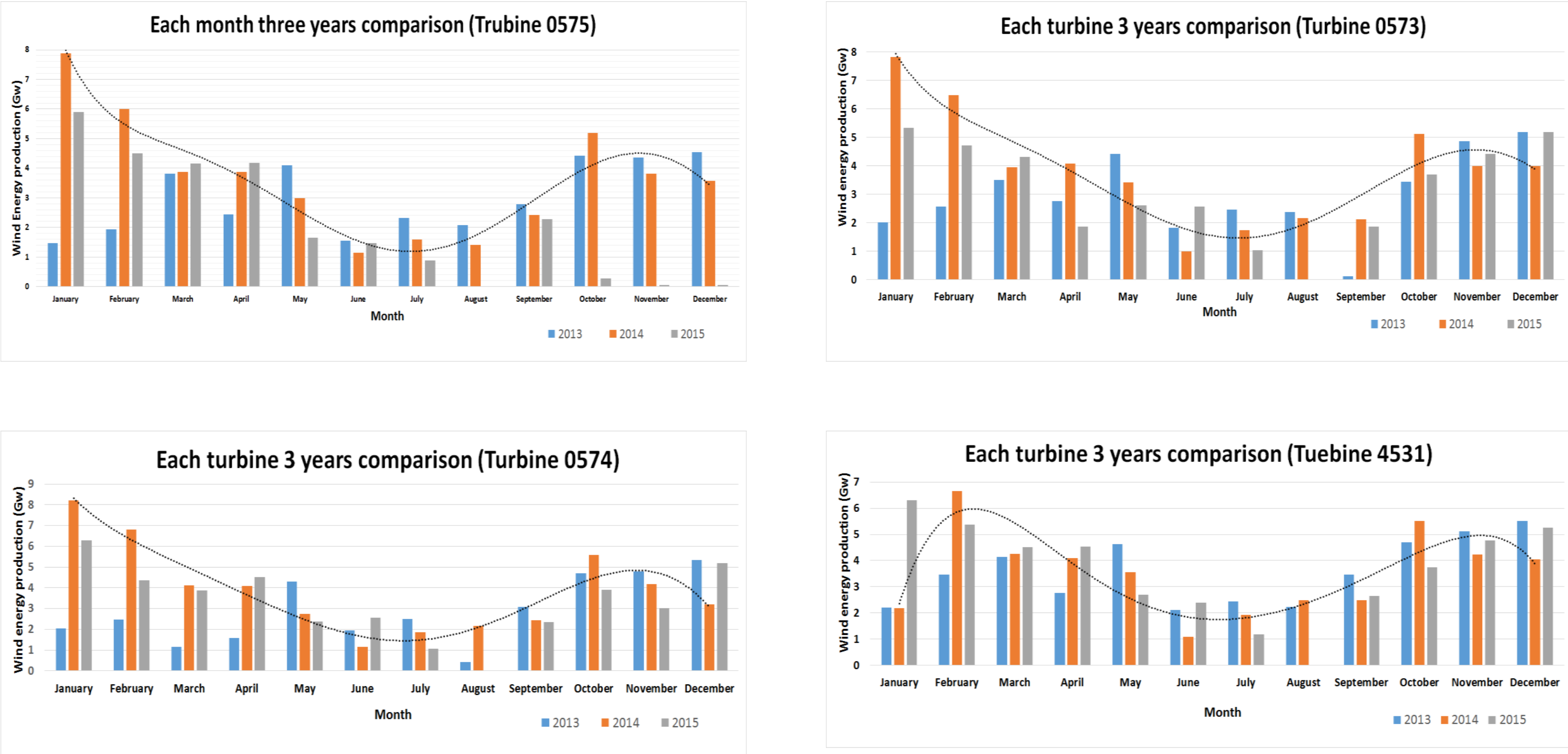
i. In 2013, 2014 and 2015, turbine 4531, 0574 and 4531 got the maximal wind power production respectively;
ii. In 2013, 2014 and 2015, turbine 4537,4540 and 0575 got the minimal wind power production respectively;
iii. In 2014, the total wind energy was the highest; turbine 4531 produced the most wind power during 2013-2015.

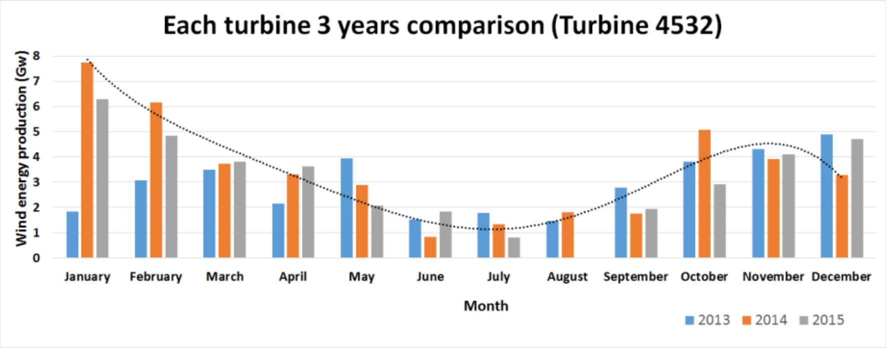
14 turbines' monthly wind energy production for the three years is shown in Figure 4-24. From these figures, we can easily see:

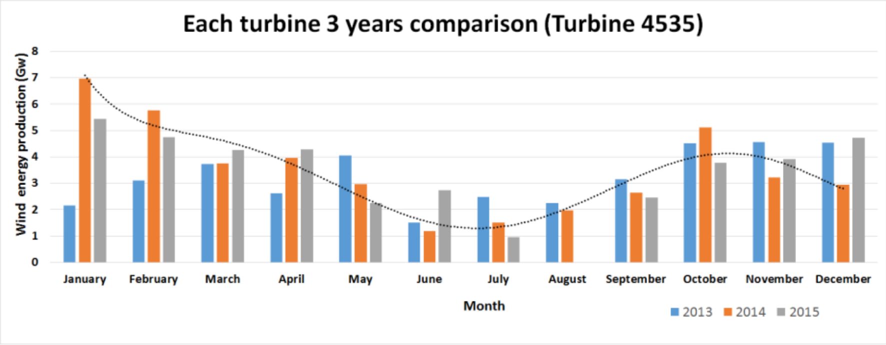
i. The wind energy production in each year is highest in winter (*October in first year to March of next year*) and lowest in summer.

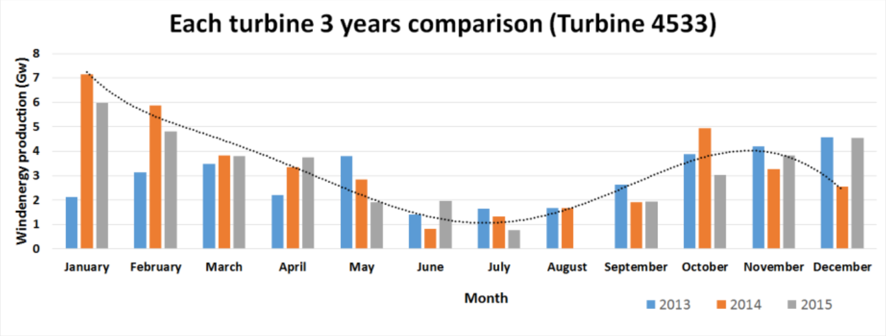
ii. Figure 4-24 confirms that the observed trend of Wind Power Production over time in Figure 4-21 holds for 2013 and 2015 as well.

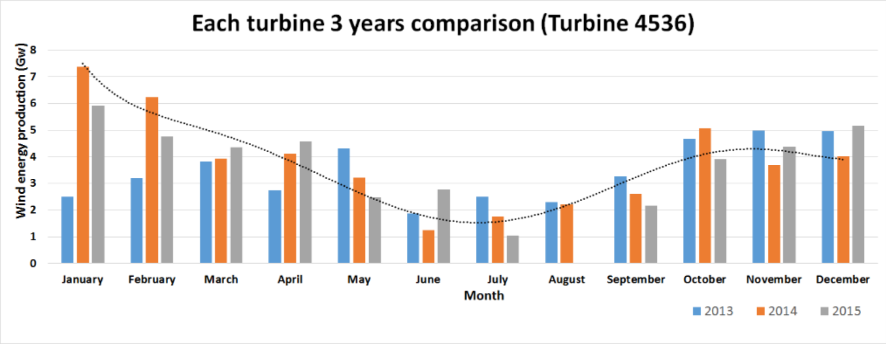
Figure 4-24 Wind energy of each turbines three years' comparison

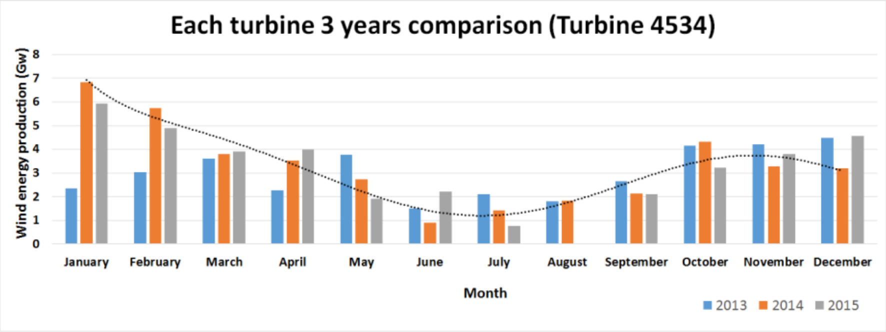


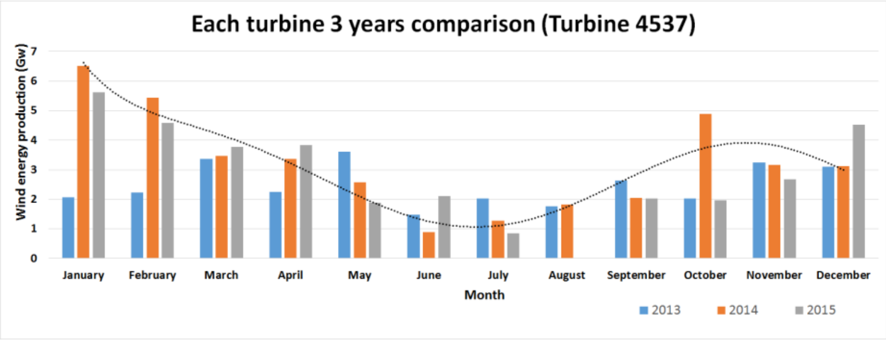

Each turbine 3 years comparison (Turbine 4532)
Wind energy production (Gw)
0
1
2
3
4
5
6
7
8
January
February
March
April
May
June
July
August
September
October
November
December
Month
2013
2014
2015

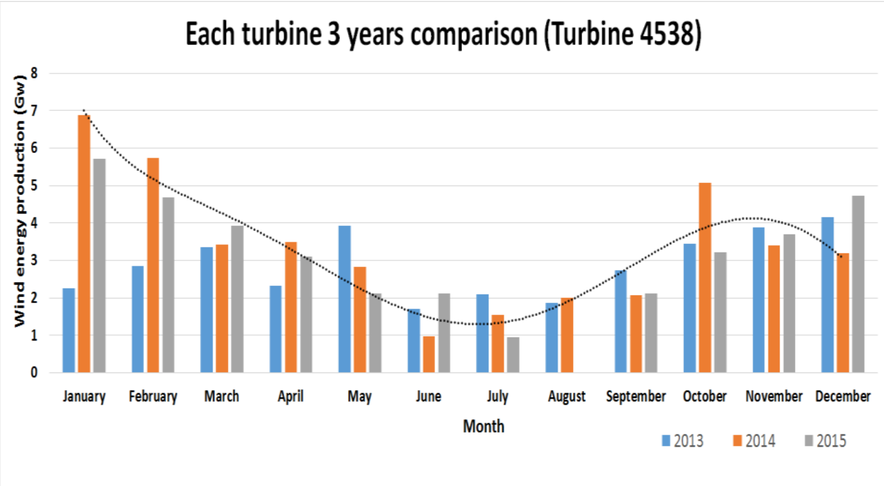

Each turbine 3 years comparison (Turbine 4535)
Wind energy production (Gw)
0
1
2
3
4
5
6
7
8
January
February
March
April
May
June
July
August
September
October
November
December
Month
2013
2014
2015

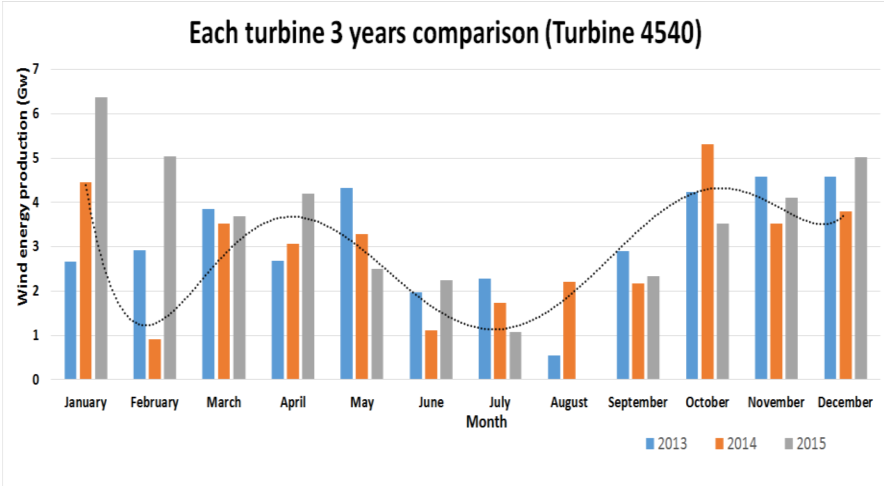

Each turbine 3 years comparison (Turbine 4533)
Windenergy production (Gw)
0
1
2
3
4
5
6
7
8
January
February
March
April
May
June
July
August
September
October
November
December
Month
2013
2014
2015

