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Wind Energy Assessment using a Wind Turbine with Dynamic Yaw Control

Md Nahid Pervez
Grand Valley State University

Thesis Title Page

Wind Energy Assessment using a Wind Turbine with Dynamic Yaw Control

Md Nahid Pervez

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Dedication

This thesis is dedicated to my parents. There is no word that can describe their contribution to my life and success.

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Abstract

The goal of this project was to analyze the wind energy potential over Lake Michigan. For this purpose, a dynamic model of a utility-scale wind turbine was developed to estimate the potential electrical energy that could be generated. The dynamic model was supported by wind data collected by an unmanned buoy based Laser Wind Sensor data acquisition system that has been deployed in Lake Michigan since October, 2011. Data summarization tools were also developed to help profile the wind resource based on the collected data.

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Chapter 1

1.1 Introduction

The current energy crisis and the adverse effects of global warming are pushing us towards alternative and renewable energy sources. Among all the alternative energy sources wind energy has been the one that has attracted significant attention of scientists, engineers and energy policy makers. This is mainly because of its success in several European countries. These countries have utilized both onshore and offshore wind potential. In the United States efforts have been directed to both onshore and offshore wind technology advancement. It is projected that by 2020 the United States can meet 20% of its electrical energy demand by wind energy [1].

This recent emphasis on the wind energy has made the government and privately owned energy companies look for potential locations for wind farms. Since a wind farm requires a lot of land resources, not only onshore but also offshore wind farms seem quite attractive to wind farm developers because of the low land cost. Moreover, the wind on the offshore location has very low turbulence. That is very favorable for wind turbine performance. However, the cost of developing the base and maintenance of turbines on an offshore location is very high.

Assessing the wind energy potential of a location is an extensive and time consuming process. It requires a collaborative effort of different organizations and mutual sharing of expertise. The preliminary work is to collect the wind data at different altitudes. Analyzing wind data for different altitudes give a better picture of the wind profile of that location. Moreover, reliable high altitude data help to assess the wind potential more accurately. Present utility-scale wind turbines have a hub height of 50 m to 100 m. Typically at onshore locations the wind data are collected by setting up a MET tower and equipping it with wind speed and wind direction sensors. The MET tower height should be high enough to collect the real-time hub height data. However for offshore locations measuring and collecting high altitude wind data by installing a MET tower is quite troublesome and expensive. This is because of the high installation cost of establishing the foundation of the MET tower. In some of the offshore locations the installation of the MET tower is not permitted by state or federal law.

If MET tower is not an option the wind data can be collected by a small tower and then data can be extrapolated by using the power law relationship between wind speed and altitude. This is just an estimation process and the accuracy of this method varies from location to location. However, the present state of the art LIDAR technology can also be used to collect the wind data. In this technology there is no need of high towers. Therefore, this technology can operate even in marine environment.

The collected data then has to be processed and analyzed to estimate the wind energy that can be harnessed from that location. Several methodologies are available at present to analyze the wind data to estimate the energy that can be harnessed. However due to the intermittent and uncertain nature of wind it is very difficult to estimate the energy accurately. The current estimation methodologies employ gross simplifying assumptions and could consider more parameters of the utility-scale wind turbine to estimate the amount of wind energy that can be harnessed more accurately. In most cases the wind farms on average can generate 25% of total generation capacity. As a result by design the wind farm has to be oversized to be able to meet the demand of energy. This implies a large installation cost which is detrimental to the popularity of this technology.

Michigan Alternative and Renewable Energy Center (MAREC) is a research and technology development entity of Grand Valley State University. MAREC is currently conducting a research project entitled, “Lake Michigan Wind Energy Assessment Project” in collaboration with University of Michigan, and Michigan State University. The primary purpose of this project, as the title suggests, is to conduct an assessment of wind energy potential over Lake Michigan. In this project wind data was collected from Lake Michigan (offshore location) with the help of an unmanned buoy named “Wind Sentinel” equipped with a LIDAR (light detection and ranging) sensor. It was the first time the LIDAR sensor was used on a marine environment in an unmanned buoy. The wind data were collected at a frequency of 1 Hz.

The data collected by the Wind Sentinel were used to estimate the potential wind energy that can be harnessed from Lake Michigan. To improve the accuracy of the estimation of wind energy a novel methodology to estimate the potential wind energy that can be converted into electricity was developed in this study. This method was capable of considering the effect of dynamic yaw movement of the wind turbine. The data sets collected by the Wind Sentinel required some pre-processing in order to eliminate the issues they had such as missing data and missing time stamps. A data pre-processing module was developed to perform the pre-processing task.

A parametric study was also performed to analyze the effect of the frequency of the data set on the energy estimate. This study required data sets averaged over different time periods. An averaging module to generate data sets averaged over 30 seconds, 1 minute, 2 minutes, 5 minutes, and 10 minutes was developed.

For representation of wind data a representation module capable of generating the typical wind regime representing techniques: wind roses and frequency distributions was also developed in this study.

1.2 Background

Great Lakes region is a great location for offshore wind energy generation. Several studies have been conducted on this area for wind energy assessment. An example is the Wisconsin Focus on Energy on Lake Michigan Offshore Wind Resource [2].

MAREC acquired an unmanned buoy system named Wind Sentinel that is capable of collecting meteorological data in marine environment on a moving platform. It has a state-of-the-art LIDAR sensor along with other sensors such as bird and bat sensors. This system was made by AXYS Technologies, Inc, Sydney, British Columbia, Canada. It is a stand-alone system capable of acquiring wind data at altitudes up to 175 m, at six different altitudes at a frequency of 1 Hz. It eliminates the necessity of putting a MET tower in an offshore location. This reduces the cost of data collection and the developer or research team does not have to go through the legal issues to acquire the permit to put up a MET tower on offshore location.

The most important feature of this data acquisition system is the LIDAR wind data collecting device. With the help of this technology it is now possible to sense the real time wind data at a height of 150 m or above. Previously one had to rely on the empirical models to estimate the wind speed at that height. This real time data is very useful for validating the existing models of boundary layer theory and also can be used to create a boundary layer model over a marine environment.

Two major studies were performed with the data collected from the Wind Sentinel. One was the validation of the LIDAR technology on a moving platform in a marine environment. The technology was new and had never been tested on a floating platform in a lake or sea. The other study was the wind energy potential assessment over the Lake Michigan. For this, the Wind Sentinel has been deployed since October 2011 in different parts of the lake at different times and collected valuable wind data. At regular intervals the collected data were retrieved from the buoy for further analysis.

1.3 Literature review

Estimation of the potential for electrical energy generation from wind at a location is quite complex and prone to non-precise estimation due to the uncertain nature of the winds. It is very hard to capture all the sources that affect the energy output by any model. The possible changes of the wind regimes at a particular location could be daily and seasonal variations. Moreover, this variation can never be predicted accurately as there are so many parameters that affect the speed, direction and turbulence in prevailing winds. As a result, the estimation of wind energy potential will always have a margin of error. Moreover, the energy output is also largely dependent on the wind energy conversion systems (WECS) such as different types of wind turbines. Different wind turbines will have different energy outputs over the same period of operation at a given location based on the turbine characteristics. For this reason the term 'wind power density' is widely used as a non-turbine-specific parameter. It refers to the available wind power per unit area for that location and can be found by the following equation.

$$P_{avail} = \frac{1}{2}\rho v^3 \quad (1)$$

where, P_{avail} is the available power in the prevailing wind in W/m^2, ρ is the density of the wind in kg/m^3, and v is the wind speed in m/s.

The term wind power density fails to provide any information about the energy that can be harnessed from that location. Researchers have been trying to develop mathematical models for assessing the performance of the wind turbines for quite a long time and significant improvements have been seen in this area. Generally the WECS such as wind turbines have a conversion factor that can be a constant value or a function of wind speed. By using this conversion factor the energy that can be harnessed can be estimated. In the case of wind turbine, this conversion factor is called the power coefficient.

A pure analytical approach is the starting point for the estimation of energy output by a generic wind turbine model. This approach is helpful for understanding the physics of flow of air through a wind turbine. Almost all of the pure analytical models deal with a generic wind turbine model. Some analytical models include Betz analysis, Gluert model, GGS model, and One two three equation [3].

However, in siting analysis of a wind farm these generic models fail to provide an accurate turbine specific estimation of the wind energy that can be harnessed. To eliminate this problem another technique is widely used. This technique uses the power curve of the utility-scale wind turbine and statistical wind data from the location of interest and estimates the energy output of the turbine. Several estimation processes based on this approach are available. These include Kiranoudis model, Polynomial modeling, Random number generation, and INL wind energy analysis model.

These models are described in the following section along with the assumptions they employ and their shortcomings.

1.3.1 Betz analysis

Albert Betz, a German physicist, proposed a theoretical approach [3] to estimate the ideal power coefficient of a wind turbine. A simplified diagram showing the model parameters can be found in Figure 1.1.

By using this model, the maximum theoretically possible power output by an ideal wind turbine can be found by the following equation

$$P_{max} = \frac{16}{27} \; \frac{1}{2} \rho \, A \, v^3 \tag{2}$$

where, P_{max} is the maximum power output, ρ is the density of the wind, A is the area of the rotor, and v is the prevailing wind speed.

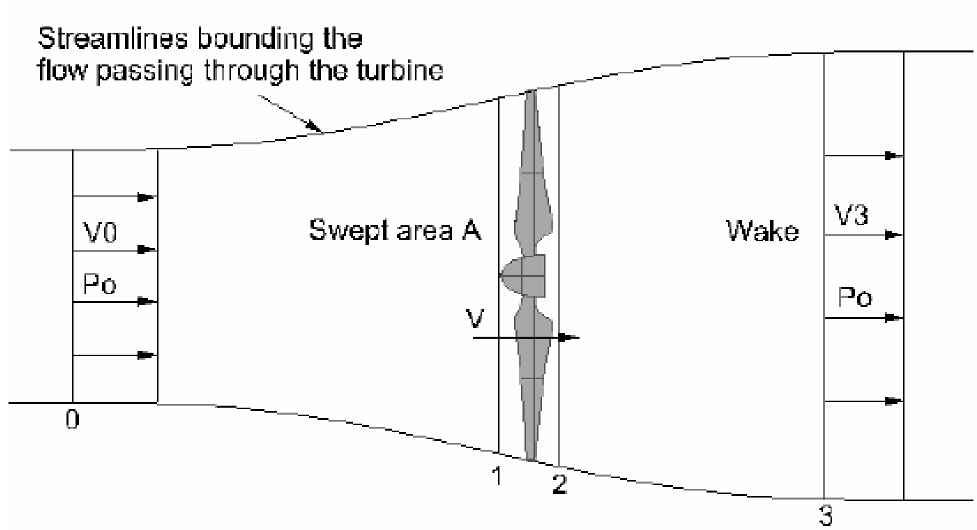


Figure 1.1 Betz model

The wind power density can also be found by rearranging the Equation (2).

$$\frac{P_{max}}{A} = \frac{16}{27}\ \frac{1}{2}\,\rho\, v^3 \tag{3}$$

where, $\frac{P_{max}}{A}$ is the maximum power density for ideal wind turbine.

From Equation (3) and Equation (1) it can be found that

$$\frac{P_{max}}{A} = \frac{16}{27}\ \ P_{avail} \tag{4}$$

Equation (4) presents the theoretical maximum power coefficient as $\frac{16}{27}$ or 0.593. This means that, even with ideal wind turbine at most only 59.3% of the available wind power can be harnessed. This model also assumes the power coefficient to be a function of axial induction factor. Axial induction factor is the fractional decrease in wind velocity between the free stream and rotor plane and can be expressed by the equation:

$$a = \frac{V_0 - V}{V_0} \tag{5}$$

where, V_0 is the upstream velocity and V is the downstream velocity of the turbine.

The functional relationship between the power coefficient and the axial induction factor can be observed from Figure 1.2 [4].

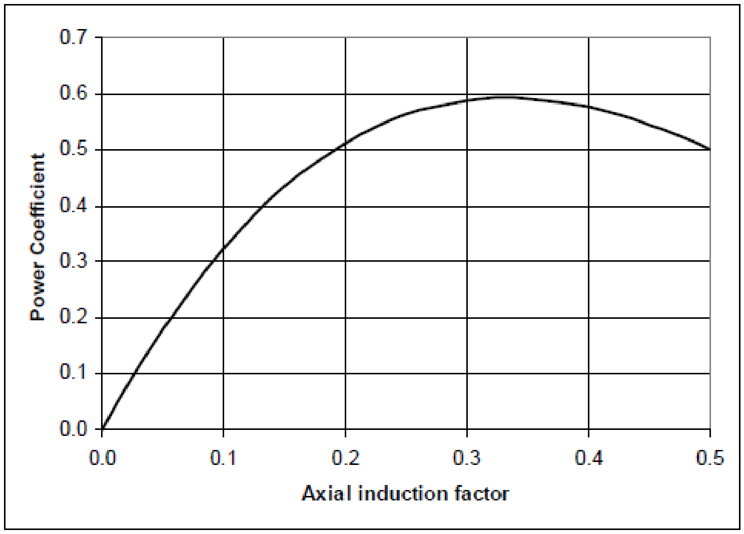


Figure 1.2 Power coefficient by Betz model as a function of axial induction factor

The major assumptions of this model are:

1. The rotor does not possess a hub; this is an ideal rotor, with an infinite number of blades which have no drag. Any resulting drag would only lower this idealized value.
2. The flow into and out of the rotor is axial. This is a control volume analysis, and to construct a solution the control volume must contain all flow going in and out. Failure to account for that flow would violate the conservation equations.
3. The flow is incompressible and inviscid. The flow is isothermal.

By analyzing the assumptions it can be stated that, the model is a very simplistic approach to a complex and unpredictable system. However, this model sets up the maximum theoretical limit for the power coefficient and gives a general idea about how much energy can be generated from any potential wind farm site. A real wind turbine never achieves this limit because of the following reasons [4]:

1. Rotation in the wake caused by the reaction with the spinning rotor.

2. A non-uniform pressure distribution in the turbine plane. The turbine plane is a virtual plane created by the turbine blades.
3. Aerodynamic drag due to viscous effects.
4. Energy loss due to vortices at the blade tips.

1.3.2 One two three equation

Carlin [6] proposed a mathematical model for estimating the generated energy by a WECS. The wind regime is modeled as a Rayleigh distribution and the average power output of a WECS is found by Equation (6). The hourly averaged wind speed, v_{ave}, is based on the Rayleigh distribution model. The annual energy, E_{ann} , can be found by Equation (7) which he called the one two three equation.

$$P_{ave} = \frac{\rho}{\rho_0}(\frac{2}{3}D)^2 v_{ave}^3 \tag{6}$$

$$E_{ann} = 8760\frac{\rho}{\rho_0}\left(\frac{2}{3}D\right)^2 v_{ave}^3 \tag{7}$$

where, P_{ave} is the available power in the prevailing wind in watts, ρ is density of the wind at that temperature in kg/m^3, ρ_0 is the density of the wind at standard temperature and pressure (STP) condition in kg/m^3, D is the diameter of the wind turbine in use in m, v_{ave} is the wind speed in m/s, and E_{ann} is the annual energy in joules.

Several assumptions were made to simplify the mathematical model in this technique. The major assumptions were [6]:

1. The rotor and power train have no inertia and are therefore at all times in equilibrium with the local wind both in rotational speed and in yaw alignment. There is neither friction nor any other mechanical loss.
2. The local wind speed probability density is given by the Rayleigh density expression. It is also assumed that a single number is sufficient to describe the instantaneous wind at the rotor disk.
3. The power coefficient of the turbine will be $C_p = {}^{16}/_{27}$, which is the classical Betz limit.

Although the accuracy of this method is not so high, it is widely accepted for its simplicity. An important issue is that the power coefficient is assumed to be the classical Betz limit which is not possible in real cases as stated before. However, only three parameters are needed for the estimation. That makes this method easy to apply.

1.3.3 Kiranoudis model

Kiranoudis proposed a method [7] of estimating the energy output of a wind turbine. In this method the power coefficient of a WECS is assumed to be a function of wind speed which is true for every WECS. The relation is found by the following Equation (8).

$$C_p = C_{pr} e^{\frac{(\ln v - \ln v_r)^2}{2(\ln s)^2}} \tag{8}$$

Here, the turbine characteristics are the nominal power coefficient, C_{pr}, the rated wind speed, v_r, and a parameter expressing the operating range of wind speed, s. The annual energy, E_{ann}, can be expressed as:

$$E_{ann} = 8760 \frac{\rho}{\rho_0} \frac{P_r}{v_r^3} \left(\int_0^{v_f} e^{\frac{(\ln v - \ln v_r)^2}{2(\ln s)^2}} \right) v^3 f(v) dv \tag{9}$$

The nominal power coefficient, C_{pr}, is the maximum value of power coefficient, C_p, for a given wind speed value representing the nominal performance of the turbine.

The assumptions for this model are:

1. The wind speed pattern can be modeled as Weibull distribution.
2. The power coefficient of the turbine is a function of wind speed.
3. The turbine rotor will face the wind direction normally at any instant.

This model needs six input parameters for estimating the energy output. That makes it hard to apply in energy estimation process. However this model has a considerably higher accuracy than the One two three equation [8].

1.3.4 Polynomial modeling

In Polynomial method [10-12], wind turbine power curve is approximated by a polynomial like the following equation.

$$P(v) = \begin{cases} 0 & v < v_c \, or \, v > v_f \\ P_r & v_r < v < v_f \\ (v^m - v_c^m)/(v_r^m - v_c^m) & v_c \le v \le v_r \end{cases} \tag{10}$$

where, $P(v)$ is the power output of the turbine in kW, P_r is the rated power output of the turbine , v_c , v_r , v_f are the cut-in speed, rated speed and the cut-out speed of the wind turbine respectively, and m is the order of the polynomial. In most of the cases the value is assumed to be 1 or 2.

The annual energy, E_{ann}, can be found by Equation (7).

$$E_{ann} = 8760 \, \frac{\rho}{\rho_0} \left(\int_{v_c}^{v_r} \frac{v^m - v_c^m}{v_r^m - v_c^m} \, f(v) dv + \int_{v_r}^{v_f} f(v) dv \right) \tag{11}$$

where, $f(v)$ is the Weibull distribution function, v_c , v_r , v_f are the cut-in speed, rated speed and the cut-out speed of the wind turbine respectively.

This model has higher accuracy of estimating the energy for pitch controlled wind turbines [8]. A wind turbine can have three types of control and the power curve varies for each case. Figure 1.3 shows the typical power curve shape for pitch control, stall control and yaw control wind turbine.

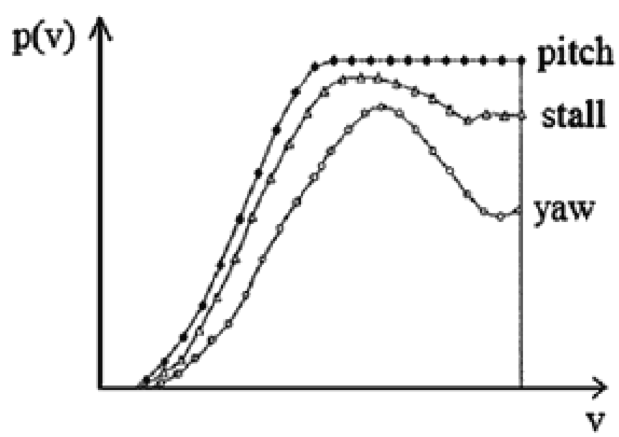


Figure 1.3 Typical power curves of modern utility-scale turbines

Nowadays mostly the pitch control turbine is used for its steady power output (rated power) for a range of wind speed.

As in previous estimation techniques this method has an assumption that the turbine has no inertia or mechanical resistance that prevents yaw rotation, i.e., the turbine rotor will face the wind perpendicularly at any instant.

1.3.5 Random number generation

In random number generation method [8], hourly wind speed values during a period of year are synthesized by means of generation of 8760 random numbers based on the Weibull distribution. For this the parameters of Weibull distribution have to be known a priori. The annual energy output, E_{ann}, can be estimated by the following equation.

$$E_{ann} = \frac{\rho}{\rho_0} \sum_{i=1}^{8760} P(v_i) * \Delta t \quad (12)$$

where, $P(v_i)$ is the available power in the prevailing wind in watts in a time averaged period (wind data such as wind speed, wind direction are not a continuous stream of data; rather a time averaged value of wind speed and direction is generally stored), Δt is length of the time step of data in seconds, ρ is the density of the wind at that temperature in kg/m^3, ρ_0 is the density of the wind at standard temperature and pressure (STP) condition in kg/m^3.

The density of the wind has to be known in this method. The result is also dependent on the random number generation technique [8]. Moreover, the power curve of the turbine has to be known.

The assumptions employed in this method are:

1. The wind regime follows the Weibull distribution.
2. The wind turbine rotor faces the wind perpendicularly at any instant.

1.3.6 INL wind energy

INL (Idaho National Lab) has a wind energy program [12] based on MS Excel® for estimating wind energy based on the statistical data available for any location. In this method, the power curve of the wind turbine has to be known. The energy can be found by the following equation

$$E = \sum_{i=1}^{t} P(v_i) \times \Delta t \quad (13)$$

where, $P(v_i)$ is the available power in the prevailing wind in watts in a time averaged period, Δt is length of the time period in seconds and E is the energy of the entire time duration of interest.

The accuracy of this method depends on the frequency of available data. The advantage of this method is that the wind regime does not have to follow any statistical distribution. However, this method also assumes that the turbine will face the prevailing wind perpendicularly at all times.

1.4 Limitations of current estimation techniques

Detailed literature review suggested some possible approaches to estimate the electrical energy that can be harnessed from wind energy of a location. However, every approach had their advantages and limitations. Since a utility-scale wind farm requires a comprehensive estimate of the energy, the turbine specific approach is always preferred.

Most of the turbine specific energy estimation techniques except the Kiranoudis method mentioned in the literature review section, utilized the power curve of the turbine used to estimate the energy output of that turbine placed at that location. They all assumed that the rotor and power train have no inertia and are, therefore, at all times in equilibrium with the local wind both in rotational speed and in yaw alignment. In addition, they assumed that there is neither friction nor any other mechanical loss.

However, in reality, utility-scale wind turbines have a large inertia, and the yaw rotation of the turbine is limited to 0.3 ~ 5 deg/sec [10] in order to minimize the gyroscopic effect. The wind direction may change continuously. However, the utility-scale wind turbines do not change their yaw orientation continuously to match the wind direction. It is normally done at a regular or variable time interval in order to increase the life of the yaw bearing and other mechanical components [10]. The reasons for this are to eliminate the controller complicacy and to save the bearing and other mechanical components from wearing out quickly. This leads to a possibility of the turbine to be misaligned with the prevailing wind. A turbine controller takes the decision to yaw the turbine by sensing the wind direction and then finding the misalignment. The wind direction sensed by the sensor is already past the turbine. Therefore, the turbine will align itself with the wind that has already passed through the turbine. While doing that the wind direction has already changed. This means that the turbine may always have some misalignment with the prevailing wind. This misalignment is termed as yaw error of the turbine.

Yaw error reduces the power output of the turbine. Assuming the wind direction vector and the vector normal to the face of the rotor are at an angle θ, the active velocity becomes $u = v\cos\theta$. Thus the power equation becomes

$$P = \frac{1}{2}\rho C_p A v^3 cos^3\theta \qquad (14)$$

From this equation it can be seen that for $\theta = 20^o$ the power output decreases by 17%.

A dynamic mathematical model of the yaw control of a utility-scale turbine can be developed to consider the effects of yaw error on the power output of the turbine. If the yaw error is considered in the estimation process the results would be more accurate than the other methods available at present.

While considering the yaw error some other questions also needed be answered. For example, what is the effect of yaw rate on the energy output of the turbine? And how frequently should the turbine align itself with the prevailing wind direction? To answer these questions some terms such as ‘Time step’ and ‘Delay time’ are needed to be defined now as they will be used frequently from this point on.

Time step: The frequency of the data set that will be the input of the dynamic model.

Delay time: The time period in between two consecutive changes in the orientation of the turbine.

Chapter 2

2.1 Methodology

Based on the literature review, the major steps of the research were identified. The primary goal was to develop a dynamic yaw control model of wind turbine to assess the energy that can be harnessed from any location. The statistical wind data were fed to the dynamic model to estimate the output energy by any specific turbine. The data had to be quality controlled and continuous. The missing data points had to be noted as 'NaN' value to work with MATLAB coding.

The data collected from the Wind Sentinel was at 1 Hz frequency. These data were managed and stored by the Watchman-500 (an AXYS data acquisition and storing system) on the buoy in a flash card. The data were physically retrieved by pulling out the data card from the buoy every 6 weeks. Watchman-500 also generated a 10 minute averaged data set and transmitted the data through cellular network, the Iridium satellite network. During the project when the buoy was within the cellular data network it transmitted 10 minute averaged data sets at a frequency of 10 minutes. While the buoy was in mid-lake position, the data were transmitted every hour via satellite to reduce the cost of transmission of data. The transmitted data were the 10 minute averaged values of wind data at the moment of transmission.