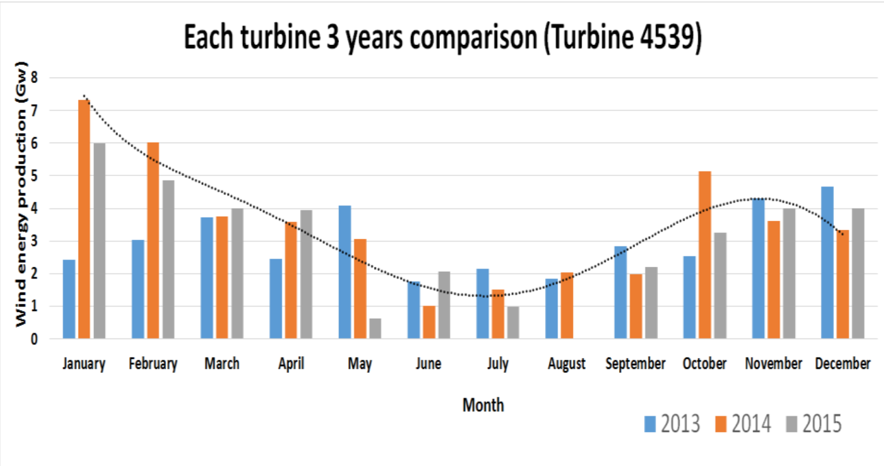

Each turbine 3 years comparison (Turbine 4536)
Wind energy production (Gw)
0
1
2
3
4
5
6
7
8
January
February
March
April
May
June
July
August
September
October
November
December
Month
2013
2014
2015

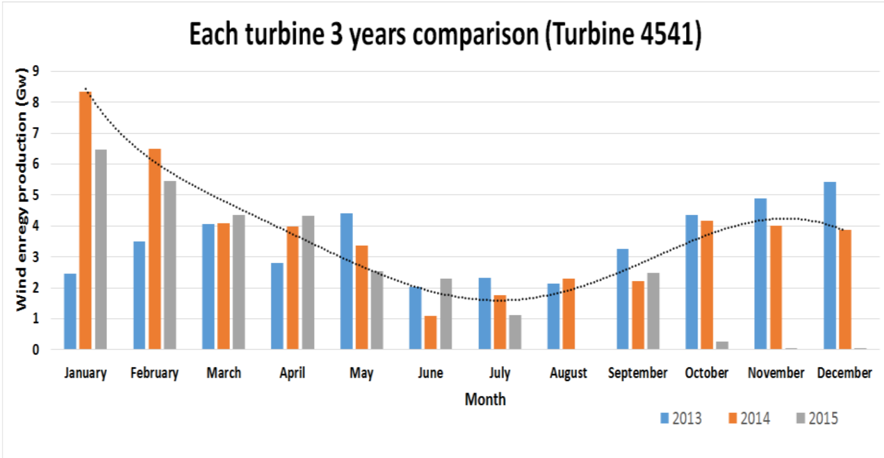

Each turbine 3 years comparison (Turbine 4534)
Wind energy production (Gw)
0
1
2
3
4
5
6
7
8
January
February
March
April
May
June
July
August
September
October
November
December
Month
2013
2014
2015


Each turbine 3 years comparison (Turbine 4537)
Wind energy production (Gw)
0
1
2
3
4
5
6
7
January
February
March
April
May
June
July
August
September
October
November
December
Month
2013
2014
2015


Each turbine 3 years comparison (Turbine 4538)
Wind energy production (Gw)
Month
January
February
March
April
May
June
July
August
September
October
November
December
2013
2014
2015


Each turbine 3 years comparison (Turbine 4540)
Wind energy production (Gw)
Month
January
February
March
April
May
June
July
August
September
October
November
December
2013
2014
2015


Each turbine 3 years comparison (Turbine 4539)
Wind energy production (Gw)
Month
January
February
March
April
May
June
July
August
September
October
November
December
2013
2014
2015


Each turbine 3 years comparison (Turbine 4541)
Wind enregy production (Gw)
Month
January
February
March
April
May
June
July
August
September
October
November
December
2013
2014
2015

4.5 Findings

Chapter 4 presents the results of SCADA data analysis for 3 years (2013-15) using all 14 wind turbines of Nygårdfjellet wind park. Comprehensive Vertical Interpolation analyses are presented with a comparison between different polynomial (4^{th} to 9^{th}) forms, including linear analysis as reference. Based on the comparison, the best polynomial curve is chosen. Comprehensive Horizontal Interpolation analysis shows 1 year and each turbine's comparison between 6 functions (4 variables combination), then chooses the best correlations. Specific vertical and horizontal analysis shows with 3 years' data each turbine's best polynomial curve (with linear reference) fitting and the comparison between highly related functions, as well as the inner comparison within each turbine (7^{th} polynomial with linear reference and 6 different functions). Windrose analysis shows for the year 2014 the graphical comparison between turbines' wind direction & wind speed. Below are the main findings of these analyses.

i. 7^{th} degree polynomial curve fitting (linear as reference) is found to be the best choice for wind park SCADA data regression analysis in this study.
ii. Average Wind Speed & Wind Power Production and Time & Average Temperature are found to be the most suitable correlations.
iii. Average Wind Velocity and Wind Power Production have the same trends over time (positive correlation), but the Average Temperature has the opposite trend with them (negative correlation);
iv. Windrose analyses show that for Nygårdfjellet Wind Park, West↔East wind direction is the most common wind direction.
v. In 2013, 2014 and 2015, turbine 4531, 0574 and 4531 got the maximal wind power production respectively; In 2013, 2014 and 2015, turbine 4537,4540 and 0575 got the minimal wind power production respectively;
vi. In 2014, the total wind energy got the most, which is 589.719 Gw; turbine 4531 produced the most wind power during 2013-2015.

Below are some issues experienced during SCADA data sorting and analysis:

i. Row database from Nygårdfjellet wind park has some missing items, so Excel combination and MATLAB importation should do some numerical format change;
ii. Data '0' and 'NONE' have different meaning. '0' means that the sensor may have no data import but it worked. 'NONE' means that the turbine is probably logged or no data collection;
iii. In 2015 turbine 01 (0375), the goodness of fit of the Average Wind Velocity & Wind Power Production curve is just 30%. The reason may be too many missing items, which requires specific research afterwards;
iv. In 2015 turbine 02 (0374), the plot of Average Wind Velocity & Wind Power Production has data exception situation: Normally wind power production could be around 0 to 2290, but in this case, its range is just 0 to 20. The reason may be that the sensor in turbine 02 has some measurement or detection problems.

5 Numerical Simulations

The wind resource assessment most commonly uses microscale and mesoscale models. Microscale is the scale applicable order of 100 Km. In other words, microscales are used to show wind resource assessment over large areas, which can cover hundreds of square kilometres. Mesoscale describes the meteorological phenomena with 20 to 2000 Km spatial resolution. Moreover, the temporal resolution ranges from hours to days. Computational Fluid Dynamics (CFD) based microscale approach can simulate airflow behaviour over complex terrain, including thermal effects. It can be done by solving the Navier-Stokes equation, which is a nonlinear problem [21]. Three main inputs for CFD model are: elevation (digital terrain model), roughness map and stratification (wind data at multiple locations in a period) as shown in Figure 5-1[22].

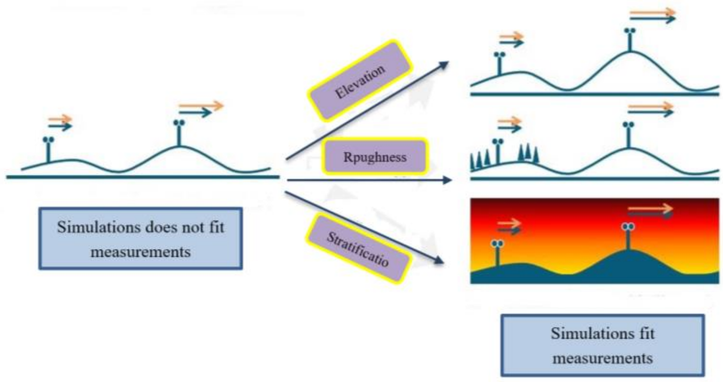


Figure 5-1 CFD simulation approach [22]

For this master thesis work we have used ‘WindSim’ software which is a modern Wind park Design Tool (WFDT) that helps to optimize the wind parks energy production within acceptable limits by using non-linear mathematical methods. One year SCADA data (2014) for 14 wind turbines of Nygårdsfjellet Wind Park have been used for this study. Table 5-1 shows the main inputs required to setup the WindSIM simulations.

Input Files	Significance
.gws	Grid WindSim File
.wws	Climatology File
.pws	Power WindSim File
.ows	Object WindSim File

Table 5-1 WindSim main input files

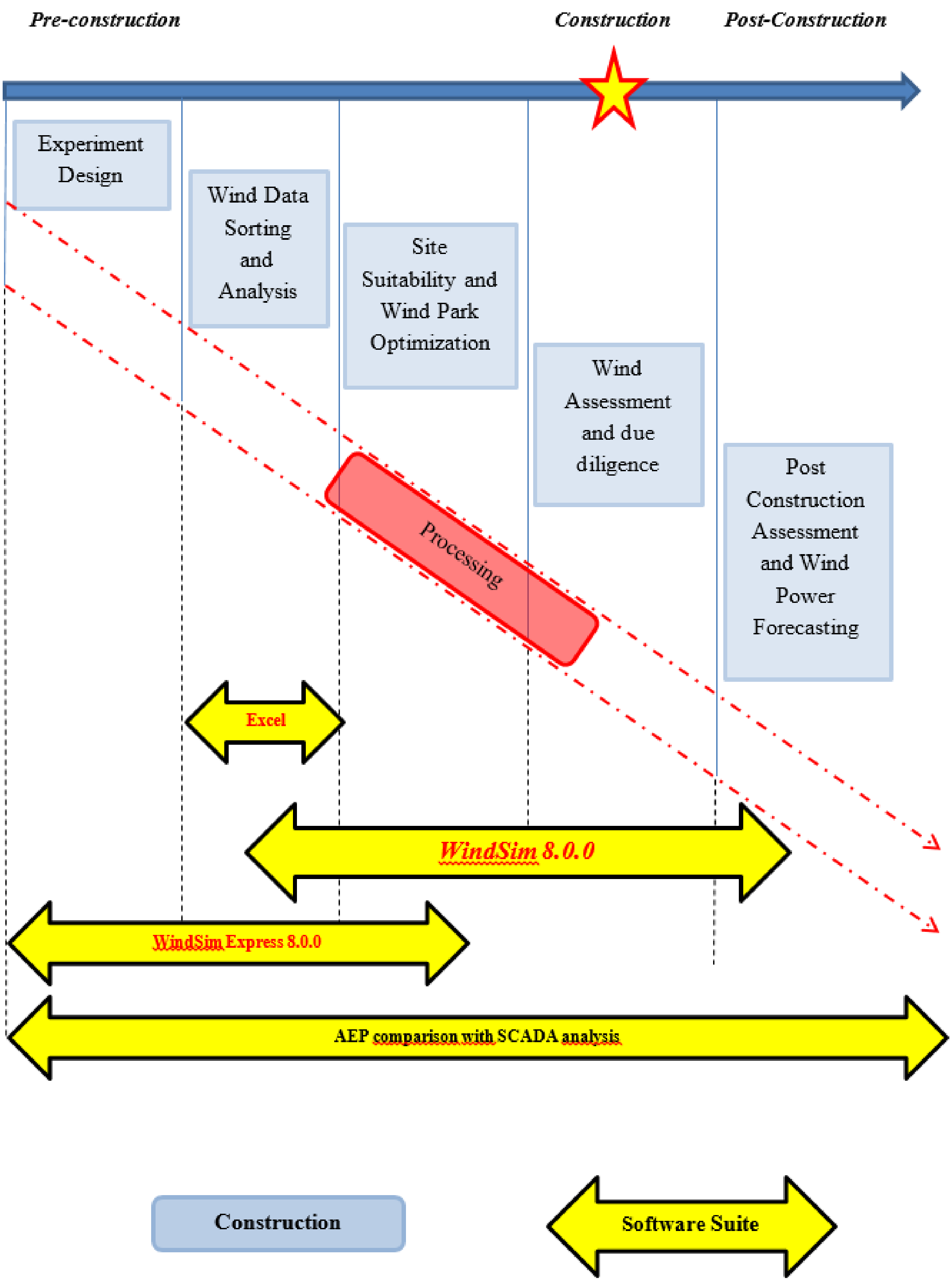


Figure 5-2 WindSim simulation structure

5.1 CFD software- WindSim

Four main inputs are required for WindSim 8.0.0 CFD simulations: *'.ows', '.gws', '.pws', '.wws'.* Among them, '.pws' is built from Nygårdfjellet Nordkraft Vind Company based on real wind product condition; '.ows' and '.gws' files could be built with WindSim Express 8.0 at the same time; '.wws' could be built in Excel and then put into Notepad. WindSim is a new climatology Wind park Design Tool (WFDT) to optimize the energy production for target wind park design. Moreover, it can generate a digital terrain, which is called micro-siting numerical wind fields. The modules in WindSim are Terrain, Wind Fields, Objects, Results, Wind Resources and Energy. A complete micro-siting process needs to finish all these six modules in turn as shown in Figure 5-3 from left to right.

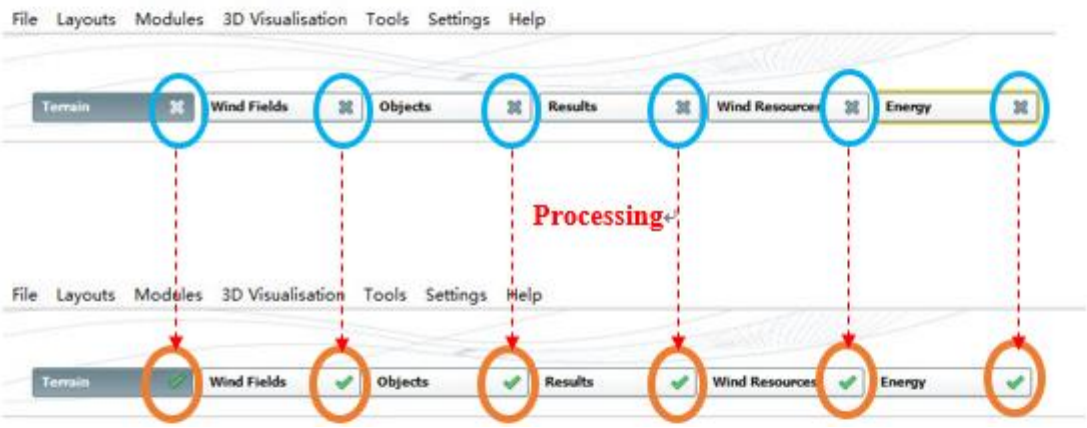


Figure 5-3 WindSim modules processing

The functions of those six modules are:

a) **Terrain**—establish the numerical model based on the data of elevation and roughness;
b) **Wind Fields**—calculation of the numerical wind parks model;
c) **Objects**—set up and process the climatology database and wind turbines;
d) **Results**—analyze numerical wind parks;
e) **Wind Resources**—through statistical methods, using climatology data and numerical result from wind parks to provide Wind Resources maps.
f) **Energy**—through statistical methods, using climatology data and numerical result from wind parks to calculate Annual Energy Production (AEP), contains wake loses. Moreover, make sure the characteristic for wind turbine loads.

For the WindSim 8.0.0 simulation of Nygårdfjellet wind parks, following steps have been used for the six modules.

1. Create a new project named Nygardfjellet, give a name of layout and then define customer. In addition, choose '.gws', which is created from WindExpress (shows as 5.1.2). Click 'ok'. As Figure 5-4 shows.

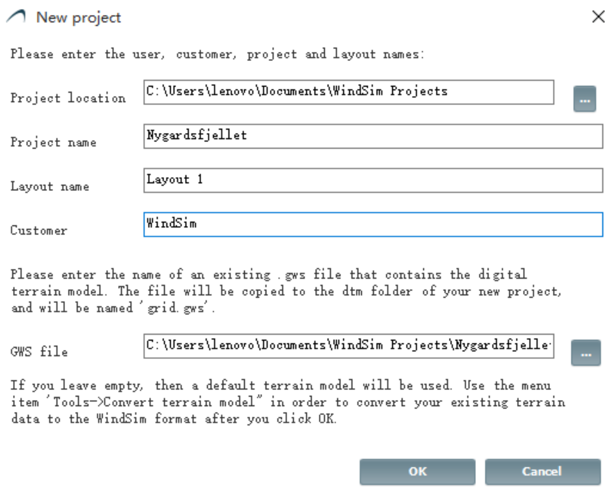


Figure 5-4 Create new project in WindSim

2. Change the properties as Figure 5-5 shows. The terrain extension values need to contains Nygårdfjellet wind parks region. In this projectwind park, the roughness and elevation are chosen from the grid generated from WindSim Express. The number of cells in Z direction is the default number 20.

Figure 5-5 Properties setup in terrain module

3. In Wind Fields module, choose 12 for the number of sectors and uniform distribution of the sector angles for the input type, and 300 meters of boundary layer height, wind parkbased on the actual conditions of the wind parks. In addition, in physical models, for the turbulence model choose 'RNG k-epsilon', because ReNormalization Group (RNG) modifies standard k-ε model. The range of iteration number is from 100 to 1000. Choose 500 as Nygårdfjellet wind parks simulation iterations and 0.0001 as convergence criteria standard in this model. The General Collected Velocity method (CGV) solar chosen from parameter calculation have two features: First, CGV methods could use a block-structured multi-block formulation; second, CGV can handle highly non-orthogonal girds that could cover angles as small as 10 degrees and does much better than separation solver. It is worth emphasizing that convergence monitoring X and Y spot values are the centre points of the ranges of X and Y from step 2, which are defined in terrain extension model. The properties setup in Wind Files module is shown as Figure 5-6.

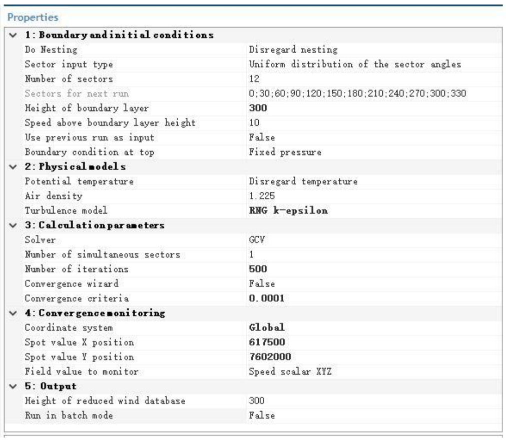


Figure 5-6 Properties setup in Wind Fields module

4. The Object module is used to position wind turbines and transfer climatology. . Climatology object needs to be built in the start. In this project, choose turbine 0575 as climatology object. Shows as Figure 5-7. See Section 5.1.3 for how to build the climatology files (‘wws’). 14 turbines in Nygårdfjellet wind parks are transferred to this climatology object.

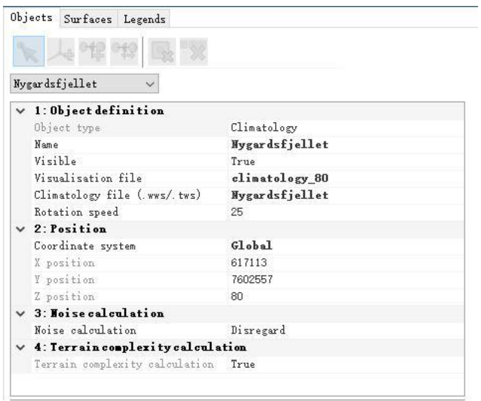


Figure 5-7 Climatology object built

5. Once the climatology is built (in step 4) and the 14 turbines are transferred from WindSim Express (see following section 5.1.2), we can set up the objects as Figure 5-8 shows.

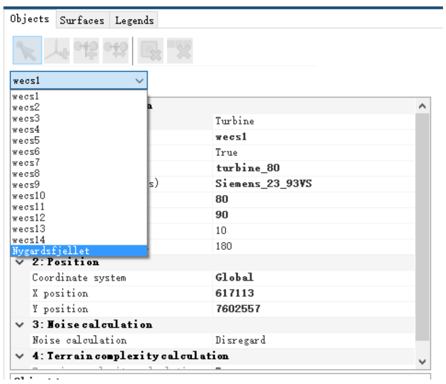


Figure 5-8 Climatology and 14-transfer climatology objects setup

6. The results of wind fields are stored in a database which could keep wind data from ground to the ‘Height of reduced wind database’. Choose ‘Speed scalar XYZ’ in normalisation variable and planers heights are 60 and 80 meters. The properties are shown in Figure 5-9.

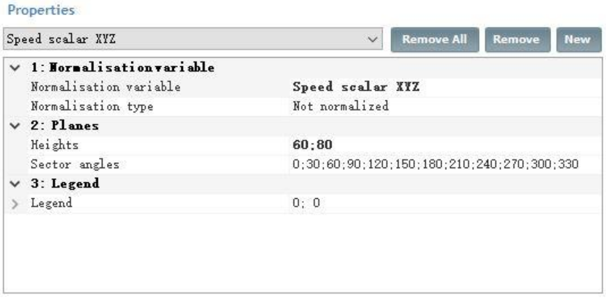


Figure 5-9 Properties setup in Objects module

7. In the Wind Resources module choose Wake Model 1—‘Jensen model’[30], which leads the wake decay factor to increase with increasing level of ambient turbulence whose typical range is from 0.04 to 0.075. The properties are shown in Figure 5-10.

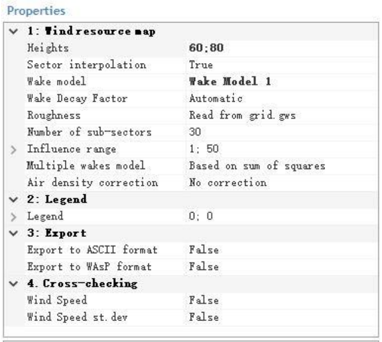


Figure 5-10 Properties setup in Wind Resources module

8. In Energy Module, choose Wake Model 1 as in step 7. The heights of reference product are 60, 80 and 100 meters. 80 meters is the climatology Wind turbine’s position. The properties are shown in Figure 5-11.

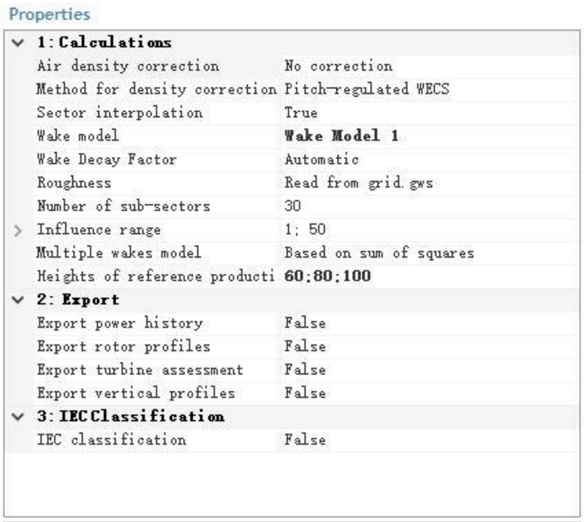


Figure 5-11 Properties setup in Energy module

5.1.1 WindSim Express

WindSim Express accompanies WindSim to create CFD model-based micro-siting procedures. We use it to create the '.ows' file (obtain '.gws' file) which will be imported to WindSim to complete CFD modules.

1. Open 'WindSim Express 8.0' software and click 'Next' bottom in the right corner, as Figure 5-12 shows.

Figure 5-12 Start WindSim Express

2. Create a new project in 'WindSim project' which is located at C Disk (the same disk as WindSim builder is), define layout and customer and then click 'Next' as Figure 5-13 shows.

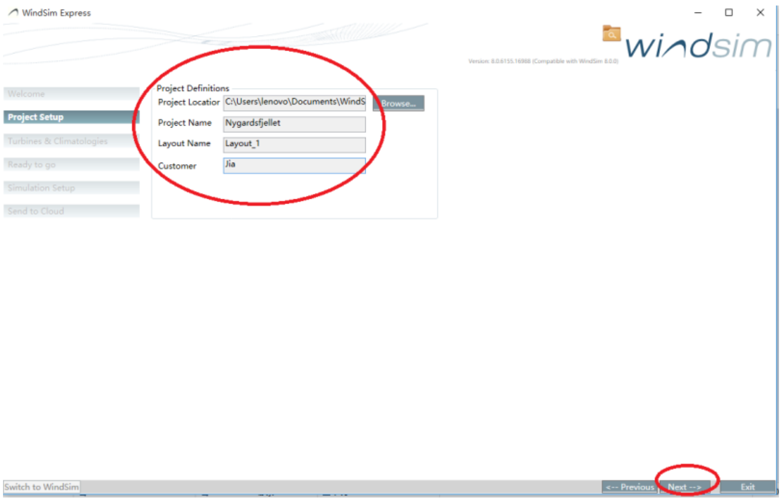


Figure 5-13 WindSim project

3. Build '.ows' files in layout. Choose '.pws' files which is from Nygårdfjellet Nordkraft Vind Company. Define the turbine height as 80m, and the rotator diameter as 90m. Select UTM 33 zone in Coordinate Systems (datum is WGS84 and the units is METERS) and input 14 turbines' coordinates. Click 'Ok'. See Figure 5-14.

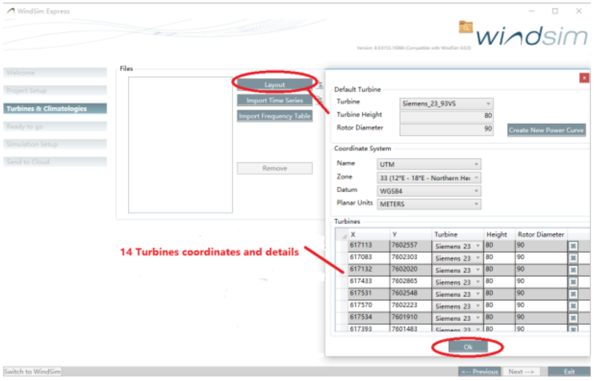


Figure 5-14 Object layout

4. After ‘ows’ files is built, choose map data source:
    a. Elevation—dataset from ‘ASTER.GDEM V2 Worldwide Elevation Data’;
    b. Roughness—dataset from ‘GlobCover ESA 2009 (Global Land Cover)’;
    c. Map Image—dataset from ‘World Imagery’;
    d. Chose ‘No’ at import map.

   Click ‘Next’ as Figure 5-15 shows.

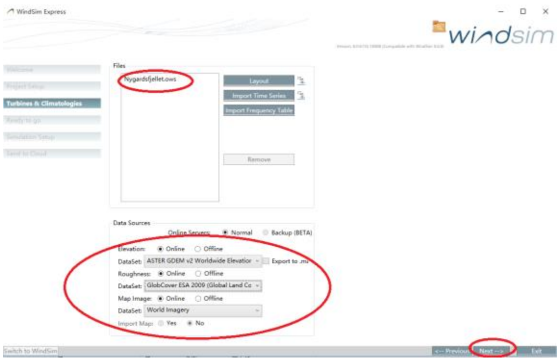


Figure 5-15 Map dataset

5. The simulated wind park which we build according to the parameters of Nygårdsfjellet wind park is shown (with an enlarged view of the selected area) in Figure 5-16. Click ‘Switch to WindSim’ bottom at left corner. (Alternatively, click ‘Next’ bottom at right corner and switch to cloud.)