In theory the 1 Hz data would have a continuous stream of 86400 data points per day. However, in practice the data set did not have 86400 data points and a large number of data as well as the time stamps were missing. The missing data were denoted by character 'Â' by the Watchman system. This 1 sec data were not usable in MATLAB code due to discontinuity of time stamp and the special character in the data set. Moreover, it was not a wise decision to feed the 1 Hz data into the MATLAB code. Generally the utility-scale turbines have a large moment of inertia, which makes them slow responding systems. The turbine cannot respond to the quick fluctuations of wind speed due to the turbulence in wind. These reasons discouraged the use of 1 Hz data in the dynamic model.

Therefore, the data set had to be preprocessed to create the time stamps for the missing time stamps and replace the missing values denoted by 'Â' characters with 'NaN' character. The data set also had to be averaged over a longer time frame to feed into the MATLAB code and it also had to be quality controlled. To address these issues a separate data preprocessing tool was developed.

To present the wind pattern over the location of interest a wind data representation tool was developed. This module generated the wind rose and frequency distribution based on the processed wind data set collected by the Wind Sentinel system.

To compare the results with other models of wind energy estimation, separate modules capable of estimating wind energy by using the same data set were developed as well. These modules assessed the wind potential based on several methods described in the literature review and finally compared the findings to the dynamic yaw control model.

Just to give an idea of how much data had to be processed, each day had a data set with 86401 rows and 146 columns. In total 395 days of data had to be processed. The total size of data collected was approximately $20\ GB$. Processing these large scale data sets required large computing power. The computing facilities of the Padnos College of Engineering and Computing were used for this project, namely the Tesla machine was capable of handling such large scale data and calculation steps. This machine was used extensively in the current study.

The following steps were followed to complete this study:

1. Development of a dynamic yaw control model of a utility-scale turbine to estimate wind energy.
2. Development of a data preprocessing tool to refine the raw data to feed in the dynamic model.
3. Development of post processing tools to represent the wind pattern over the location of interest.
4. Development of computational modules to estimate the wind energy using other methods stated in literature review for comparison.

These steps required their own methodology to develop. Brief description of the methodology of each step is presented in the following section.

2.1.1 Energy estimation with dynamic yaw control model

For energy estimation the INL wind analysis program was taken as a starting point. It was considered as the base dynamic model of the turbine. The energy estimating module took in the wind data – wind speed and wind direction. Then the corresponding power output by the turbine at that specific wind speed was sought out from the power curve. The power curves obtained from the INL wind analysis program were not continuous function of wind speed; rather they provided sets of discrete power outputs corresponding to the wind speeds. The resolution of the wind speed in that power curve was 0.01 mph. All the wind speed values were rounded to two significant digits.

In the case of INL wind analysis program the energy per time step was found by multiplying the power output at that time step found from the power curve of the turbine with the time step of the input wind data. The effect of the yaw error was not considered in that program. The dynamic model developed in this study considered yaw error of the turbine while estimating the energy.

An important factor to keep in mind is that if the yaw error is not more than a threshold value, the turbine does not change its orientation in modern utility-scale wind turbines. A possible reason for this is the amount of energy needed to rotate these large turbines is more than the turbine can generate by aligning itself with the wind. Another reason for this is that this way the mechanical components of the turbine, such as the bearings, will experience less wear and tear as they go through less working strain. This threshold value is different for different operating region of a turbine. The operating regions of a pitch-controlled turbine are presented in Figure 2.1.

From Figure 2.1 it can be seen that Region 1 and Region 4 do not generate any power. During these regions the yaw brake is enabled to protect the valuable turbine components. Region 2 is the maximum power coefficient mode of a turbine. In this region the turbine tries to extract as much energy as possible from the wind. The accepted yaw error window is very small (approximately 8°) in this region in order to reduce the losses [11]. Region 3 is the maximum power output mode. Here the turbine operates to generate the maximum power – rated power of that turbine. The yaw error allowance is slightly greater (approximately 18°) in this region.

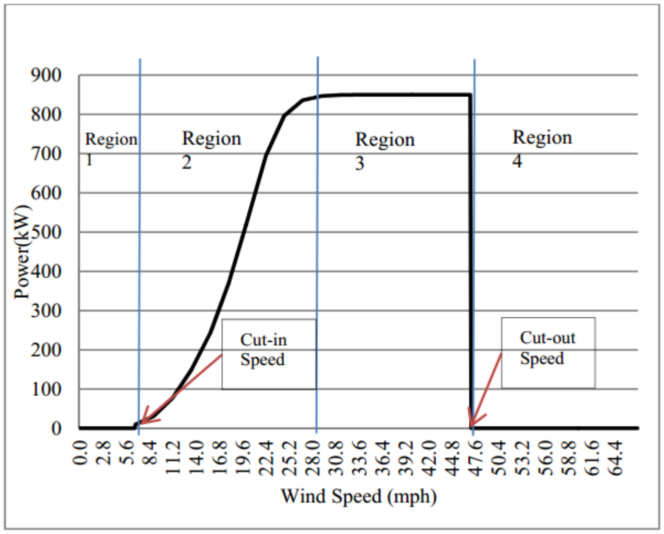


Figure 2.1 Different operating regions of a pitch controlled wind turbine (Gamesa Eolica G58-850kW)

In order to include the effect of yaw error, several new parameters had to be known – the yaw rate, the wind direction, the turbine orientation at that time step, the threshold values of the accepted yaw error and the time period in between two consecutive changes in the orientation of that turbine (delay time). In the dynamic model, while calculating energy generation within a single time step (the time resolution of input data) these parameters were all considered.

Among these parameters, yaw rate and time period between two consecutive changes in turbine orientation (delay time) were not dependent on the wind speed but the threshold value of accepted yaw error was dependent on the wind speed. An algorithm for dynamic yaw control taking these points into account was developed and presented by the flow chart in Figure 2.2. In this figure *fixed value 1* and *fixed value 2* are the allowed yaw errors in Region 2 and Region 3 respectively.

Based on this control model the turbine orientation was calculated at any instant. For a time step, the wind direction was assumed to be fixed. Therefore, for a given time step, the yaw error was found at a fixed time interval for the turbine. By using this yaw error and the wind speed for that time step the active speed (normal component of speed on the wind turbine blade) for the turbine was found by Equation (15).

$$active\ speed = prevailing\ wind\ speed * cosine\ of\ yaw\ error \tag{15}$$

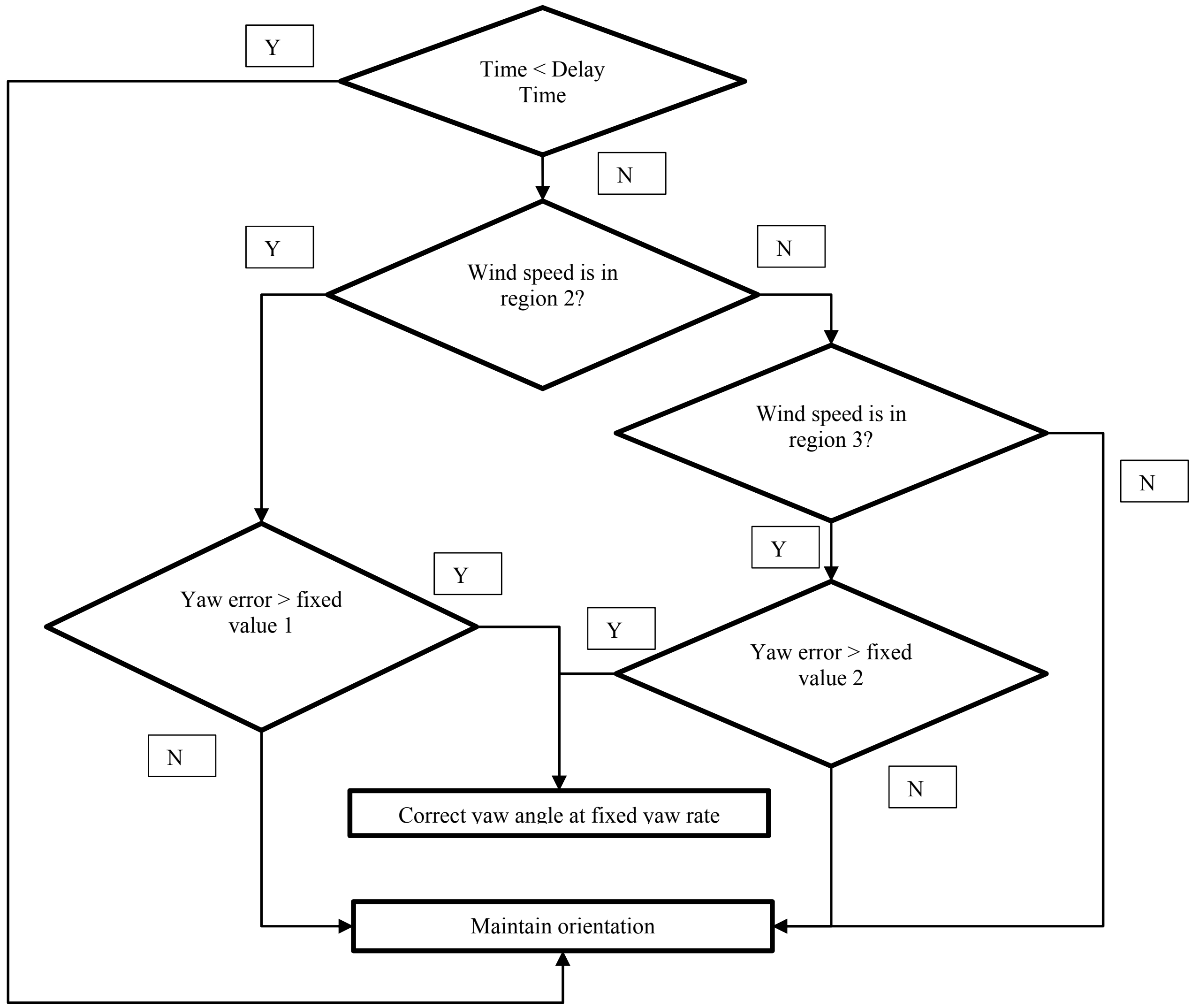


Figure 2.2 Yaw control module flow chart

The power output for that active speed was sought out from the power curve and used as the power output for that time interval. The total energy output was found by integrating the power output as in Equation (14). A flow chart outlining the energy estimation process from the dynamic control model is presented in Figure 2.3.

Based on the control algorithm presented in Figure 2.3 a MATLAB code was developed. The detailed MATLAB code is attached in Appendix A.1 for further understandings and future reference.

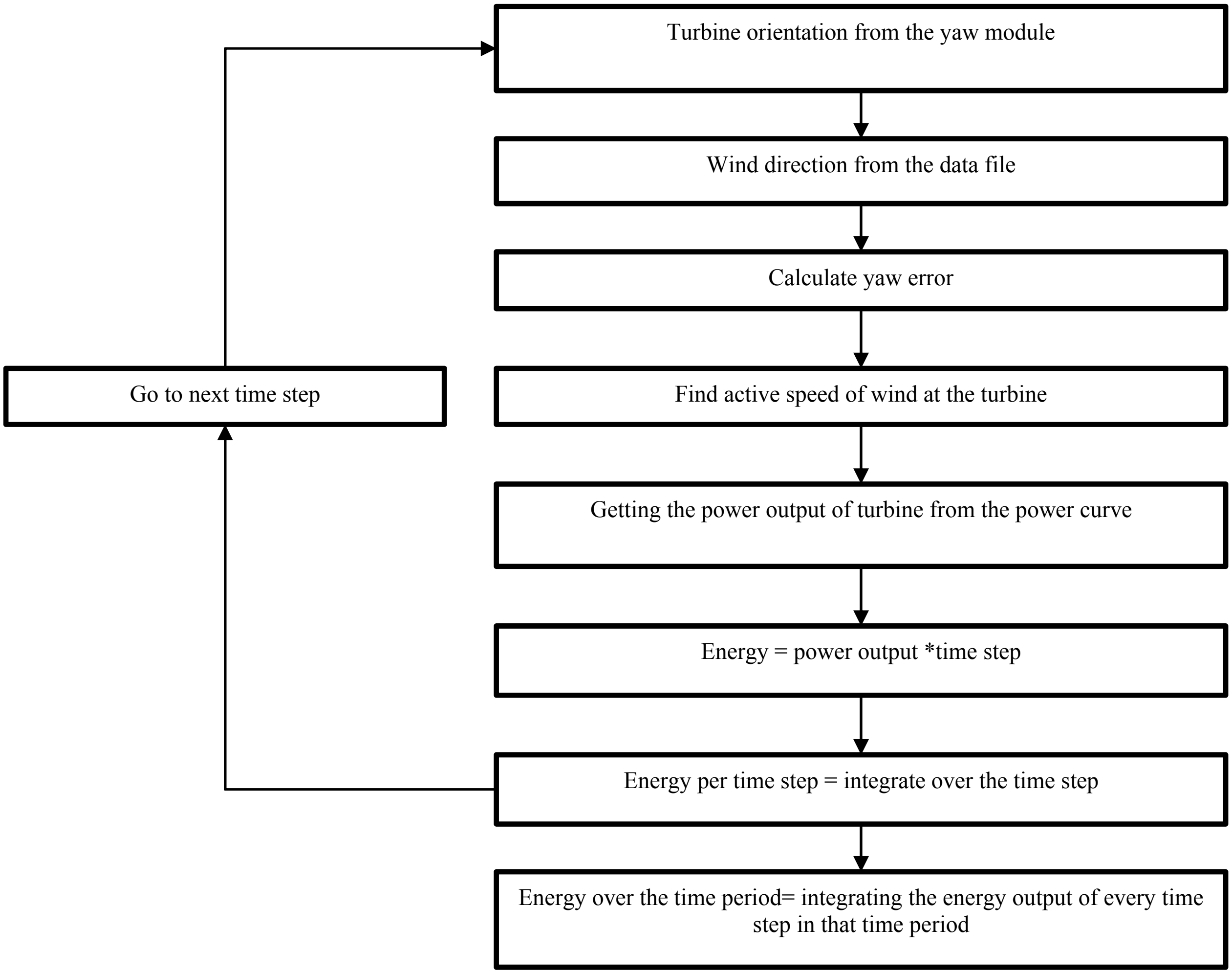


Figure 2.3 Energy estimation process flowchart

2.1.2 Energy estimation by other models

2.1.2.1 Wind energy density

First the power density of the prevailing wind was calculated by using Equation (1). For doing that the density of the air at the height of the data had to be known but the data set did not have the density of the wind at the height of measurement. The density was modeled according to the U.S. standard atmosphere model 1976 version [16]. The model parameters are:

Sea level standard atmospheric pressure p_0= 101.325 kPa

Sea level standard temperature T_0= 288.15 K

Earth-surface gravitational acceleration g= 9.80665 m/s^2.

Temperature lapse rate L= 0.0065 K/m
Ideal (universal) gas constant R = 8.31447 $J/(mol \cdot K)$
Molar mass of dry air M = 0.0289644 kg/mol

The highest altitude of wind data was 175 m which was within the troposphere of the earth's atmosphere (17 km) so the temperature at that altitude was found by using Equation (16).

$$T = T_s - Lh \tag{16}$$

where, T_s is the temperature at water surface measured by the buoy in K, L is the temperature lapse rate inside troposphere in K/m, and h is the altitude of interest in m.

Then the pressure at that altitude was found by the following Equation (17).

$$p = p_0(1 - \frac{Lh}{T_s})^{\frac{gM}{RL}} \tag{17}$$

where, p_0 is the pressure at sea level in kPa, L is the temperature lapse rate inside troposphere in K/m, h is the altitude of the data set in m, T_s is the temperature at the water surface in K, g is the earth-surface gravitational acceleration in m/s^2, M is the molar mass of dry air in kg/mol, and R is the universal gas constant in $J/(mol. K)$.

By using the pressure and temperature at the given height the density of the air was found by Equation (18).

$$\rho = \frac{pM}{RT} \tag{18}$$

where, ρ is the molar density of air in kg/mol, p is the pressure in kPa, M is the molar mass of dry air in kg/mol, R is the universal gas constant in $J/(mol. K)$, and T is the temperature in K.

By using the density of air at the height of the data set the power density of wind was found. The averaged power density of wind per month was used to simplify the calculation. The available energy density of wind was found by multiplying the time step for the data set with the power density of wind found in Equation (1). The MATLAB code for this process is presented in Appendix A.2.1.

2.1.2.2 Betz analysis

Wind energy by the Betz analysis was easily found by using Equation (4). The available wind energy density was calculated by the methodology presented in section ***2.1.2.1***. The energy estimated by Betz analysis is 59.3% of the available wind energy density.

2.1.2.3 One two three equation

Electrical energy that can be generated from the available wind energy can be estimated by using this method with the help of Equation (7). The average density was found from the buoy data set and then extrapolated using the US standard atmospheric model [16]. The energy was normalized by dividing by the density of air at standard temperature and pressure. The MATLAB code for this method is attached in the Appendix A.2.1.

2.1.2.4 Polynomial modeling

In this method the power curve of the wind turbine was modeled with the help of Equation (11). The order of the polynomial,m, was assumed to be 2. Then the power output by the turbine was determined by using the power curve model equation. The energy was found by multiplying the power output with the time step of data. Then integrating over the entire time period the total energy was found. The MATLAB code of this module can be found in Appendix A.2.2.

2.1.2.5 Random number generation

For this method the Weibull parameters of the wind regime had to be determined. Then it was used to determine the wind energy by using generating random values of wind speed. This method is useful for a site where the long term statistical wind data are available. This site did not have long term statistical wind data to estimate energy by random number generation. Therefore, the energy that can be harnessed from the available wind energy could not be estimated by this method.

2.1.2.6 INL wind energy

Energy can be estimated by the simple approach of finding the power output of the turbine at any specific wind speed from the power curve and then multiplying it with the time period of data.

For this a discrete set of wind power curves were needed. The power curves were collected from the INL wind energy software. The MATLAB code is presented in Appendix A.2.3.

2.1.3 Data preprocessing

The dynamic control model needed a continuous stream of data with proper time stamps. The number of data points should be 86400 per day for 1 sec data set. The data preprocessing module took in the raw unrefined data set. In MATLAB a continuous set of time stamps was created to compare with the time stamps of the raw data file. By doing this the missing time stamps were found and were filled in according to the time stamps created in the program.

The missing data points were denoted by 'NaN' values to make them compatible with MATLAB. Then the refined data set were saved as comma separated values in daily data. The steps are presented as a form of flow chart in Figure 2.4.

Based on the flow chart a MATLAB script was developed to refine the raw data. The MATLAB code is presented in Appendix A.3 for reference.

As stated earlier it is not desirable to feed in the 1 sec data into the dynamic model. Therefore, the data set had to be average to different time steps. Four averaging time periods were considered, i.e., 30 sec, 1 min, 2 min, 5 min and 10 min. During averaging the data was checked for quality. If the number of samples was less than 50% of the number of data points in ideal case in the averaging time period the averaged value was considered as invalid and was omitted from the averaged data set. Then the data set was stored in the comma separated value (CSV) format. The associated data set had the average wind speed and average wind direction per time step.

Wind speed is a scalar quantity and can be averaged using normal averaging formula. However, the wind direction is a vector quantity. Therefore, averaging the wind direction is not a simple straight forward procedure. The average angle in a time averaged period can be found by Equations (19), (20) and (21)

$$sine = \sum \sin(\theta_i) \tag{19}$$

$$cosine = \sum \cos(\theta_i) \tag{20}$$

$$\theta = \arctan(sine/cosine) \tag{21}$$

In MATLAB the sign convention is different than that of the input wind data file. Therefore, the angle was converted before any calculation and similarly again converted to normal notation which is 0° due north, 90° due east, 180° due south and 270° due west. The overall procedure is presented in a flow chart format in Figure 2.5.

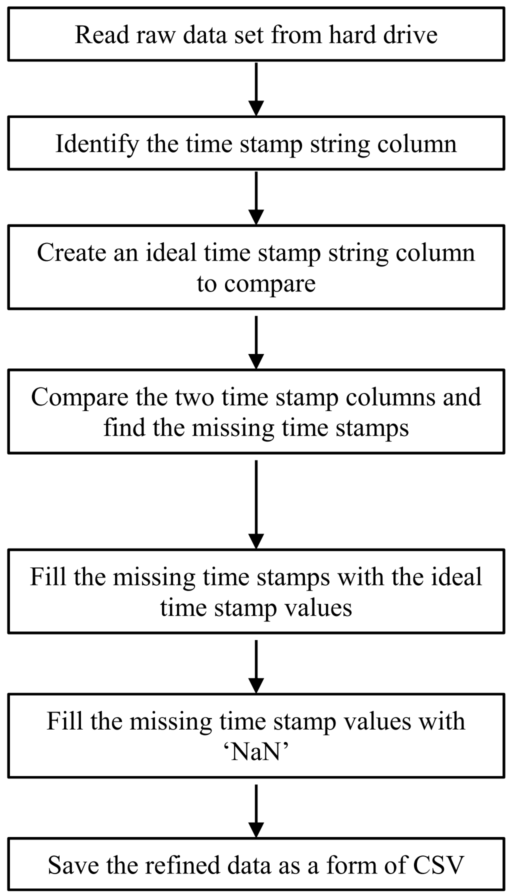


Figure 2.4 Data processing module flow chart

With the help of this flow chart presented in Figure 2.5, a separate MATLAB code was developed. The code can be found in Appendix A.4.

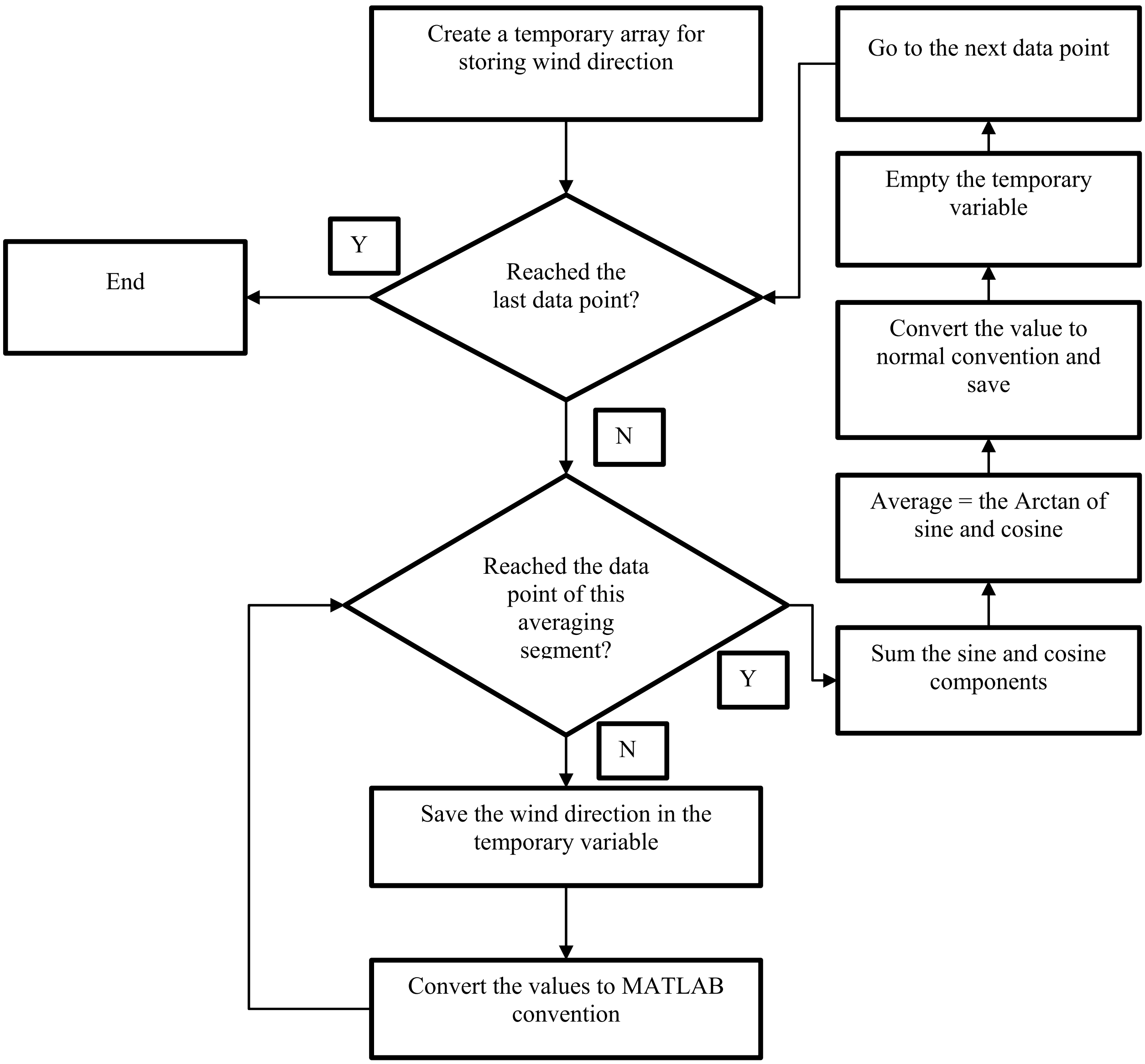


Figure 2.5 Averaging module flowchart

2.1.4 Representation of the results

Wind data representation is different than any other representation as the wind velocity is a vector quantity. In most of the reports and technical papers a special type of graph is used. It is called the wind rose. The wind rose is the graphical representation of the average wind speed or average duration of wind in any particular range of direction. It is essentially a bin sorting process or histogram where the bin criterion is the wind direction.