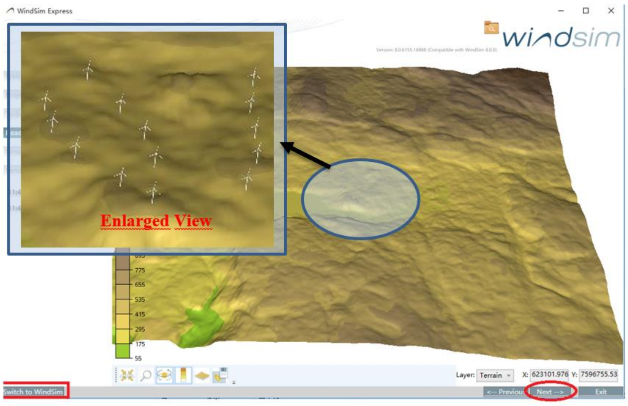
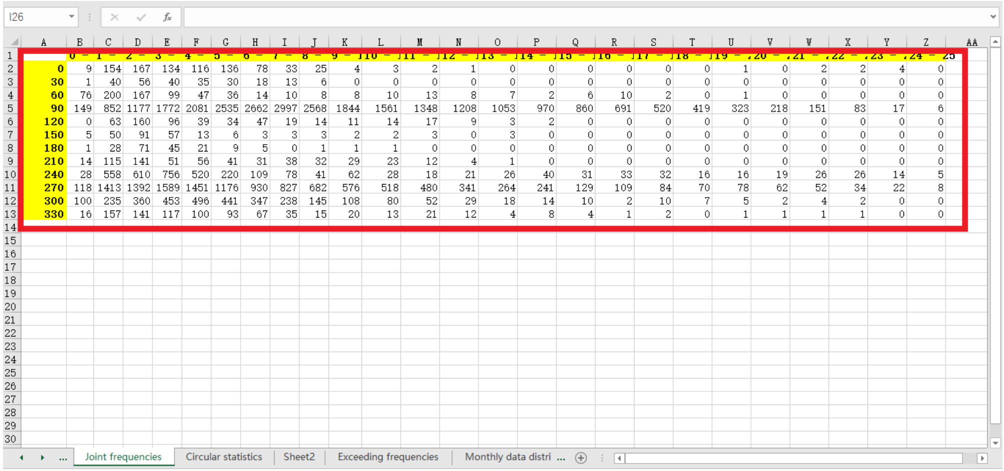


Figure 5-16 Nygårdsfjellet wind park

5.1.2 MS Excel to Notepad

The dataset output from WindRose PRO3 (in chapter 4) is of MS Excel format. We need to reorganize this dataset and generate 14 '.wws' files for the 14 turbines respectively. Here we take turbine 0575 for an example. Others turbine's '.wws' files are created in the same way.

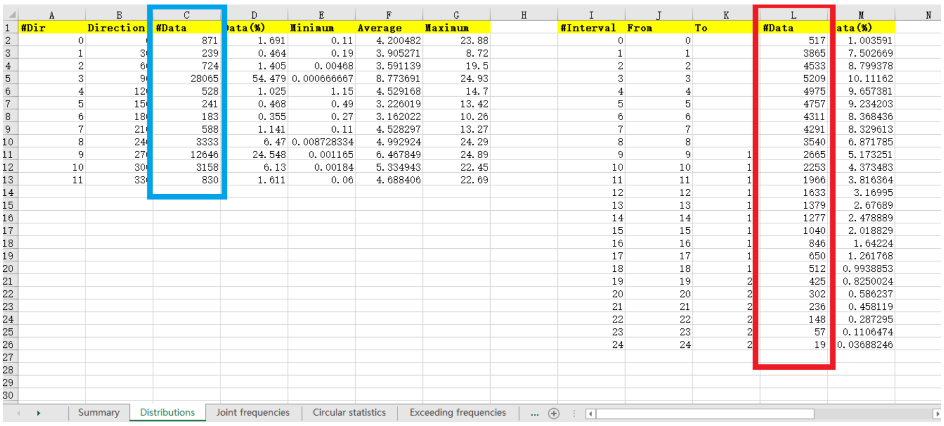
1. Copy 'Joint frequencies' and transpose to another Excel work sheet, shown as Figure 5-17.



	0 –	1 –	2 –	3 –	4 –	5 –	6 –	7 –	8 –	9 –	10 –	11 –	12 –	13 –	14 –	15 –	16 –	17 –	18 –	19 –	20 –	21 –	22 –	23 –	24 – 25
0	9	154	167	134	116	136	78	33	25	4	3	2	1	0	0	0	0	0	0	1	0	2	2	4	0
30	1	40	56	40	35	30	18	13	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	76	200	167	99	47	36	14	10	8	8	10	13	8	7	2	6	10	2	0	1	0	0	0	0	0
90	149	852	1177	1772	2081	2535	2662	2997	2568	1844	1561	1348	1208	1053	970	860	691	520	419	323	218	151	83	17	6
120	0	63	160	96	39	34	47	19	14	11	14	17	9	3	2	0	0	0	0	0	0	0	0	0	0
150	5	50	91	57	13	6	3	3	3	2	2	3	0	3	0	0	0	0	0	0	0	0	0	0	0
180	1	28	71	45	21	9	5	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
210	14	115	141	51	56	41	31	38	32	29	23	12	4	1	0	0	0	0	0	0	0	0	0	0	0
240	28	558	610	756	520	220	109	78	41	62	28	18	21	26	40	31	33	32	16	16	19	26	26	14	5
270	118	1413	1392	1589	1451	1176	930	827	682	576	518	480	341	264	241	129	109	84	70	78	62	52	34	22	8
300	100	235	360	453	496	441	347	238	145	108	80	52	29	18	14	10	2	10	7	5	2	4	2	0	0
330	16	157	141	117	100	93	67	35	15	20	13	21	12	4	8	4	1	2	0	1	1	1	1	0	0

Figure 5-17 Database in 12 wind directions and 25 different ranges of wind speed

2. Copy blue box of '#Data' as the sum of different directions (12 sectors), and copy red box of '#Data' as the sum of different ranges of wind speed (25 ranges) to the Excel created in step 1, as Figure 5-18 shows.



#Dir	Direction	#Data	ata(%)	Minimum	Average	Maximum
0		871	1.691	0.11	4.200482	23.88
1	3	239	0.464	0.19	3.905271	8.72
2	6	724	1.405	0.00468	3.591139	19.5
3	9	28065	54.479	0.000666667	8.773691	24.93
4	12	528	1.025	1.15	4.529168	14.7
5	15	241	0.468	0.49	3.226019	13.42
6	18	183	0.355	0.27	3.162022	10.26
7	21	588	1.141	0.11	4.528297	13.27
8	24	3333	6.47	0.008728334	4.992924	24.29
9	27	12646	24.548	0.001165	6.467849	24.89
10	30	3158	6.13	0.00184	5.334943	22.45
11	33	830	1.611	0.06	4.688406	22.69

#Interval	From	To	#Data	ata(%)
0	0		517	1.003591
1	1		3865	7.502669
2	2		4533	8.799378
3	3		5209	10.11162
4	4		4975	9.657381
5	5		4757	9.234203
6	6		4311	8.368436
7	7		4291	8.329613
8	8		3540	6.871785
9	9	1	2665	5.173251
10	10	1	2253	4.373483
11	11	1	1966	3.816364
12	12	1	1633	3.16995
13	13	1	1379	2.67689
14	14	1	1277	2.478889
15	15	1	1040	2.018829
16	16	1	846	1.64224
17	17	1	650	1.261768
18	18	1	512	0.9938853
19	19	2	425	0.8250024
20	20	2	302	0.586237
21	21	2	236	0.458119
22	22	2	148	0.287295
23	23	2	57	0.1106474
24	24	2	19	0.03688246

Figure 5-18 Choose sum of the data

3. Create a new Excel sheet and follow the steps shown in Figure 5-19. Region 1 is the dataset generated in step 1 and step 2. To create region 2 (region 3), we sum the data in each row (column) of region 1 and divide every element in region 1 by the sum of its row (column), i.e., normalize data with respect to wind speed (direction). Region 4 is final region that we use in '.wws' files. The region 4 is created with the data in region 1 divided by the sum of data. Check whether the numbers in the last row of region 4 sum to 1.

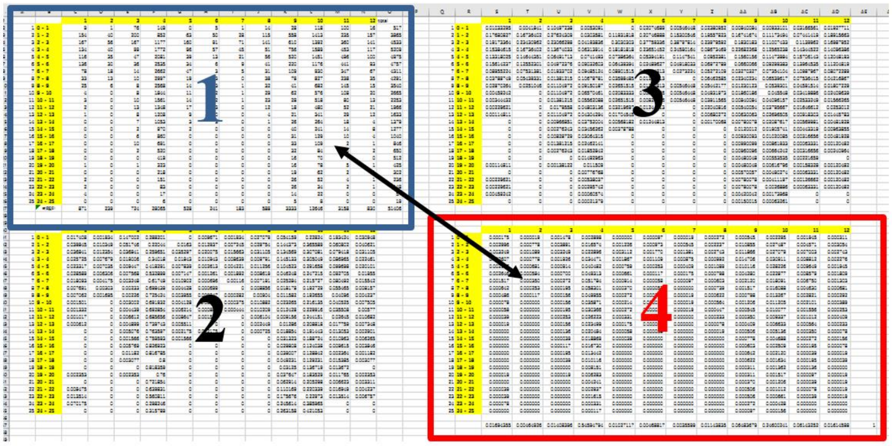


Figure 5-19 '.wws' sub model in Excel

4. Following the requirement in WindSim 8.0.0, the '.wws' files are created as Figure 5-20 shows.

```
version              : 43
site name            : Nygardsfjellet3
measurement period   : 01.01.14 - 31.12.14
site position        : 617132          7602020
coord. system        : 2
measurement height   : 80.0
number of sectors    : 12
number of bins       : 30
total records        : 0
```

		1	2	3	4	5	6	7	8	9	10	11	12
		0.009788	0.008460	0.008948	0.538450	0.022175	0.010179	0.003302	0.016216	0.024246	0.231127	0.105873	0.021237
1	0.00 - 1.00	0.000352	0.000274	0.000176	0.002286	0.000137	0.000000	0.000020	0.000059	0.000332	0.002462	0.002344	0.000313
2	1.00 - 2.00	0.002931	0.001583	0.003478	0.023816	0.004064	0.001504	0.000469	0.002032	0.004962	0.035226	0.015474	0.002931
3	2.00 - 3.00	0.003341	0.002012	0.002384	0.020045	0.004083	0.002130	0.001309	0.002384	0.004709	0.030654	0.016001	0.004279
4	3.00 - 4.00	0.001876	0.001250	0.001035	0.025653	0.003282	0.001446	0.000762	0.001778	0.004865	0.032569	0.015435	0.003067
5	4.00 - 5.00	0.000508	0.000742	0.000547	0.032041	0.001543	0.001094	0.000176	0.001192	0.004122	0.025867	0.016294	0.002735
6	5.00 - 6.00	0.000293	0.001016	0.000391	0.035324	0.001915	0.001680	0.000234	0.001465	0.001817	0.017877	0.012523	0.002462
7	6.00 - 7.00	0.000039	0.000918	0.000313	0.042259	0.001778	0.000938	0.000078	0.001465	0.000781	0.012367	0.009104	0.001485
8	7.00 - 8.00	0.000020	0.000469	0.000215	0.046538	0.001114	0.000742	0.000117	0.001153	0.000625	0.009417	0.006369	0.001270
9	8.00 - 9.00	0.000059	0.000176	0.000098	0.048922	0.000840	0.000449	0.000059	0.001114	0.000391	0.008186	0.003966	0.000606
10	9.00 - 10.00	0.000098	0.000020	0.000156	0.044135	0.000723	0.000059	0.000039	0.000606	0.000391	0.008010	0.002735	0.000645
11	10.00 - 11.00	0.000059	0.000000	0.000000	0.040286	0.000528	0.000039	0.000020	0.000723	0.000430	0.008675	0.002051	0.000488
12	11.00 - 12.00	0.000000	0.000000	0.000039	0.033604	0.000567	0.000020	0.000000	0.000684	0.000156	0.007229	0.001602	0.000215
13	12.00 - 13.00	0.000059	0.000000	0.000059	0.028974	0.000469	0.000020	0.000000	0.000567	0.000156	0.005588	0.000821	0.000098
14	13.00 - 14.00	0.000078	0.000000	0.000039	0.023093	0.000352	0.000000	0.000000	0.000391	0.000078	0.004748	0.000391	0.000098
15	14.00 - 15.00	0.000000	0.000000	0.000020	0.020045	0.000254	0.000039	0.000000	0.000117	0.000098	0.004572	0.000176	0.000234
16	15.00 - 16.00	0.000000	0.000000	0.000000	0.018580	0.000078	0.000000	0.000000	0.000137	0.000000	0.003888	0.000137	0.000117
17	16.00 - 17.00	0.000000	0.000000	0.000000	0.014829	0.000234	0.000020	0.000000	0.000020	0.000020	0.002481	0.000098	0.000039
18	17.00 - 18.00	0.000000	0.000000	0.000000	0.012543	0.000078	0.000000	0.000000	0.000039	0.000000	0.002110	0.000078	0.000020
19	18.00 - 19.00	0.000000	0.000000	0.000000	0.009808	0.000059	0.000000	0.000000	0.000020	0.000059	0.001758	0.000117	0.000020
20	19.00 - 20.00	0.000000	0.000000	0.000000	0.006838	0.000059	0.000000	0.000020	0.000117	0.000078	0.002051	0.000078	0.000020
21	20.00 - 21.00	0.000000	0.000000	0.000000	0.004572	0.000000	0.000000	0.000000	0.000117	0.000039	0.001661	0.000059	0.000059
22	21.00 - 22.00	0.000000	0.000000	0.000000	0.002579	0.000020	0.000000	0.000000	0.000039	0.000078	0.001309	0.000020	0.000020
23	22.00 - 23.00	0.000039	0.000000	0.000000	0.001133	0.000000	0.000000	0.000000	0.000000	0.000059	0.001114	0.000000	0.000020
24	23.00 - 24.00	0.000000	0.000000	0.000000	0.000371	0.000000	0.000000	0.000000	0.000000	0.000000	0.000801	0.000000	0.000000
25	24.00 - 25.00	0.000039	0.000000	0.000000	0.000176	0.000000	0.000000	0.000000	0.000000	0.000000	0.000508	0.000000	0.000000

Figure 5-20 '.wws' files

5.2 CFD simulation

CFD simulation has been carried out using WindSim for Nygårdsfjellet wind park. The simulated wind climate is contrary to the real wind climate in Nygårdsfjellet. The average wind conditions of Nygårdsfjellet wind park are used to calibrate wind resources and estimate annual energy production (AEP).

5.2.1.1 Local wind climatology

For wind climatology *Turbine 0575* of Nygårdsfjellet wind park is used (Table 5-2). Wind rose shown in Figure 5-21 (output from WindSim same as turbine 0575 wind rose shown in chapter 4), with the average wind speed distribution divided in wind direction (sectors) and velocity intervals (bins). The original wind speed is 1m/s per bins. Graphical wind rose shows all occurrences of wind speed above 16 m/s. The wind directions are divided into 12 sectors, where the first sector is pointed centre of north. In addition, the frequency distribution has been fitted to Weibull distribution, shown as Figure 5-22. Table 5-3 shows Weibull frequency distribution.

File name	Nygardsfjellet		
Time Period	01.01.14 to 31.12.14	-	
Position: easting, northing, z (agl)	617113.0	7602557.0	80.0
Average wind speed, Weibull k, A	7.52	1.62	8.43

Table 5-2 Climatology characteristics including average wind speed (m/s) for all sectors, Weibull shape (k) and scale (A) parameters for all sectors

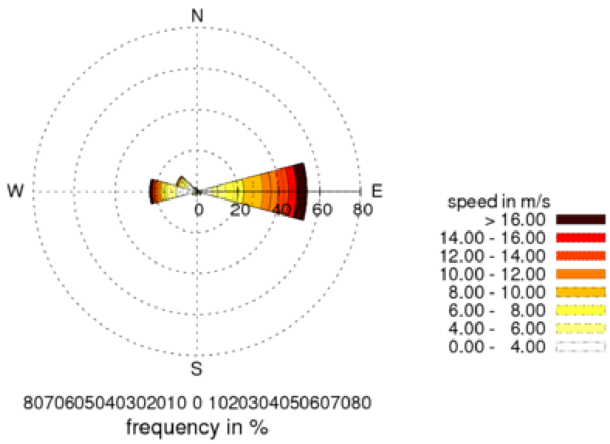


Figure 5-21 Wind Rose of climatology

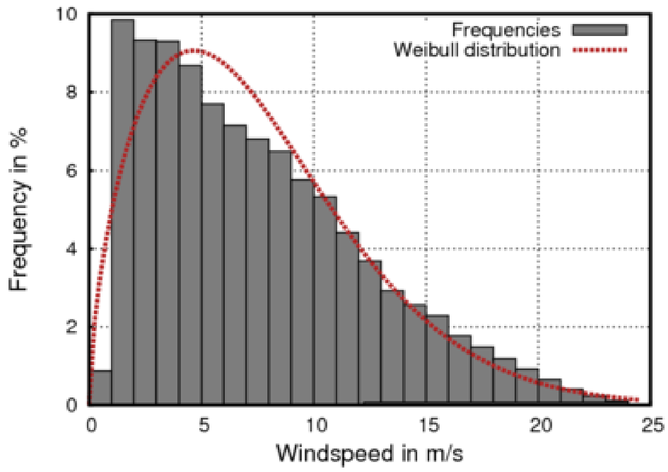


Figure 5-22 Frequency distribution with Weibull fitting

	1	2	3	4	5	6	7	8	9	10	11	12
Average wind speed (m/s)	3.01	3.78	3.07	9.29	5.17	4.38	3.51	6.20	4.09	6.32	4.68	4.78
Frequency (%)	0.98	0.85	0.90	53.85	2.22	1.02	0.33	1.62	2.42	23.11	10.59	2.12
Weibull shape, k	0.88	1.80	1.04	2.12	1.31	1.97	1.16	1.56	1.15	1.14	1.63	1.38
Weibull scale, A	2.61	4.14	2.69	10.50	5.46	4.98	3.27	6.94	4.12	6.16	5.19	5.10

Table 5-3 Average wind speed, frequency and Weibull shape (k) & scale (A) parameters versus sectors Wind parks layout and turbines

Nygårdsfjellet wind park layout is presented in figure 5-23. Turbine 0575 is used as climatology for this study.

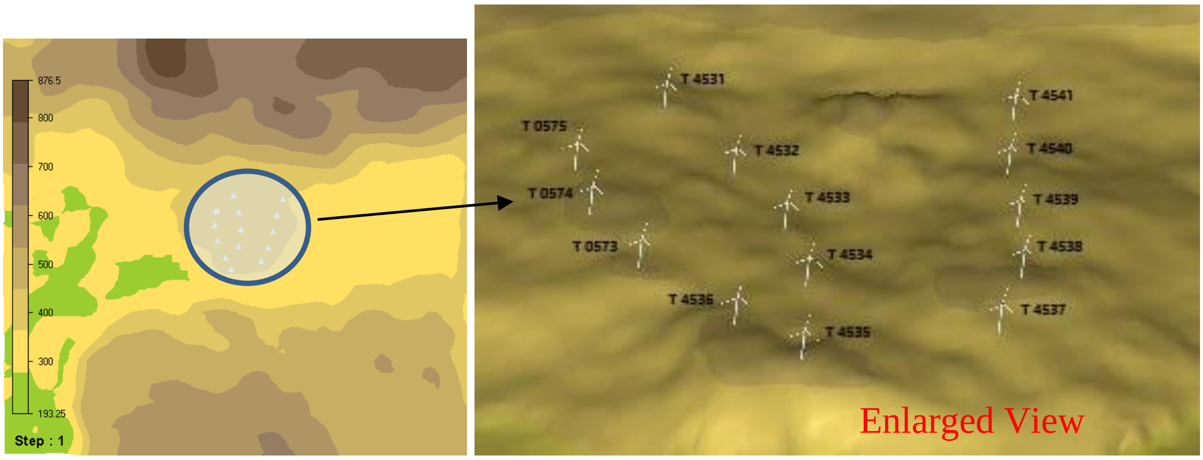


Figure 5-23 Nygårdsfjellet wind park 14 turbines layout

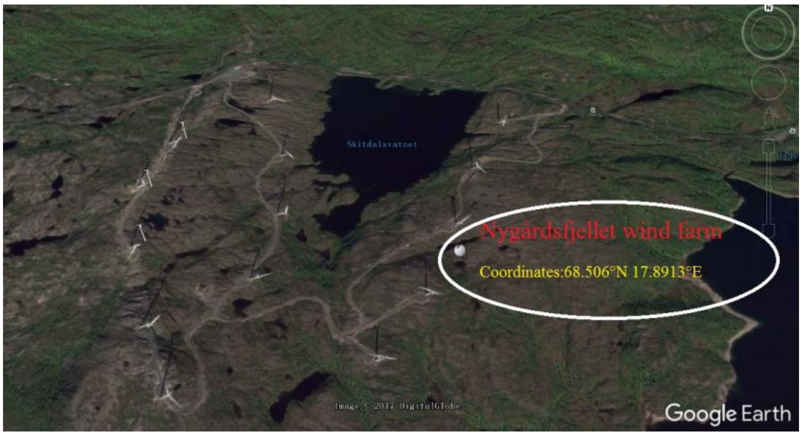


Figure 5-24 Google Earth map of Nygårdsfjellet wind park 14 turbines layout

Turbine	Turbine name	Turbine type	Hub height	East	North	z
0575	wecs1	SWT-2.3-93VS	80.0	617113.0	7602557.0	406.4
0574	wecs2	SWT-2.3-93VS	80.0	617083.0	7602303.0	415.1
0573	wecs3	SWT-2.3-93VS	80.0	617132.0	7602020.0	404.6
4531	wecs4	SWT-2.3-93VS	80.0	617433.0	7602865.0	395.7
4532	wecs5	SWT-2.3-93VS	80.0	617531.0	7602548.0	383.0
4533	wecs6	SWT-2.3-93VS	80.0	617570.0	7602223.0	385.6
4534	wecs7	SWT-2.3-93VS	80.0	617534.0	7601910.0	400.8
4535	wecs8	SWT-2.3-93VS	80.0	617393.0	7601483.0	404.6
4536	wecs9	SWT-2.3-93VS	80.0	617285.0	7601695.0	417.9
4537	wecs10	SWT-2.3-93VS	80.0	617950.0	7601635.0	391.1
4538	wecs11	SWT-2.3-93VS	80.0	618084.0	7601877.0	410.4
4539	wecs12	SWT-2.3-93VS	80.0	618174.0	7602185.0	395.9
4540	wecs13	SWT-2.3-93VS	80.0	618244.0	7602485.0	389.7
4541	wecs14	SWT-2.3-93VS	80.0	618358.0	7602797.0	370.1

Table 5-4 Wind turbine specifications

Turbine type	SWT-2.3-93VS	
Cut-in wind speed (m/s)	3m/s	
Cut-off wind speed (m/s)	25m/s	
Diameter (m)	90.00	
air density (kg/m3)	1.225	
Wind Speed (m/s)	**Power (kW)**	**Thrust Coefficient**
0.00	0.00	0.000
1.00	0.00	0.000
2.00	0.00	0.000
3.00	0.00	0.000
4.00	98.00	0.810
5.00	212.00	0.840
6.00	385.00	0.830
7.00	625.00	0.850
8.00	941.00	0.860
9.00	1350.00	0.870
10.00	1835.00	0.790
11.00	2223.00	0.670
12.00	2297.00	0.450
13.00	2299.00	0.340
14.00	2300.00	0.260
15.00	2300.00	0.210
16.00	2300.00	0.170
17.00	2300.00	0.140
18.00	2300.00	0.120
19.00	2300.00	0.100
20.00	2300.00	0.090
21.00	2300.00	0.070
22.00	2300.00	0.070
23.00	2300.00	0.060
24.00	2300.00	0.050
25.00	2300.00	

Table 5-5 Nygårdsfjellet wind park technical specifications

By using turbine SWT-2.3-93VS and importing the '.ows' files from WindSim Express 8.0.0, the turbine characteristics with power and thrust coefficient are shown as Figure 5-25.

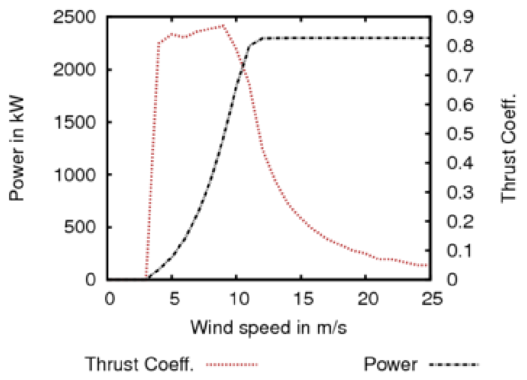


Figure 5-25 Turbine characteristics with power and thrust coefficient

5.2.2 Numerical simulation

In this section, we establish a CFD simulation model of the numerical wind database from Nygårdsfjellet Wind park, and explain how it is built, simulated and validated. This numerical simulation is used to study the wind condition from the measurement point to the position of wind turbine hub.

5.2.2.1 Digital terrain model

As Figure 5-26 and Table 5.6 demonstrate, a digital terrain model with elevation and roughness data has been established for the area.

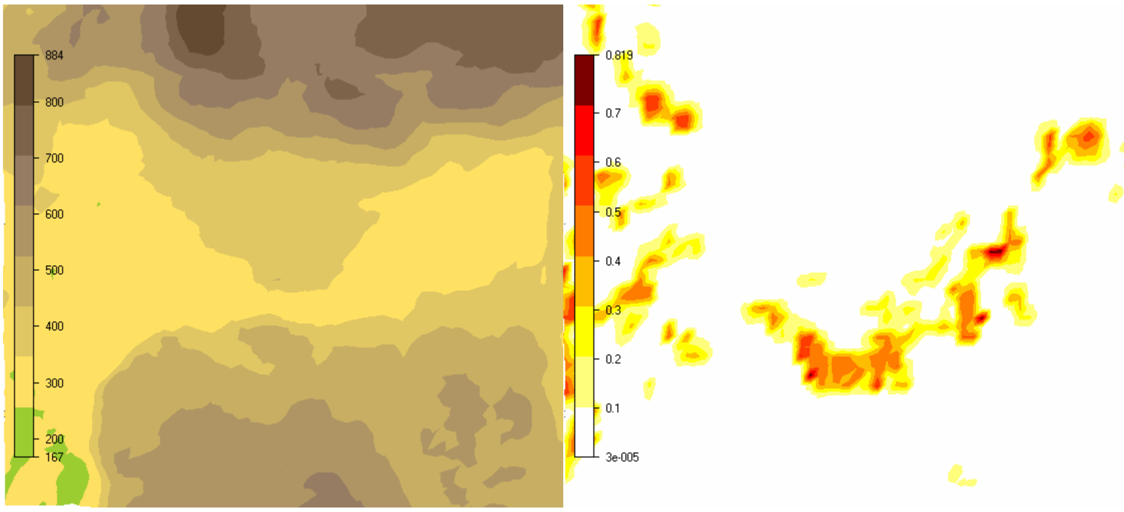


Figure 5-26 Terrain elevation (m) (left) and roughness (m) (right)

	Min (m)	Max (m)	Extension (m)	Resolution Terrain Data (m)
East (m)	612971.0	621950.0	8979.0	38.0
North (m)	7597858.0	7605924.5	8066.5	38.0

Table 5-6 Digital terrain model referring to coordinate system

The coordinate system is UTM and in 33 zone (Datum: WGS84), which is the coordinate system in Google Earth. In Nygårdsfjellet project, choose ASTER GDEM v2 as the elevation data map and GlobCover ESA 2009 (Global land Cover -300m Resolution) as roughness data map. The complexity of wind park site depends on the change of elevation and roughness data. The Terrain inclination and logarithmic roughness are shown as Figure 5-27.

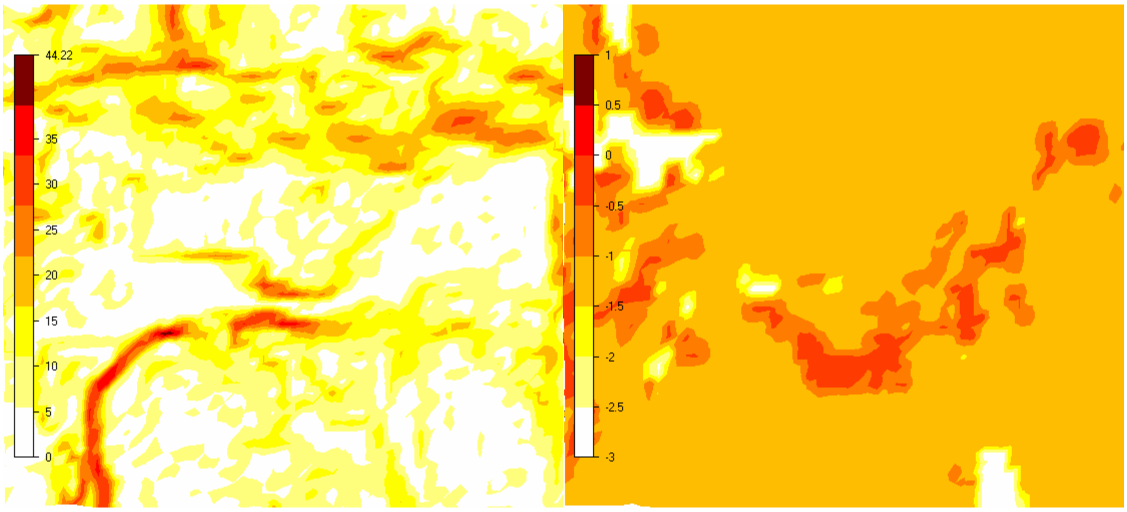


Figure 5-27 Terrain inclination (deg) (left) and logarithmic roughness (m) (right)

5.2.2.2 3D model setup

The elevation and roughness model defined above is also used to define the 3D ground level that is divided in 20 cells (*could be a variable vertical and horizontal resolution*), shown as Table 5-7. The grids are generated and optimized from digital terrain model as Figure 5-28.