Therefore, in order to generate the wind rose for representation, the wind data were sorted in different bins. That means, in a certain direction range the average wind speed or averaged duration of wind blowing in that range was sorted out from the data file. Then the wind speed was averaged and assigned for that particular range. Duration of time wind blowing in that direction as a percentage of total time of the data set was also calculated. The scheme for this sorting and averaging is presented in a flow chart format in Figure 2.6. However, the built-in function of MATLAB to generate wind rose was unable to represent the result. Therefore, Microsoft Excel was used as a plotting solution. Radar type plot was used to represent the data calculated by MATLAB. The MATLAB code for this module is attached in Appendix A.5.

Another form of representing wind data is the frequency distribution. It is the averaged wind speed and duration of time of wind blowing in a particular range of wind speed. It is similar to the wind rose but the bin criterion is the wind speed.

Similar to wind rose, a sorting scheme was adapted and also a MATLAB code was developed. However, in this case the built-in MATLAB plotting solution was sufficient enough to represent the results. The algorithm for this process can be found in Figure 2.7 and the MATLAB code is presented in Appendix A.6.

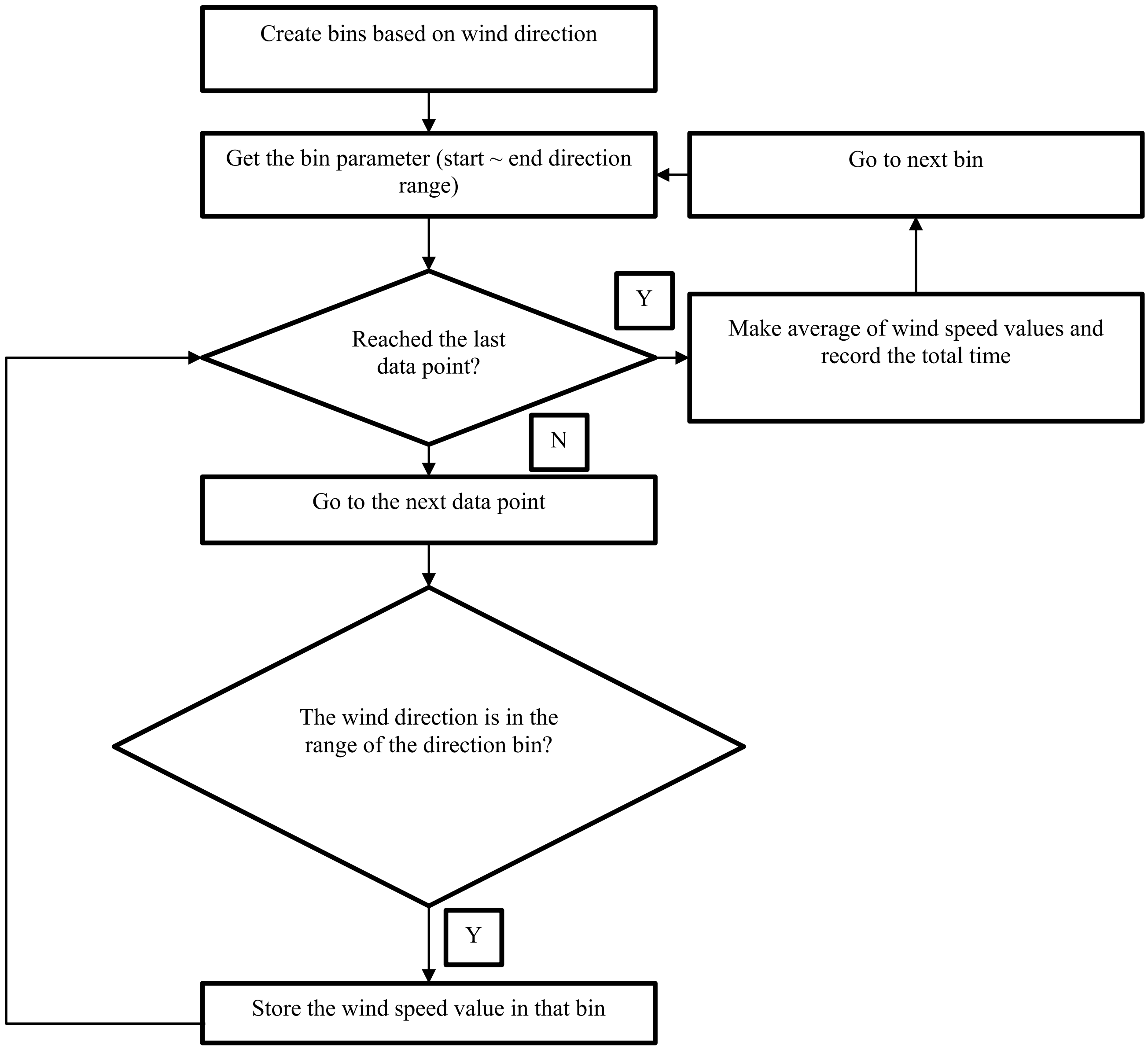


Figure 2.6 Wind rose generating flow chart

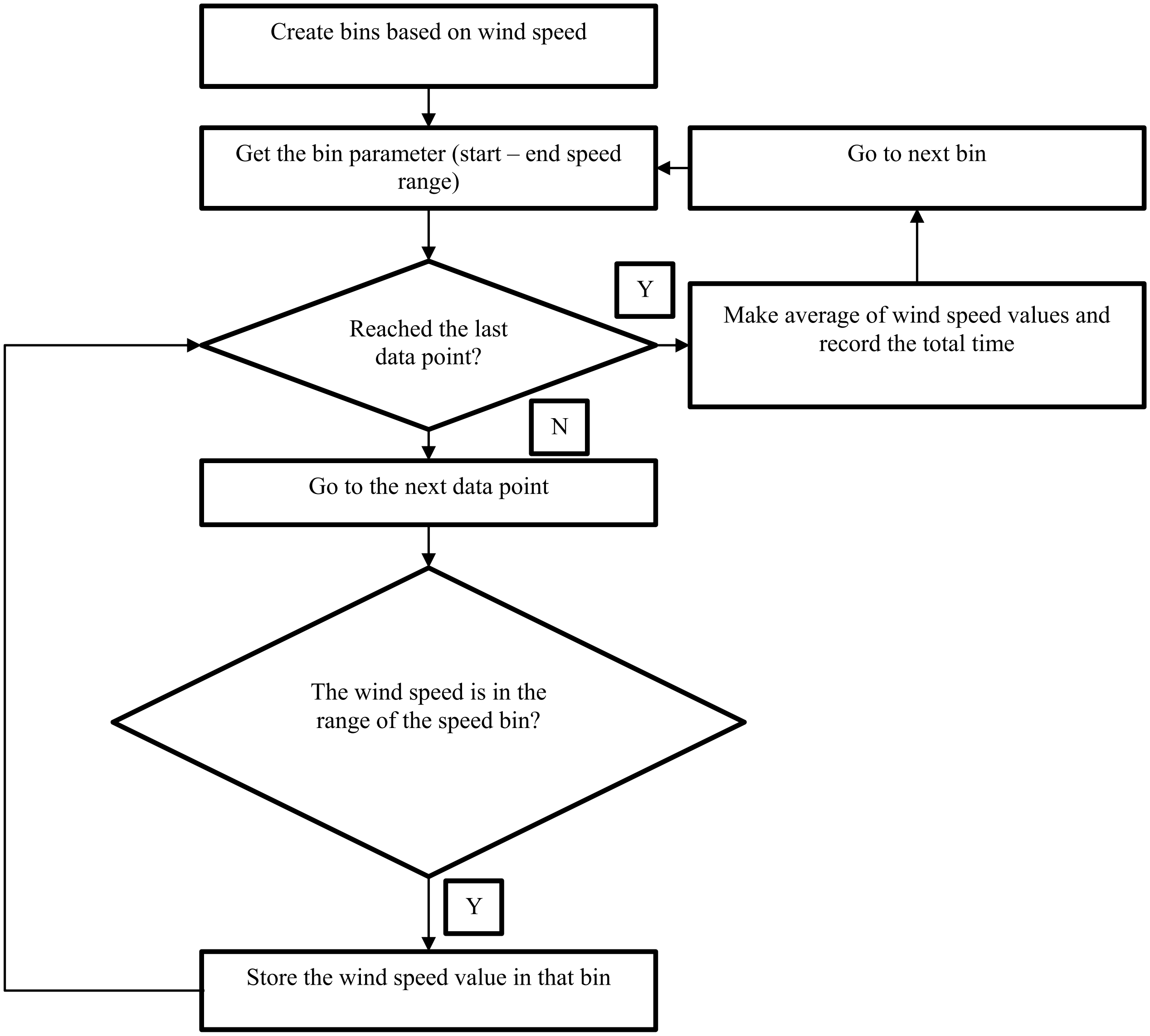


Figure 2.7 Frequency distribution generating flow chart

Chapter 3

3.1 Energy estimation by the dynamic control model

3.1.1 Validation of the dynamic model

For validating the developed model the codes were organized in such a way that the dynamic model can be deactivated or activated for total energy estimation. If the dynamic model is deactivated during the calculation, the model assumes that the turbine will face the wind direction at any instant similar to the other estimation techniques. As the base model is similar to the INL wind energy model, for the same data sets the results should be very close for both cases. To test this, a sample data set collected from INL website was used. The metadata of the data file: Site: Idaho [17]; Latitude: 43.7058^{o}N; Site Number: 1041; Longitude: 111.731^{o}E; Site Description: Louise Twitchell site; Turbine model: Games Eolica G58-850 kW; Project Code: Idaho; Project Description: Idaho Wind; Location Description: Near Archer, ID; Site Elevation: 5360 ft; Start time: 6/22/2006 19:50; End time: 2/4/2007 18:00; Hours in file: 5446.33 hours; Time Zone: GMT-7. The results are presented in Table 3.1 and the results are similar as expected.

Table 3.1 Comparative results of the INL wind energy and MATLAB code developed

INL wind energy	MATLAB code	Difference
956,875.69 kWh	956,875.90 kWh	0.0005%

Figures 3.1 and Figure 3.2 show a comparative analysis of the percentage of total time and percentage of total energy in different direction bins obtained from the two codes. The results are very close, verifying the accuracy of the MATLAB code developed.

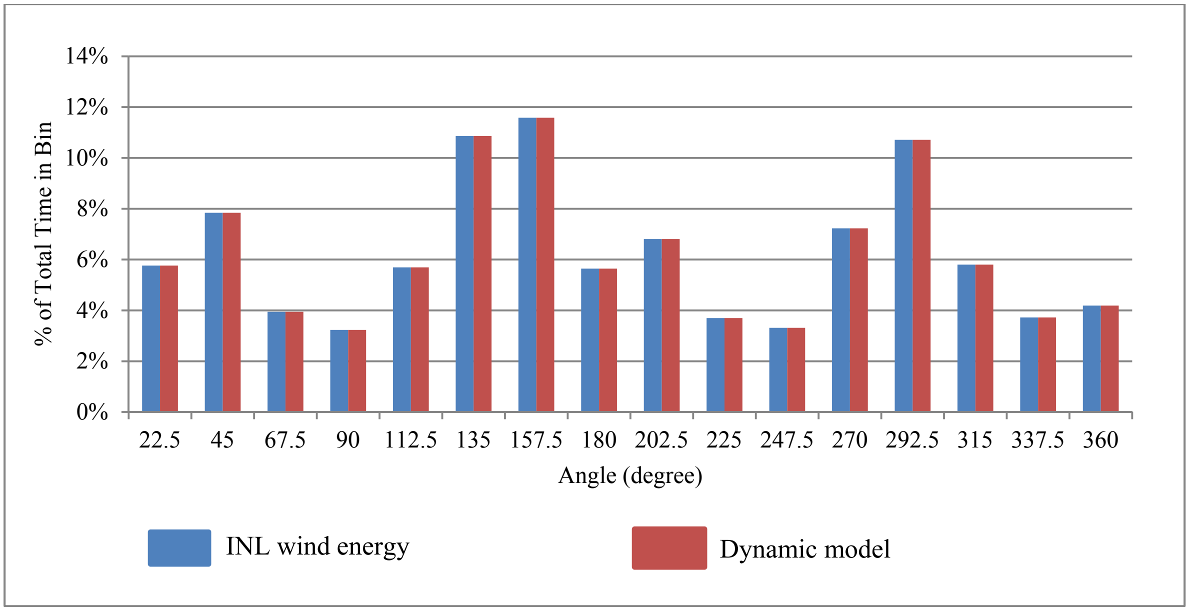


Figure 3.1 Comparative results of percentage of total time in every direction bin