	East	North	z	Total
Grid spacing (m)	152.2-152.2	152.2-152.2	Variable	-
Number of cells	59	53	20	62540

Table 5-7 Grid spacing and cells

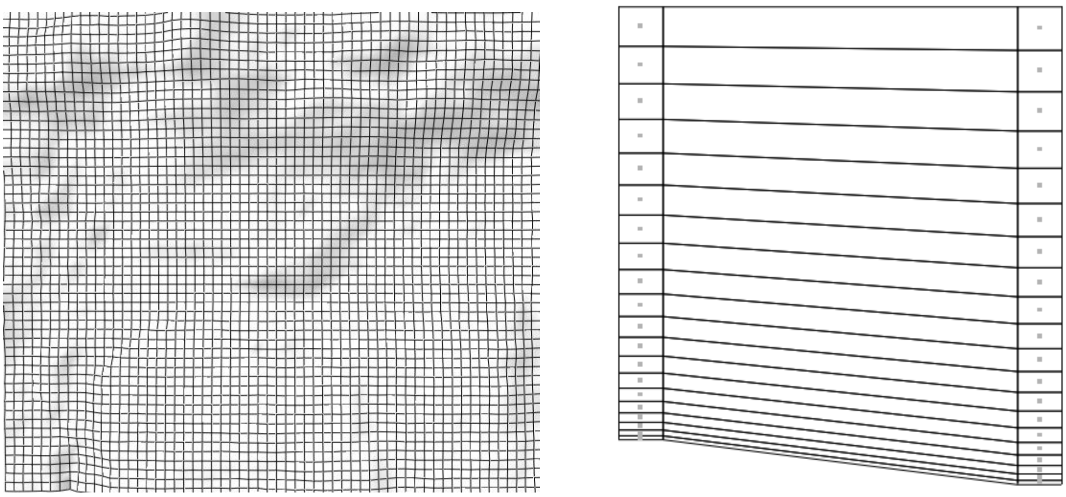


Figure 5-28 Horizontal grid resolution (left) and schematic view of the vertical grid resolution (right)

The grids maximum and minimum of the points' elevation could be displayed in a schematic view of the distribution. Distribution of elevation of the first 10 nodes in z-direction, relative to the ground, are shown in Table 5-8.

	1	2	3	4	5	6	7	8	9	10
z-dist. max (m)	31.4	109.0	216.4	353.6	520.4	717.0	943.4	1199.5	1485.3	1800.8
z-dist. min (m)	34.6	120.4	238.9	390.3	574.5	791.5	1041.3	1324.0	1639.5	1987.8

Table 5-8 Elevation of first 10 nodes in Z direction

The open area between the ground and upper boundary is calculated as the model is traversed in west-east and south-north direction. The maximum area is displayed as black rectangles while a red profile displays the ground level of the minimum area. The upper plot is for the traverse in west-east direction and the lower plot for the traverse in south-north direction. If the fraction between the minimum and maximum of the open area becomes too small, blocking effects might lead to unphysical speed-ups. See Figure 5-29 and Table 5-9 below.

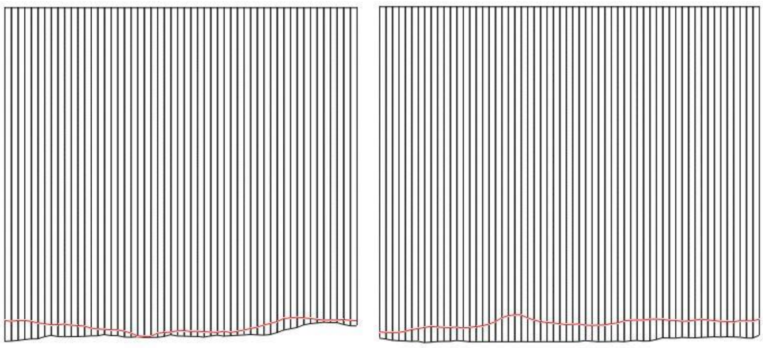


Figure 5-29 3D model open area

	Min (m²)	Max (m²)	Min/Max
Open area, west-east traverse	59381680	60093176	0.9882
Open area, south-north traverse	63710020	67162960	0.9486

Table 5-9 Open area data

5.2.2.3 Numerical Simulation

For numerical simulation, a model that represents the Reynolds averaged Navier – Stokes equation has been solved numerically as Table 5-10 sets. Totally, 12 simulations have been performed and every 30 degree sector has a 3D wind fields. The number of iteration and simulation time are shown as Table 5-11.

Height of boundary layer (m)	300.0
Speed above boundary layer (m/s)	10.0
Boundary condition at the top	fix pres.
Potential temperature	No
Turbulence model	RNG k-e
Solver	GCV
Maximum iterations	500

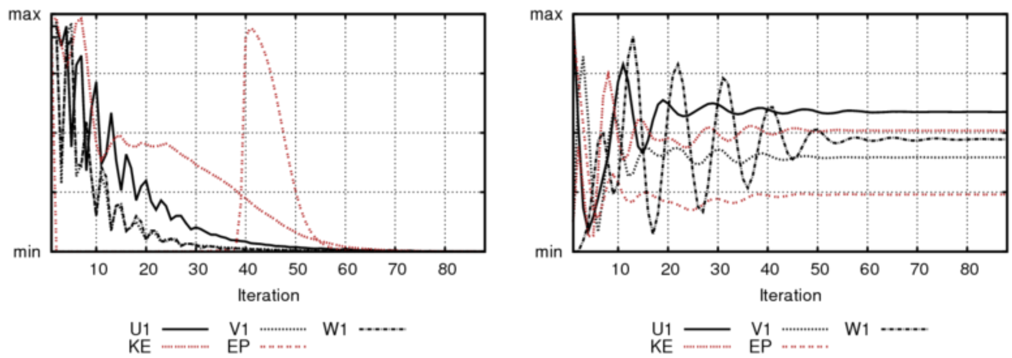
Table 5-10 Solvers settings

Sectors	Simulation time	Iterations	Status	Sectors	Simulation time	Iterations	Status
000	00:01:39	88	C	180	00:01:43	94	C
030	00:01:40	90	C	210	00:01:32	82	C
060	00:01:37	88	C	240	00:01:35	85	C
090	00:01:47	97	C	270	00:01:48	98	C
120	00:01:44	84	C	300	00:01:45	84	C
150	00:01:41	85	C	330	00:01:41	84	C

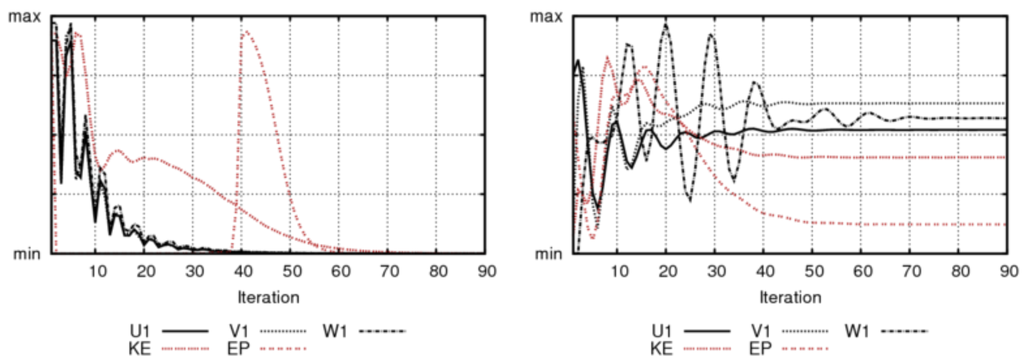
Table 5-11 Simulation time, number of iterations and convergence status

In Table 5-11, Status 'C' means the numerical procedure has converged. It means this solution is an actual solution of our specified problem. If the status shows 'D' for divergence or a '-', it indicates that the solution procedure has reached the maximal number of interactions before convergence. In order to assess the convergence of Nygårdsfjellet wind field, we need to check the spot and residual values of velocity components (U1,V1,W1), the turbulent kinetic energy (KE) and its dissipation rate (EP). According to the maximum and minimum, all the variables are scaled during the simulation. The simulation stops automatically when the solution falls below a certain convergence criteria, and the solution is called to be convergent. The 12 spot values and residual values are shown in Figure 4-30 (1) to (12).

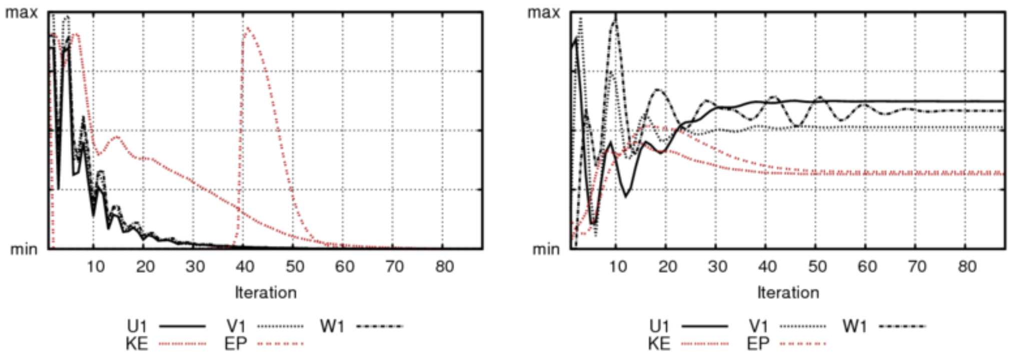
Figure 5 30 Spot values and residual values in assessment