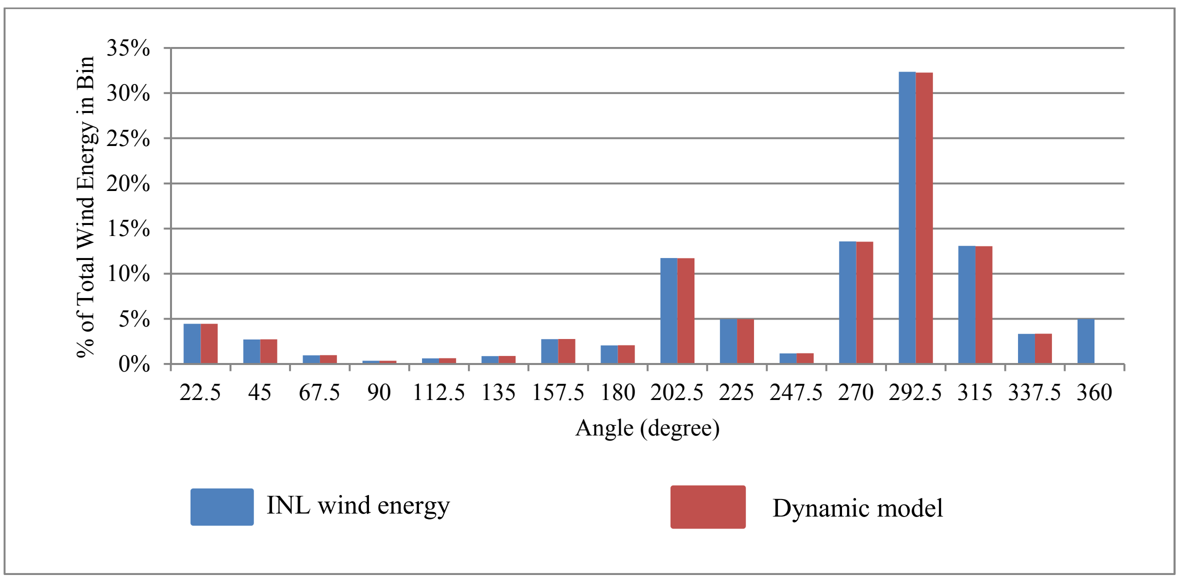


Figure 3.2 Comparative results of Percentage of total energy in every direction bin

Figures 3.3 and Figure 3.4 depict a comparative analysis of the results from two codes with respect to the total energy generation and relative frequency in different speed bins. Again, as may be seen these results are very close.

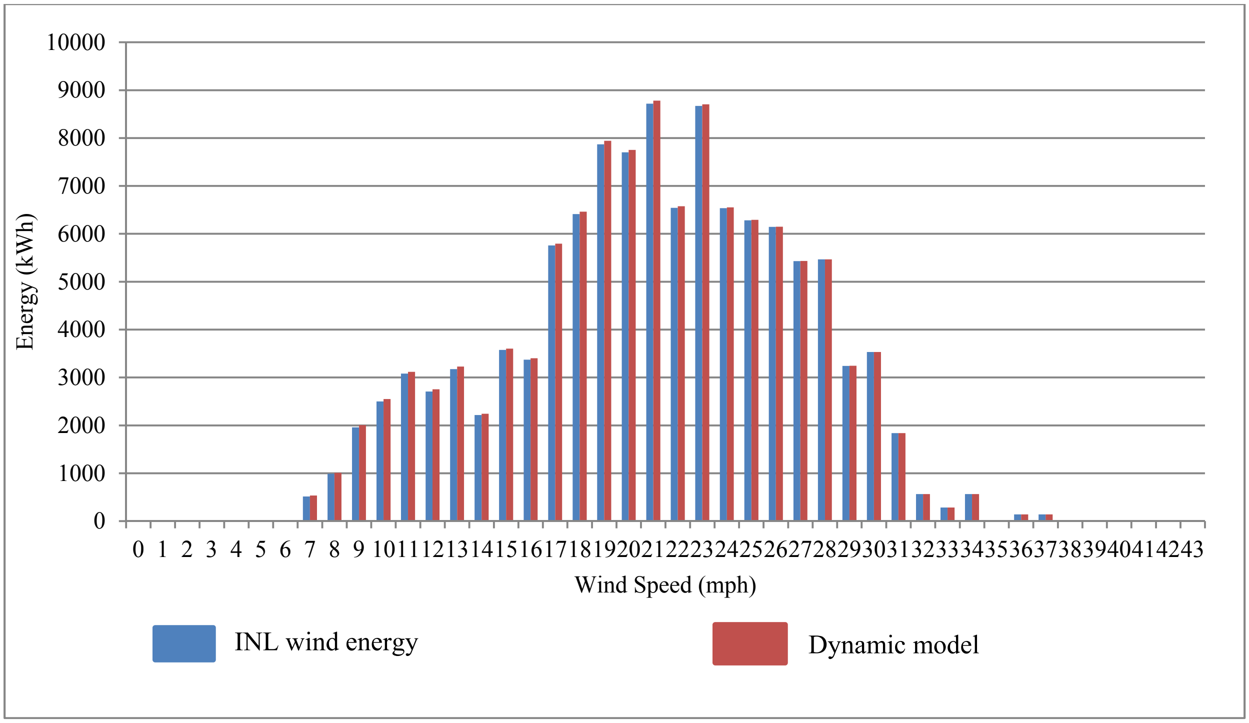


Figure 3.3 Comparative results of energy at different speed bins

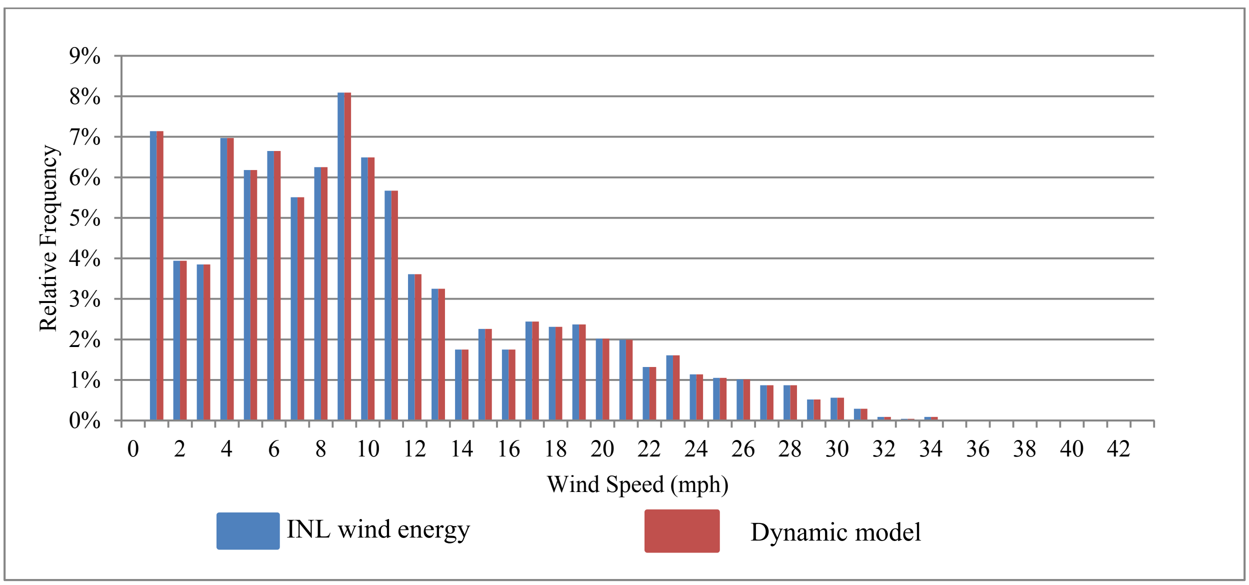


Figure 3.4 Comparative results of the frequency distribution of wind

In the speed bins, the difference between the total energy generations in each bin from the two codes was generally below 2.5% with the exception of the bin of 7 mph where the difference was approximately 3.5%. The direction bins show relatively lower differences, with the highest difference being 0.09%.

The base model without the dynamic yaw misalignment correction generates similar results as other estimation techniques confirming the validity of the model.

3.1.2 Time line of data set

At different stages of the project, the buoy was deployed at different locations. The range gates (RG) of the Wind Sentinel were varied for different locations. The timeline, locations and altitudes of the buoy are presented below:

Table 3.2 Time line of the buoy location

Time frame	Location	Duration
October 7, 2011 to November 3, 2011	Lake Muskegon	28 days
November 8, 2011 to December 30, 2011	Lake Michigan (near shore)	53 days
January 5, 2012 to May 7, 2012	NOAA field station (Muskegon)	124 days
May 7, 2012 to December 15, 2012	Mid-lake plateau of Lake Michigan	223 days

Table 3.3 Altitudes of different range gates at different deployments

Location	Altitudes (m)					
	RG1	RG2	RG3	RG4	RG5	RG6
Lake Muskegon	55	60	75	90	110	120
Lake Michigan (near shore)	55	60	75	90	110	120
NOAA field station (Muskegon)	55	60	75	90	110	120
Mid-lake plateau of Lake Michigan	75	90	105	125	150	175

The results of longest deployment (mid-lake plateau) and range gate 1 are presented here. The other deployment results are attached in Appendix B for further reading.

3.1.3 Effect of yaw rate and delay time

The dynamic control model required two important parameters, yaw rate and delay time, to estimate the energy that can be harnessed. The effect of yaw rate on the energy output can be observed from Figure 3.5. The figure presents the estimated energy at a hub height of 75 m (RG1) for mid-lake deployment. The data sets were averaged over 1 minute time step.

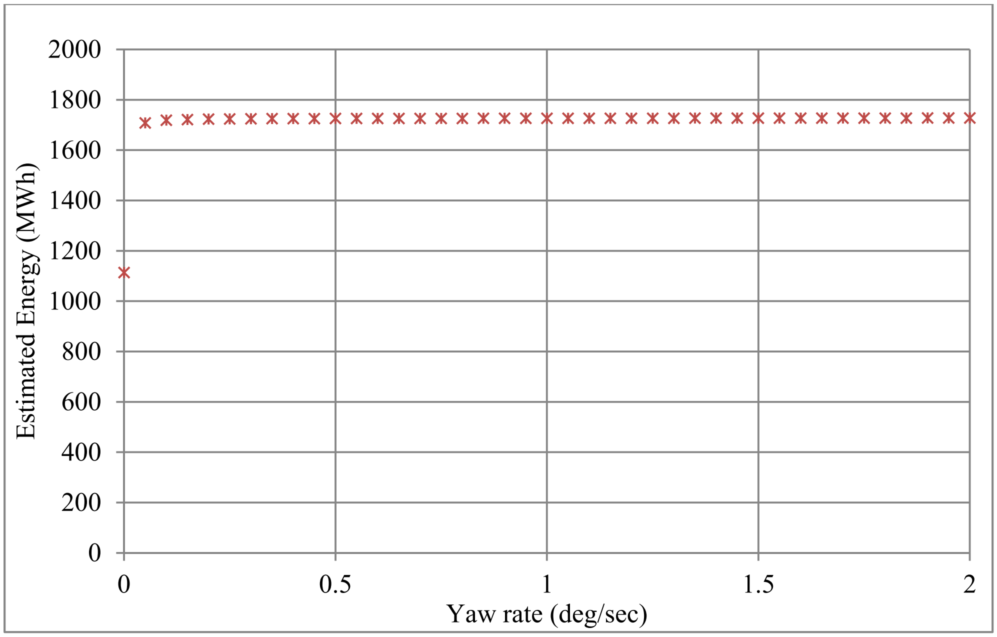


Figure 3.5 Effect of yaw rate on estimated energy

A close up look of the very slow yaw rate can be seen in Figure 3.6. This figure shows that the energy output increases with the increase of yaw rate. However, the relation between the energy output and the yaw rate is dependent on the turbine model and wind data.