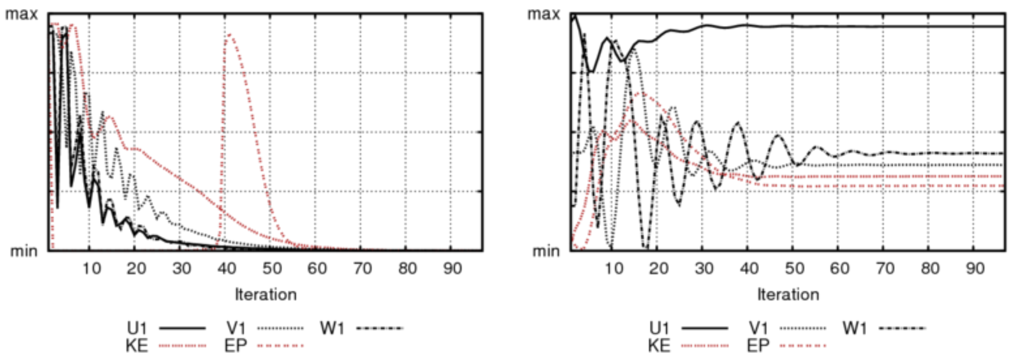
(1) Sector 000



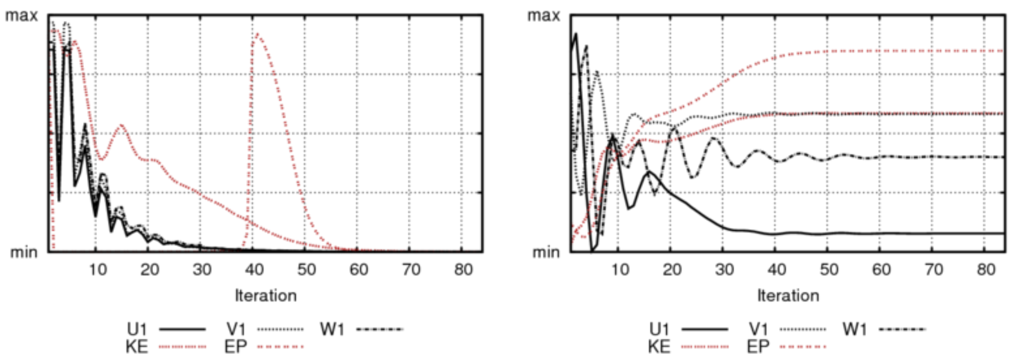
(2) Sector 030



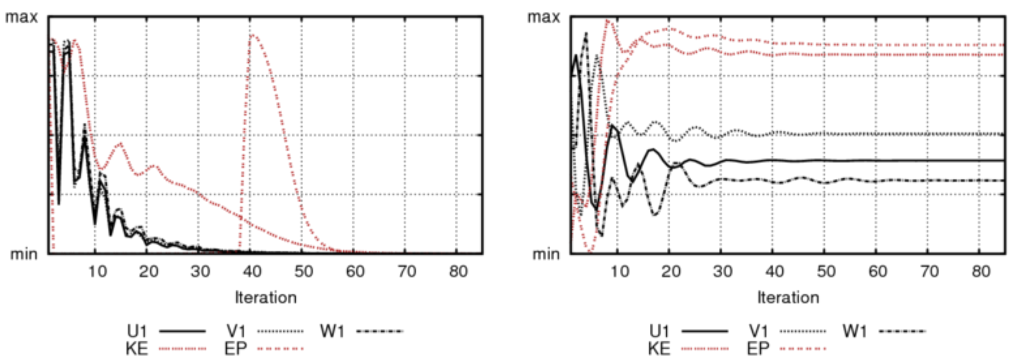
(3) Sector 060



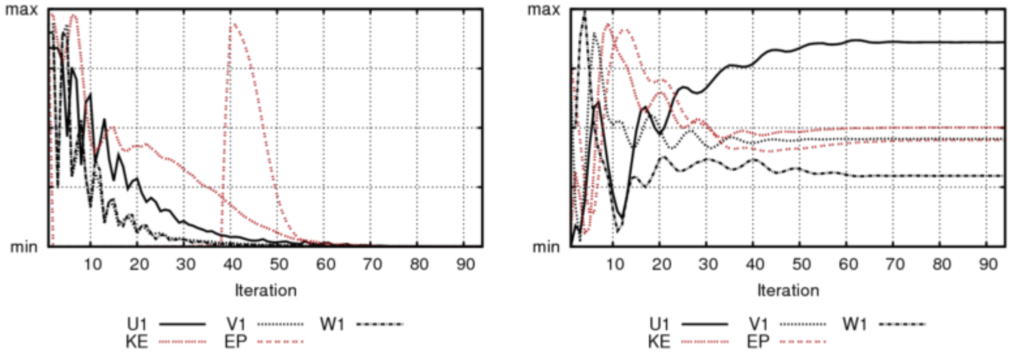
(4) Sector 090



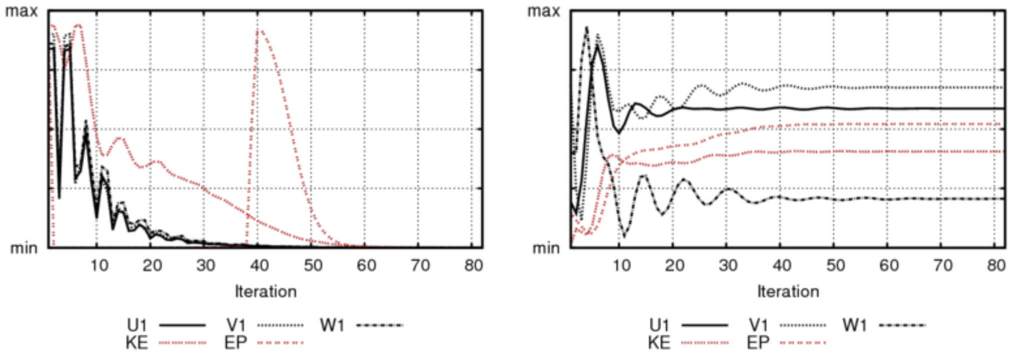
(5) Sector 120



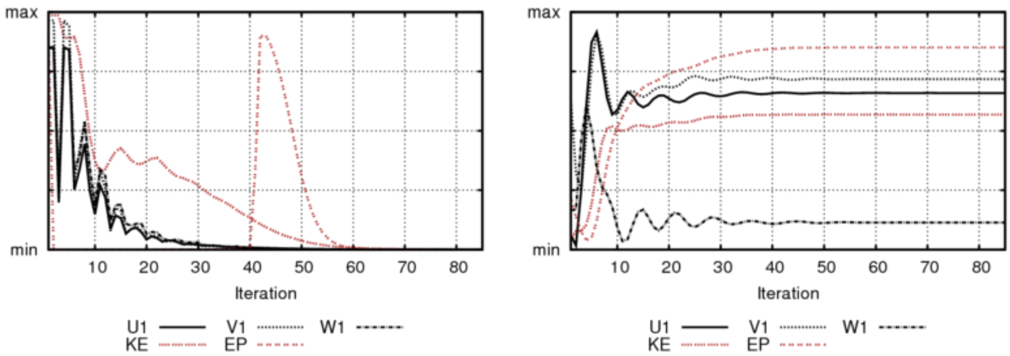
(6) Sector 150



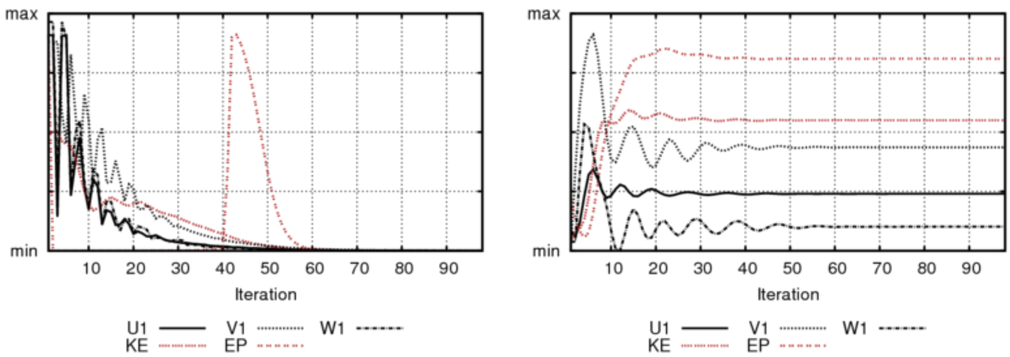
(7) Sector 180



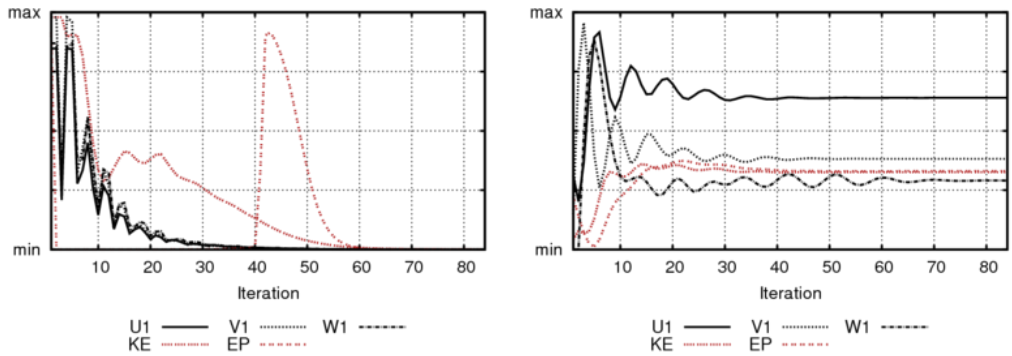
(8) Sector 210



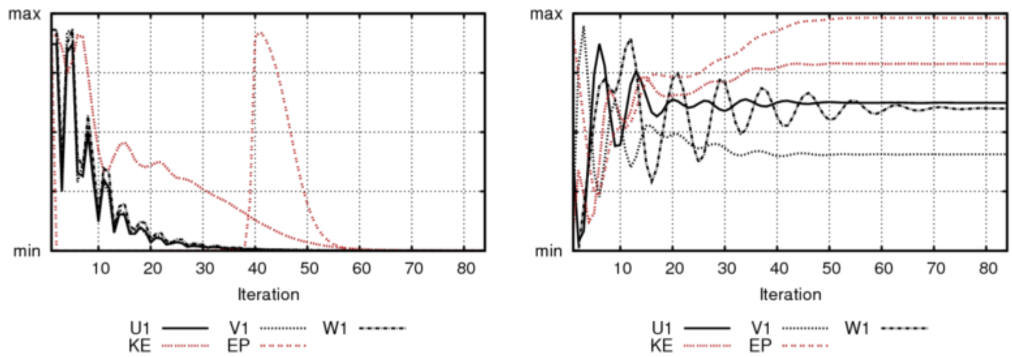
(9) Sector 240



(10) Sector 270



(11) Sector 300



(12) Sector 330

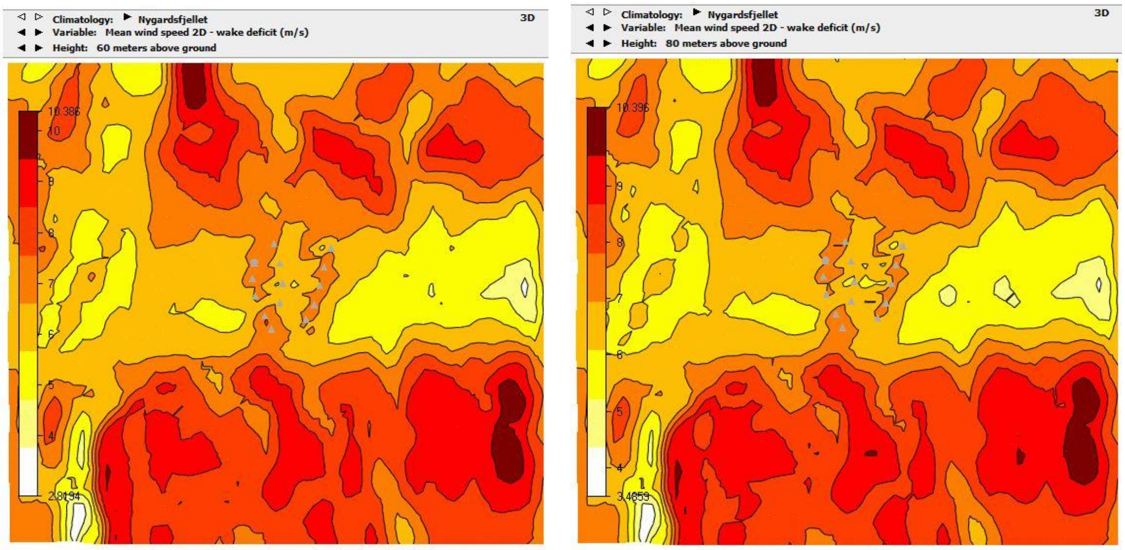
5.2.3 Annual Energy Production (AEP)

The Annual Energy Production (AEP) is the most significant parameter estimated in the majority of wind parks micro-siting projects. According to long term on-site wind production and CFD resolutions, the wind resource map and the AEP have been calculated.

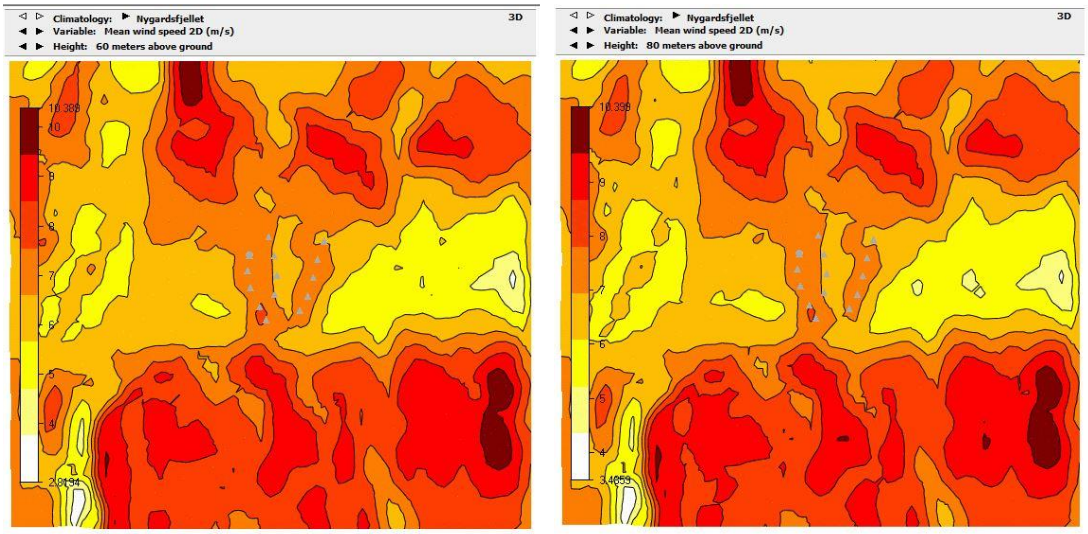
5.2.3.1 Wind resource map

Based on the average wind velocity, wind resource map identifies high wind velocity regions. Combining CFD solution and the expected average conditions of wind resources together can establish the wind resource map. In Nygårdsfjellet wind park simulation, two hub heights are used for comparison, 60m and 80m. The wind resources are shown as Figure 5-30 (1) to (3).

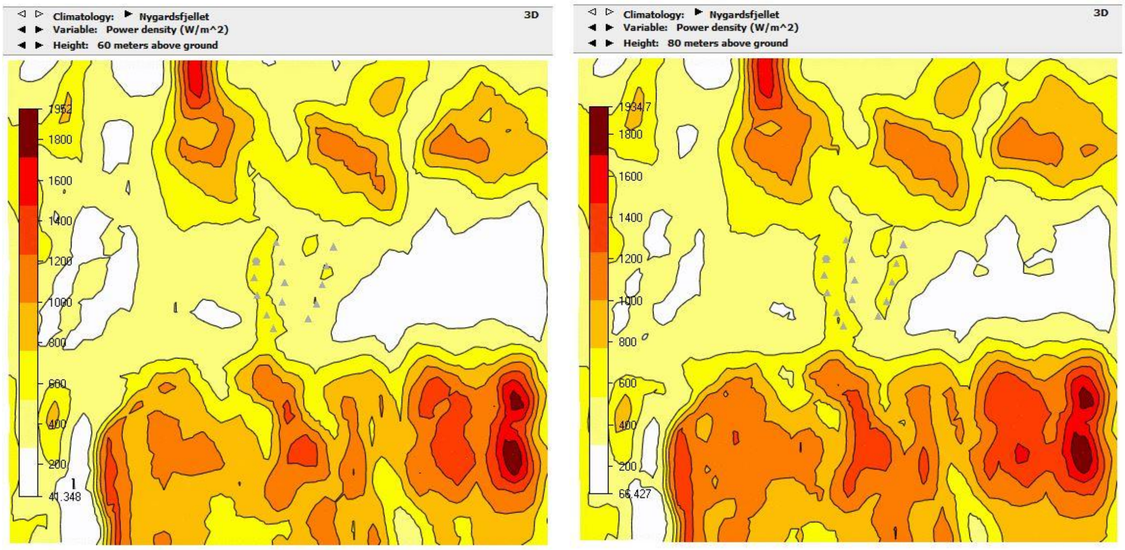
Figure 5-30 Wind resource map



(1) The wind resource map with average wind speed-wake deficit (m/s) at the hub height of 60m (left) and 80m (right) for Nygårdsfjellet wind park



(2) The wind resource map with average wind speed (m/s) at the hub height of 60m (left) and 80m (right) for Nygårdsfjellet wind park



(3) The wind resource map with power density (W/m^2) at the hub height of 60m (left) and 80m (right) for Nygårdsfjellet wind park

For a cross check in 'wind resources' part, we choose 80m as the hub height which wind turbines already use. Because only heights below the 'Height of reduced wind database' specified in the 'Wind Fields' module are valid, we choose 60 m as the hub height for comparison. From the above graphs, we can see:

1. The wind resource map with mean wind speed (with deficit or not) shows that the wind speed at the hub height of 80m is higher than that at 60m, and the high wind speed area is also larger at 80m;
2. The wind resource map with Power density (W/m^2) shows that at height 80m power production is higher than height 60m.