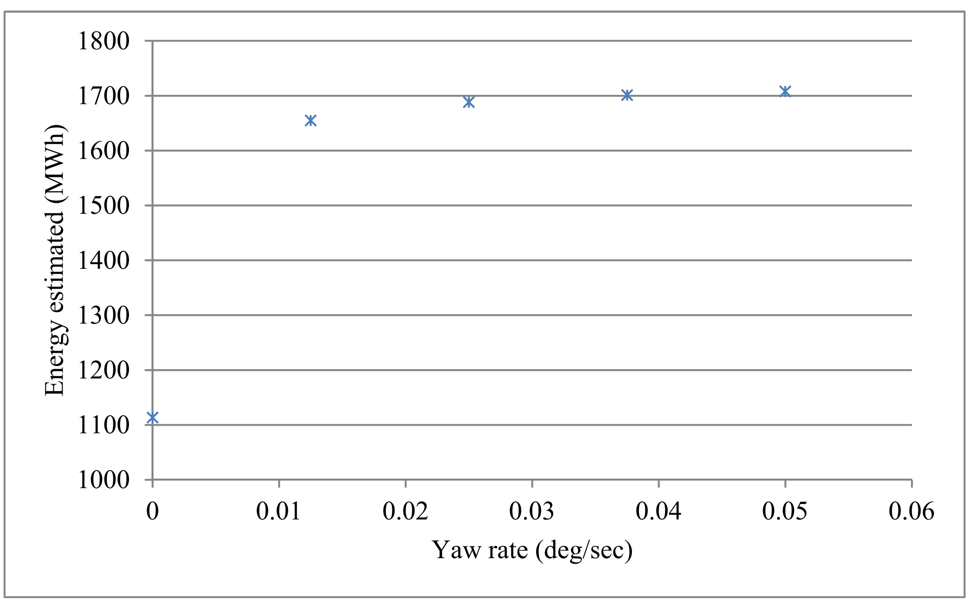


Figure 3.6 Estimated energy at slow yaw rate for Gamesa Eolica G52-850kW

The turbine model used for the analysis was Gamesa Eolica G52-850kW. The associated power curve of the turbine can be found in Figure 3.7.

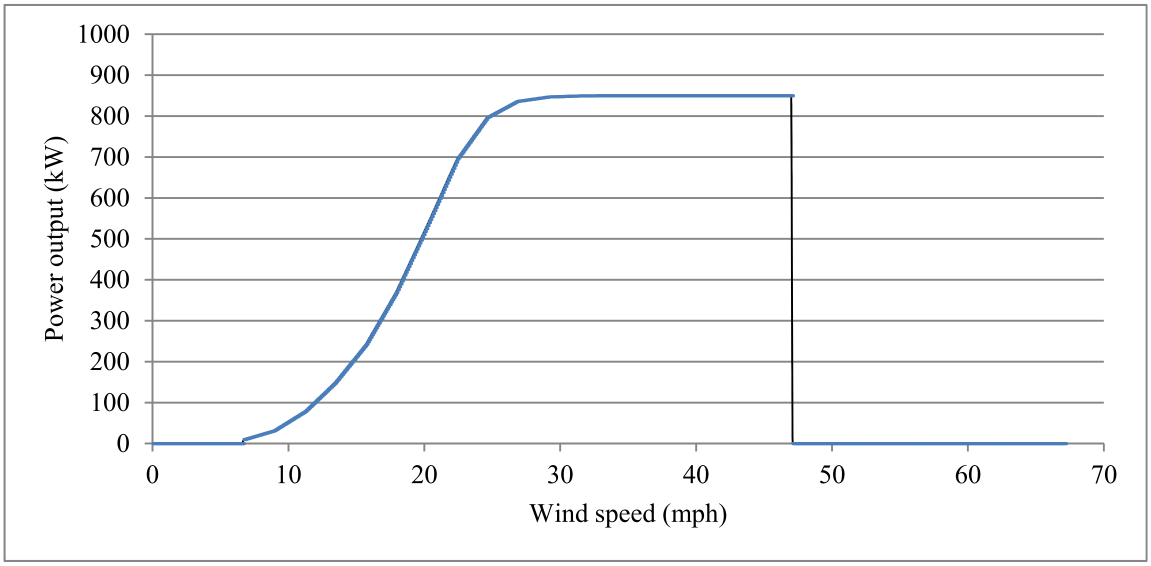


Figure 3.7 Power curve of Gamesa Eolica G52 850kW [13]

The turbine parameters are (estimated from the power curve):

Cut in speed: 8.9 mph

Cutout speed: 47 mph

Rated speed: 31.3 mph

Region 2 threshold of yaw error (assumed from a generalized estimation found in [11]): 8^{o}

Region 3 threshold of yaw error (assumed from a generalized estimation found in [11]): 18^{o}

In this study the yaw rate was varied from 0 deg/sec to 2 deg/sec at an increment of 0.05 deg/sec. It can be observed that the energy output increased with the increase of yaw rate. However, the increase is sharp from yaw rate of 0 deg/sec (no yaw movement) to 0.05 deg/sec. After that, the rate of increase decreases dramatically.

This is because the fast yawing turbine will align itself with the prevailing wind much faster that slow yawing turbine. This results a higher energy output. However, one thing that has to be considered is that the turbine first senses the wind direction and then tries to align itself with the wind direction but the wind direction may change by the time the turbine aligns. Therefore, the turbine may always be subject to yaw error as it is aligning itself with the wind that already passed the turbine. Nevertheless, higher yaw rate would help the turbine to align much faster that the slower one.

Now let us observe the effect of the delay time on the energy output from Figure 3.8. The energy output of the turbine at a yaw rate of 0.05 deg/sec at different delay times is presented here. As seen from the figure this phenomenon is quite unpredictable and solely depends on the instantaneous wind direction. The energy output varies with the delay time but not in any orderly fashion and the highest energy yield is at the minimum delay time (in this case 1 min = 60 sec). An optimized value can be suggested to reduce the wear on the turbine components by knowing the corresponding parameters such fatigue life of design, endurance limit of the materials, etc.

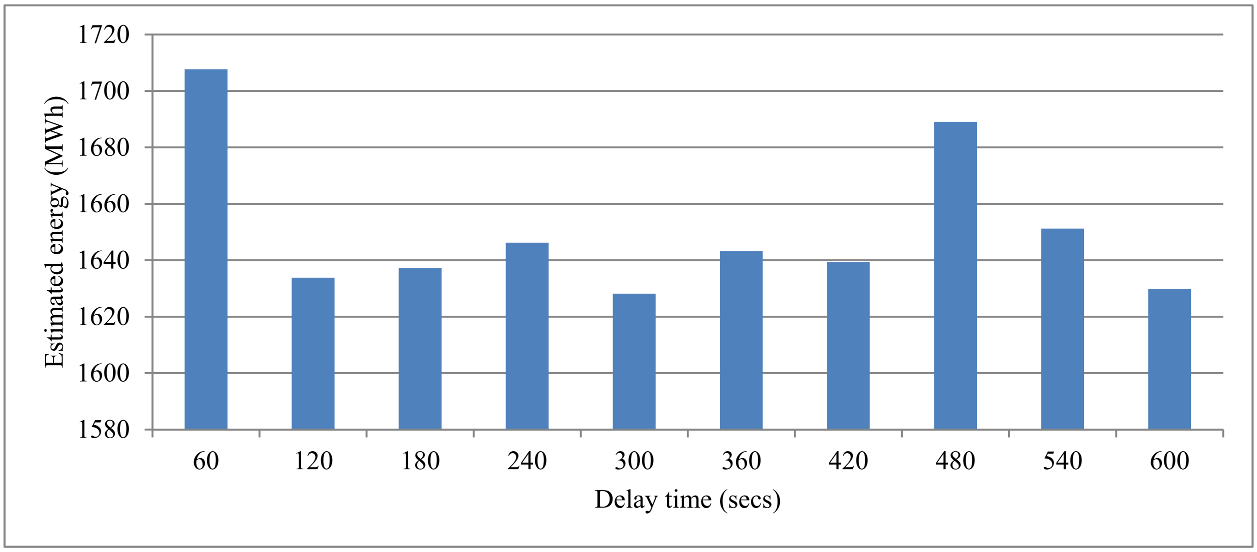


Figure 3.8 Effect of delay time on estimated energy

In the case of the delay time it is not easy to predict the variation in energy output with the change of delay time. First it is to be noticed that, the minimum delay time cannot be lower than the time step of the data. However, the delay time does not have a maximum limit. Typically it can be expected that, at longer delay time the turbine will be at yaw error for longer time if the wind direction changes within that delay time. It might happen that the direction did not change significantly during that time span. Then the energy output will not vary that much. On the other hand it might also happen that the shorter delay time may result in larger yaw error over the time because the controller takes decision by sensing the instantaneous wind direction.

For example consider Table 3.4 of wind data (wind speed in mph, wind direction in due north). In this table T.O. stands for turbine orientation due north, and A.Y.E. stands for absolute yaw error in degree. The turbine will change its orientation if the yaw error is more than 8˚. Let us assume that the yaw rate is large enough to compensate the yaw errors within a single time step for this example. From the table it can be seen that, even for shorter delay time of 5 min the average yaw error is greater than the longer delay time. The reason for this is that the yaw correction decision taken by the controller is based on the wind data at that instant. This leads the turbine to be in greater yaw error for the coming delay time. Since the energy output is a function of yaw error the energy output will vary according to the error. Also, the error affects the energy output through a cosine function relation (as in Equation (14)). Therefore, both the positive and negative error of same magnitude affects the energy output by same amount.

Table 3.4 A hypothetical case of wind data, turbine orientation and average yaw error

Time stamp	Wind Speed (mph)	Wind direction (due north)	Delay time 1 min		Delay time 5 min		Delay time 10 min	
			T.O.	A.Y.E.	T.O.	A.Y.E.	T.O.	A.Y.E.
12:00AM	8.9	160	150	10	150	10	150	10
12:01AM	9	170	160	10	150	20	150	20
12:02AM	10.1	166	170	4	150	16	150	16
12:03AM	10.4	161	170	9	150	11	150	11
12:04AM	11.1	170	161	9	150	20	150	20
12:05AM	9.2	189	170	19	150	39	150	39
12:06AM	8.8	160	189	13	189	29	150	10
12:07AM	9.1	160	189	29	189	29	150	10
12:08AM	10.1	180	160	20	189	20	150	30
12:09AM	11.1	160	180	20	189	20	150	10
12:10AM	9.5	166	160	6	189	23	150	16
Average yaw error				16.55		21.54		17.46

Another important phenomenon can be observed from Table 3.4 that even at the minimum delay time which is the time step of the data (in this example, 1 min) the turbine is never aligned with the prevailing wind. The reason for this is that the turbine controller takes decision based on the past time step. Therefore, it is theoretically not possible to truly align the turbine at every instant with the prevailing wind without measuring the wind direction at upstream of the wind turbine or predicting the wind direction up ahead. Even predicting the wind speed for a small time period is very difficult as the wind is unpredictable by nature.

It can be deduced that the effect of delay time on the energy output is random. However, it can be stated that the maximum energy output will be on the minimum delay time. Anything higher than the minimum delay time will result a lower energy output.

Moreover, it should be considered that both yaw rate and delay time dictate the energy output. Therefore, the energy output varies as their combinations change. The results of different energy output at different combinations of yaw rate and delay time are presented in Table 3.5.

Table 3.5 Energy output (MWh) at different yaw rate and delay time for Gamesa Eolica G52 850kW (mid-lake deployment, RG1, 1 min data set)

Yaw Rate (deg/sec)	**Delay Time (sec)**									
	60	120	180	240	300	360	420	480	540	600
0	1113.37	1073.65	1082.55	1085.48	1078.75	1083.21	1084.09	1109.55	1088.61	1079.35
0.05	1707.73	1633.82	1637.15	1646.24	1628.18	1643.24	1639.33	1689.08	1651.24	1629.88
0.1	1718.53	1648.22	1650.63	1661.01	1642.93	1652.28	1650.36	1700.15	1663.71	1639.13
0.15	1721.22	1654.12	1656.88	1663.38	1645.68	1657.75	1653.04	1702.78	1668.12	1642.84
0.2	1723.14	1657.98	1659.94	1667.81	1650.14	1661.00	1655.17	1705.75	1671.48	1645.51
0.25	1724.04	1660.60	1663.13	1669.32	1653.74	1663.28	1656.70	1707.31	1678.32	1648.17
0.3	1724.53	1662.47	1666.74	1672.04	1655.85	1665.20	1657.24	1708.31	1681.35	1649.82
0.35	1724.83	1664.25	1669.49	1672.61	1657.74	1666.60	1658.20	1709.18	1682.91	1650.90
0.4	1725.12	1665.67	1670.87	1673.84	1659.78	1668.17	1658.92	1710.20	1685.58	1652.91
0.45	1725.35	1666.90	1672.21	1674.86	1661.38	1668.84	1659.79	1710.49	1689.33	1654.29
0.5	1725.51	1667.97	1673.37	1675.72	1662.76	1669.50	1659.76	1710.95	1690.49	1655.31
0.55	1725.59	1668.87	1674.75	1676.51	1663.88	1670.15	1660.36	1711.19	1691.05	1655.90
0.6	1725.66	1669.64	1675.85	1677.32	1664.55	1671.59	1660.92	1711.44	1691.81	1656.72
0.65	1725.76	1670.38	1676.55	1677.67	1665.29	1675.57	1661.32	1711.81	1692.04	1657.18
0.7	1725.85	1670.88	1678.34	1677.81	1666.87	1676.82	1662.01	1712.10	1692.25	1657.40
0.75	1725.95	1671.24	1681.32	1677.93	1669.31	1677.24	1662.03	1712.38	1691.98	1657.33
0.8	1726.01	1671.68	1682.98	1678.11	1671.28	1677.47	1662.61	1712.59	1692.28	1657.87
0.85	1726.06	1672.16	1683.68	1678.36	1671.76	1677.73	1662.40	1712.56	1692.17	1657.57
0.9	1726.10	1672.54	1683.77	1678.72	1671.74	1677.65	1662.41	1712.78	1692.09	1657.71
0.95	1726.11	1672.85	1683.97	1678.81	1672.42	1677.59	1662.84	1713.01	1691.97	1657.84
1	1726.16	1673.19	1684.74	1678.75	1673.07	1677.87	1662.71	1712.61	1691.64	1657.51
1.05	1726.24	1673.50	1685.19	1679.21	1673.18	1677.68	1662.81	1712.91	1692.08	1657.62
1.1	1726.31	1673.85	1686.52	1679.20	1672.60	1677.23	1662.91	1712.88	1691.98	1657.21
1.15	1726.35	1674.28	1687.61	1679.35	1671.90	1676.38	1663.18	1712.54	1690.91	1656.63
1.2	1726.40	1674.76	1688.07	1679.61	1671.77	1676.69	1662.67	1712.03	1690.28	1656.45
1.25	1726.49	1675.23	1688.18	1679.80	1672.80	1677.70	1662.90	1712.38	1691.57	1657.60
1.3	1726.61	1675.71	1688.74	1680.00	1673.48	1678.46	1663.28	1712.66	1692.15	1658.38
1.35	1726.74	1676.07	1688.89	1680.21	1673.54	1678.63	1663.63	1712.85	1692.62	1658.74
1.4	1726.82	1676.35	1689.08	1680.30	1673.63	1678.18	1663.69	1712.86	1692.43	1658.24