The main reason why 80m is much better in terms of wind resources lies in the atmospheric boundary layer effects. When the atmospheric boundary layer changes in different altitude, the wake effects vary, so the atmospheric boundary layers have effect on this wind resources result.

5.2.3.2 Energy production estimation

Gross energy production is calculated with the free stream wind velocity (or speed) distribution according to every turbine's hub height and power curve. The wake model 1 in WindSim could simulate the free stream wind speed distribution of wind flow model based on the actual long term conditions. In addition, the potential of Nygårdsfjellet Wind Park's energy production is obtained by considering the wake losses. Through WindSim CFD simulation, the characteristics of annual Nygårdsfjellet wind park production is shown as Table 5-12.

Turbine Type	Hub Height (m)	No. of turbines	Capacity (MW)	Gross AEP (GWh/y)	Average wind speed (m/s)	Wake losses (%)	AEP with wake losses (GWh/y)	Full load hours (hours)
SWT-2.3-93VS	80.0	14	32.2	106.7	7.2	7.0	99.3	3082.5

Table 5-12 Nygårdsfjellet wind park annual energy production

In addition, the frequency distribution of wind energy production wake losses is shown as Table 5-13.

Climatology name	Gross AEP (GWh/y)	AEP with wake losses (GWh/y)	Wake losses (GWh/y)	Wake losses (%)
Nygardsfjellet	106.689	99.256	7.433	6.967

Table 5-13 Nygårdsfjellet wind park frequency distribution

Moreover, through WindSim CFD simulation, the annual energy production of each turbine is also shown in Table 5-14.

Turbine name	Turbine type	Air density (kg/m3)	Average wind speed (m/s)	Gross AEP (GWh/y)	Wake Losses (%)	AEP with wake losses (GWh/y)	Full load hours (hours)
wecs1	SWT-2.3-93VS	1.225	7.520	8.106	15.150	6.878	2990.478
wecs2	SWT-2.3-93VS	1.225	7.520	8.104	9.739	7.314	3180.174
wecs3	SWT-2.3-93VS	1.225	7.260	7.750	8.544	7.088	3081.826
wecs4	SWT-2.3-93VS	1.225	7.210	7.664	5.009	7.280	3165.087
wecs5	SWT-2.3-93VS	1.225	6.740	6.975	9.793	6.292	2735.696
wecs6	SWT-2.3-93VS	1.225	6.590	6.738	11.543	5.960	2591.478
wecs7	SWT-2.3-93VS	1.225	6.830	7.090	12.352	6.214	2701.783
wecs8	SWT-2.3-93VS	1.225	7.680	8.347	3.761	8.033	3492.478
wecs9	SWT-2.3-93VS	1.225	7.730	8.398	7.643	7.756	3372.044
wecs10	SWT-2.3-93VS	1.225	7.030	7.419	3.147	7.186	3124.348
wecs11	SWT-2.3-93VS	1.225	7.240	7.707	3.902	7.406	3220.218
wecs12	SWT-2.3-93VS	1.225	7.160	7.589	3.369	7.333	3188.435
wecs13	SWT-2.3-93VS	1.225	7.220	7.693	2.473	7.502	3261.869
wecs14	SWT-2.3-93VS	1.225	6.830	7.110	1.376	7.012	3048.652

Table 5-14 Nygårdsfjellet wind park 14 turbines annually wind production

According to the CFD simulation, the annual energy production is 103.2 GWh/y with wake losses. Comparison with AEP from SCADA part in chapter 4 is shown in Table 5-15. The yellow regions are where the SCADA AEP is bigger than the gross AEP in CFD simulation, which means the actual wind energy production is ideal in turbine 0573, 4531, 4532, 4533 and 4541. With wake loss in CFD simulation, the orange regions show where the actual SCADA AEP is smaller than the AEP with wake loss, which means the annual power production in turbine 4535, 4536, 4537, 4538, 4539 and 4540 are not ideal in this regions, and need to change or rebuild the wind turbine sites to improve the actual wind power productions.

Turbine	Gross AEP (GWh/y)	AEP with wake losses (GWh/y)	SCADA AEP (GWh/y)	SCADA AEP/Gross AEP	Production loss 1	SCADA AEP/AEP with wake loss	Production loss 2
T0575	8.106	6.878	7.291	89.95%	10.05%	106.00%	-6.00%
T0574	8.104	7.314	7.955	98.16%	1.84%	108.76%	-8.76%
T0573	7.750	7.088	7.804	100.70%	-0.70%	110.10%	-10.10%
T4531	7.664	7.280	7.826	102.11%	-2.11%	107.50%	-7.50%
T4532	6.975	6.292	7.176	102.88%	-2.88%	114.05%	-14.05%
T4533	6.738	5.960	7.016	104.13%	-4.13%	117.72%	-17.72%
T4534	7.090	6.214	6.929	97.73%	2.27%	111.51%	-11.51%
T4535	8.347	8.033	7.253	86.89%	13.11%	90.29%	9.71%
T4536	8.398	7.756	7.605	90.56%	9.44%	98.05%	1.95%
T4537	7.419	7.186	6.713	90.48%	9.52%	93.42%	6.58%
T4538	7.707	7.406	6.941	90.06%	9.94%	93.72%	6.28%
T4539	7.589	7.333	7.208	94.98%	5.02%	98.30%	1.70%
T4540	7.693	7.502	6.893	89.60%	10.40%	91.88%	8.21%
T4541	7.110	7.012	7.709	108.42%	-8.42%	109.94%	-9.94%
Total	106.689	99.256	102.319	95.90%	4.10%	103.09%	-3.09%

Table 5-15 SCADA AEP compare with AEP in CFD model

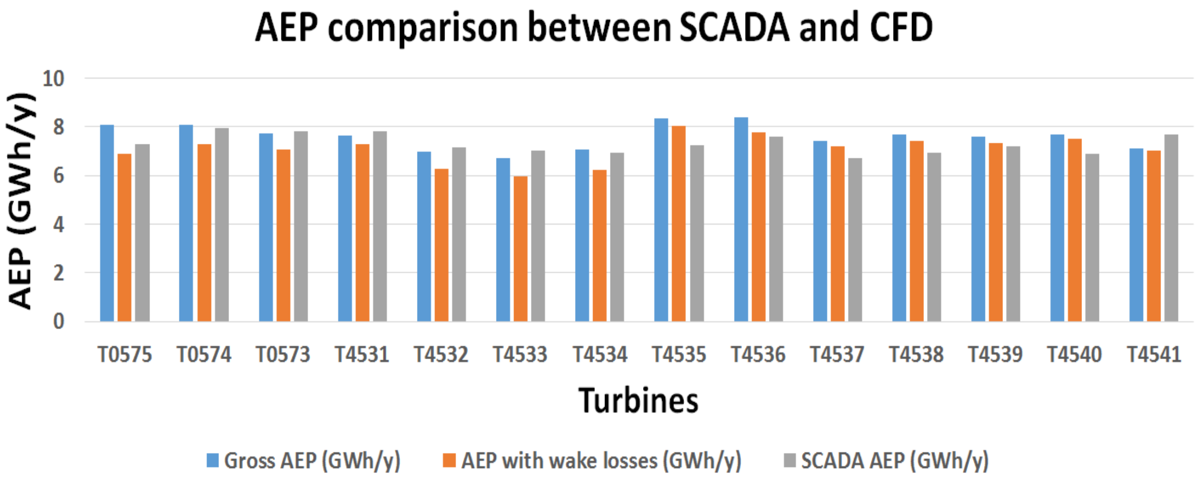


Figure 5-31 AEP comparison between SCADA and CFD

From this figure, we can easily compare the AEP of all 14 turbines in percentage. We can also compare SCADA AEP with gross AEP and AEP with wake loss. The trends show that SCADA AEP is in the middle of Gross AEP and AEP with wake loss in CFD simulation, in addition, AEP with wake loss is smaller than Gross AEP. In other words, it means SCADA AEP resolution is ideal.

5.3 Findings

WindSim has been used to do the CFD simulation of Nygårdsfjellet Wind Park for year 2014. Based on the methodology the numerical wind flow modeling is used to transfer the wind conditions from a spot value to the wind turbines position of hub height. Annual energy production estimation has been carried our in comparison with actual field SCADA data. A good agreement has been found between CFD simulations and actual wind production. In AEP estimation which has wake loss based on Jensen model [23], the AEP in 2014 is 103.2GWh/y with Jensen wake model losses (7% annually). Comparison between gross AEP and AEP with wake loss and the trends show that SCADA AEP/ Gross AEP is smaller than SCADA AEP/AEP with wake loss. In other words, it means AEP with wake loss is smaller than Gross AEP.

6 Conclusions & Future Work

6.1 Conclusions

This master thesis extends our understanding of the wind behavior in high latitude cold climate (HLCC) over complex terrain. The Nygårdsfjellet wind park, which is in high north regions of Norway, is the target site for the current research. We use 3 years (2013-2015)' data for all 14 turbines to do field SCADA data analysis and run CFD simulations. In this chapter, we conclude with a comparison between SCADA data analysis and CFD simulations.

a) SCADA data analysis:

With 3 years' data, we analyzed 4 major parameters: (1) Average wind velocity (m/s); (2) Average temperature (˚C); (3) Wind power production (kW); (4) Time series (10 mins) and do the comprehensive, horizontal and vertical cross-check respectively. We find out:

(1) Seventh (7^{th}) polynomial curve fitting is the best choice for wind park SCADA data regression analysis;
(2) The maximum power production from a wind turbine is recorded to be 2290kW;
(3) Average wind velocity and wind power production are positively correlated, but the average temperature are negatively correlated with them;
(4) There are two highly significant correlations among the 4 main parameters: one between average wind speed and wind power production, the other between average temperature and time (*nearly Normal Distribution*);
(5) From wind rose of Nygårdsfjellet wind park, the most common wind direction is from West to East;
(6) The three year's total power production is 1616.58GW. In 2014, the power production is the highest among these three years, 589.72 GW;
(7) As the reference, the annual energy production of Turbine 0575 (T01) in 2014 is 102.319 GWh/y.

b) CFD simulations:

In order to compare with field SCADA data analysis, we build a CFD model for Nygårdsfjellet wind park using the database from 2014. From CFD simulation, we find out:

(1) In Annual Energy Production (AEP) estimation with a wake loss model based on 'Jensen model', the AEP in 2014 is 103.2GWh/y for the reference turbine 0575 (T01);
(2) Based on the wake loss model, the energy production loss is 7% annually;
(3) SCADA AEP/ Gross AEP is smaller than SCADA AEP/AEP with wake loss. In other words, it means AEP with wake loss is smaller than Gross AEP.

(4) In 2013, 2014 and 2015, turbine 4531, 0574 and 4531 got the maximal wind power production respectively; In 2013, 2014 and 2015, turbine 4537,4540 and 0575 got the minimal wind power production respectively;
(5) In 2014, the total wind energy got the most, which is 589.719 Gw; turbine 4531 produced the most wind power during 2013-2015.

c) Comparison between SCADA and CFD results:

A comparison of AEP in the above two models leads to the following conclusions:

Ignoring the wake loss model, the real production from SCADA analysis is 95.90% of the ideal model in CFD simulation, but the energy loss is less than the simulation from the wake loss model 1 in WindSim (7% loss). That means the actual power production runs well.

6.2 Future work

There are some unsolved issues in this master thesis:

(1) Row database form Nygårdsfjellet Wind Park has some missing items. The reason may be that the wind speed is higher than 25m/s, the maximal wind speed which can be calculated. Another possibility is that the sensors in wind turbines have some problems so the data cannot be collected;
(2) The curve fitting for turbine 0575 using 2015 data performs much worse than for other turbines: the goodness of fit for both Average wind velocity & Wind power production is just about 30%. The reason may be too many missing items or technical issues;
(3) For the year 2015, the plot of turbine 0574 shows that the range of power production is from 0 to 20. The reason may be that the sensors in turbine 0574 have some measurement or detection problems.

There are many potential ways to extend our research in high north region’s wind assessment. Some of them are listed below:

(1) In this master thesis, SCADA data analysis and CFD simulation could be extended to meso-scale models, and compare meso-scale and micro-scale models;
(2) Other tools, like Weather Research and Forecast (WRF), can fulfill numerical weather forecasting as well. This master thesis does not use such tools for a cross check of wind assessment, which can be included in the future work;
(3) In this master thesis, we have mainly used the 2014 dataset in SCADA and CFD. In the future work, we can conduct SCADA and CFD simulations for 2013 and 2015 and compare the results from different years;
(4) SCADA data analysis of Nygårdsfjell wind park can be used to study the effect of wind park design layout on wind power production. We can focus on the relationship between energy production from each wind turbine and the environmental conditions like wind direction and temperature.
(5) For CFD simulations, we have only used model 1 ‘Jessen model’ for wake effects. In the future, we can choose other models to do simulation and compare their performance. This leads to a comprehensive CFD study of wake effects on wind power production;

(6) From AEP comparison between SCADA and CFD simulation, ice accretion may be a key factor in wind power production. In the future, could make some research in icing problems based on Nygårdsfjellet wind park;

6.3 Planned scientific publication

From this master thesis, I have a plan to publish 02 international journal papers:

1. Effect of wind park design layout on wind power production in high north.

This paper will include SCADA data analysis of wind power production of 14 turbines in Nygårdsfjellet Wind Park and will focus on highlighting that how energy production from each turbine in correlation to wind direction and temperature is being changed. The AEP calculation and comparison between 14 turbines from 2013 to 2015 will be used.

2. Wind resource assessment for a wind park in cold climate region.

This paper will include SCADA data analysis and CFD simulations result based on Nygårdsfjellet Wind Park actual database of year 2014. Comparative analysis of analytical and numerical techniques will be presented to estimate the annual energy production (AEP)

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