Yaw Rate (deg/sec)	Delay Time (sec)									
	60	120	180	240	300	360	420	480	540	600
1.45	1726.84	1676.71	1689.08	1680.28	1673.48	1677.02	1663.38	1712.54	1691.75	1656.70
1.5	1726.88	1677.06	1688.38	1679.82	1670.44	1674.48	1662.07	1712.23	1688.17	1654.58
1.55	1726.73	1677.31	1688.37	1679.80	1669.40	1673.49	1661.92	1712.31	1687.70	1653.58
1.6	1726.78	1677.67	1688.65	1679.95	1669.71	1673.54	1662.13	1712.47	1687.47	1654.07
1.65	1726.87	1678.05	1689.06	1680.18	1670.36	1674.16	1662.63	1712.50	1688.27	1654.83
1.7	1726.99	1678.46	1689.35	1680.40	1671.27	1674.99	1662.94	1712.77	1688.96	1655.67
1.75	1727.11	1678.85	1689.67	1680.96	1672.21	1675.84	1663.61	1713.01	1690.24	1656.81
1.8	1727.22	1679.24	1689.92	1681.29	1673.32	1677.00	1664.23	1713.28	1691.30	1657.80
1.85	1727.30	1679.62	1690.25	1681.63	1674.31	1678.00	1664.72	1713.47	1692.37	1658.68
1.9	1727.35	1679.89	1690.39	1681.81	1675.17	1678.55	1664.92	1713.54	1692.64	1658.80
1.95	1727.39	1680.15	1690.41	1681.77	1675.68	1679.03	1664.90	1712.97	1692.66	1658.93
2	1727.39	1680.43	1690.37	1681.58	1675.35	1678.62	1664.69	1712.13	1691.68	1658.48

The results of other deployment and other range gates are presented in Appendix B.1, B.2, and B.3.

3.1.4 Comparison with INL wind energy model

Now let us compare the energy output difference between the INL wind energy model and the dynamic model of this study. Figure 3.9 shows the energy estimated by the INL wind energy in comparison to the dynamic model developed. In both cases the same turbine model Gamesa Eolica G52-850kW was used.

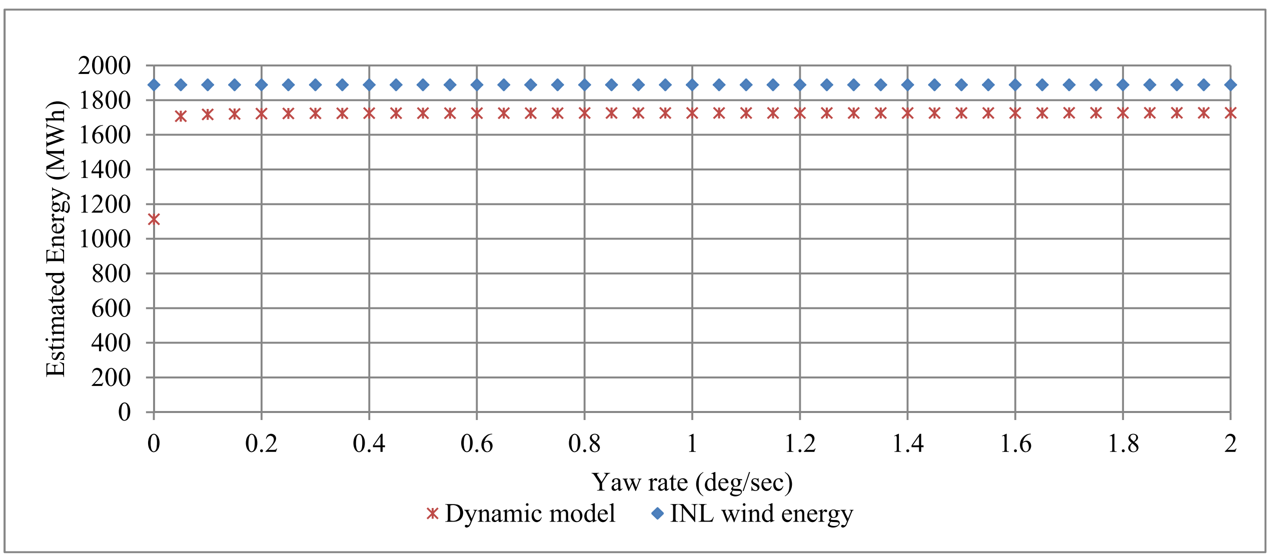


Figure 3.9 Comparison of energy estimate by INL wind energy and dynamic model

It can be seen from Figure 3.9 that the INL wind energy program overestimates the energy by 7% for this time period. This is due to the basic assumption of the INL wind energy program, which states that the turbine is aligned with the prevailing wind at any instant.

3.1.5 Comparison with other models

A comparison of the estimated energy with other energy estimation methods can be found in Figure 3.10. The available energy in the wind during that time period is also presented in the figure.

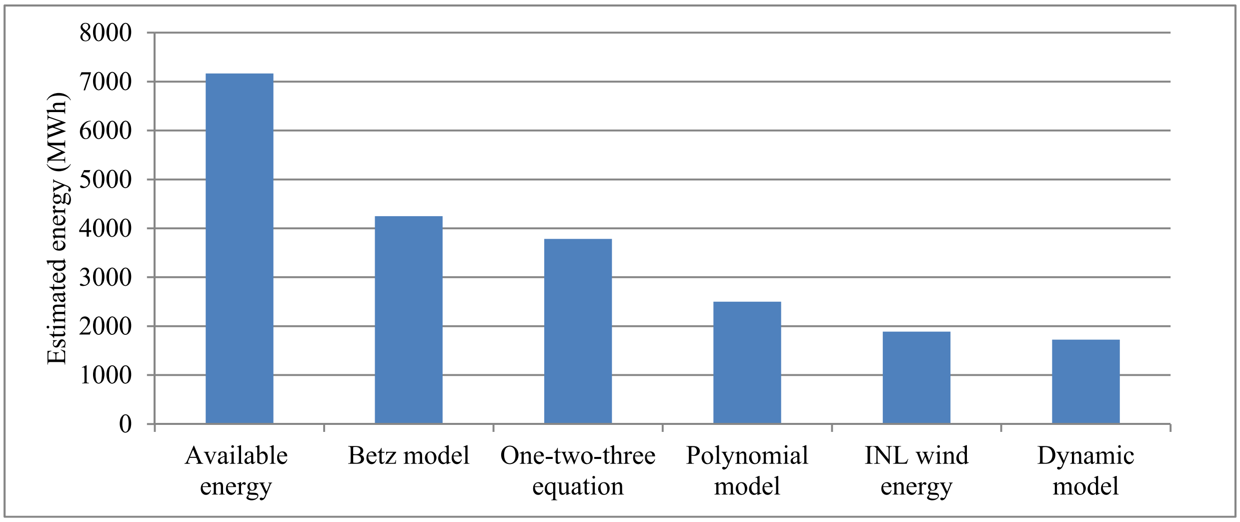


Figure 3.10 Estimated energy by different models

In Figure 3.10 the one-two-three equation, polynomial model, INL wind energy, and dynamic model are turbine specific energy estimates. It can be seen from the figure that by Gamesa Eolica G52-850kW only 24% of the available wind energy can be harnessed (estimation based on the dynamic model). Similarly for INL wind energy model the energy that can be harnessed from wind is 26% and by polynomial model it is 35%. The other range gates and other deployment results can be found in Appendix B.1, B.2 and B.3.

3.1.6 Effect of turbine model

Other turbine options were explored to observe the energy output. The wind frequency distribution for this time period is presented in Figure 3.11. From the frequency distribution we can see that most of the time the wind has a speed of 5 mph ~ 27 mph. Therefore, a turbine with high power output in this range would be a good fit for this location.

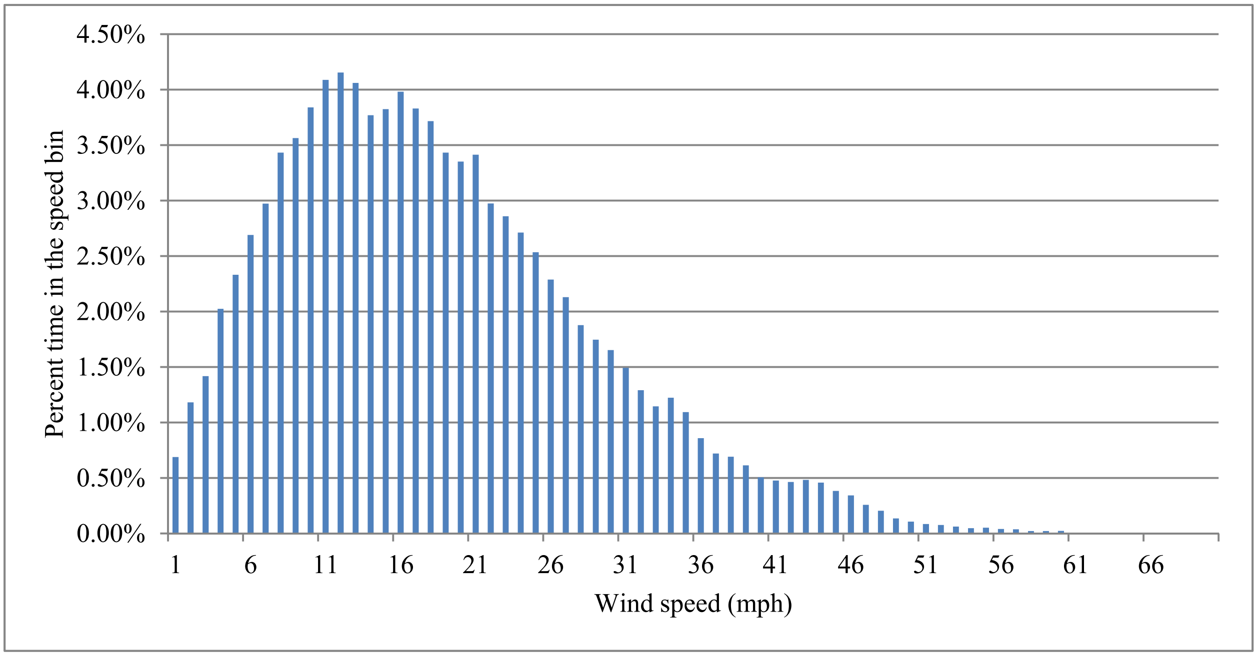


Figure 3.11 Frequency distribution of wind

The explored turbine model was Lagerwey LW72-2000kW. This turbine had a broader operating range. The power curve of this turbine is presented in Figure 3.12. The turbine parameters for the dynamic model are:

Cut in speed: 5 mph

Cutout speed: 57 mph

Rated speed: 33 mph

Region 2 threshold of yaw error (assumed from a generalized estimation found in [11]): 8^{o}

Region 3 threshold of yaw error (assumed from a generalized estimation found in [11]): 18^{o}

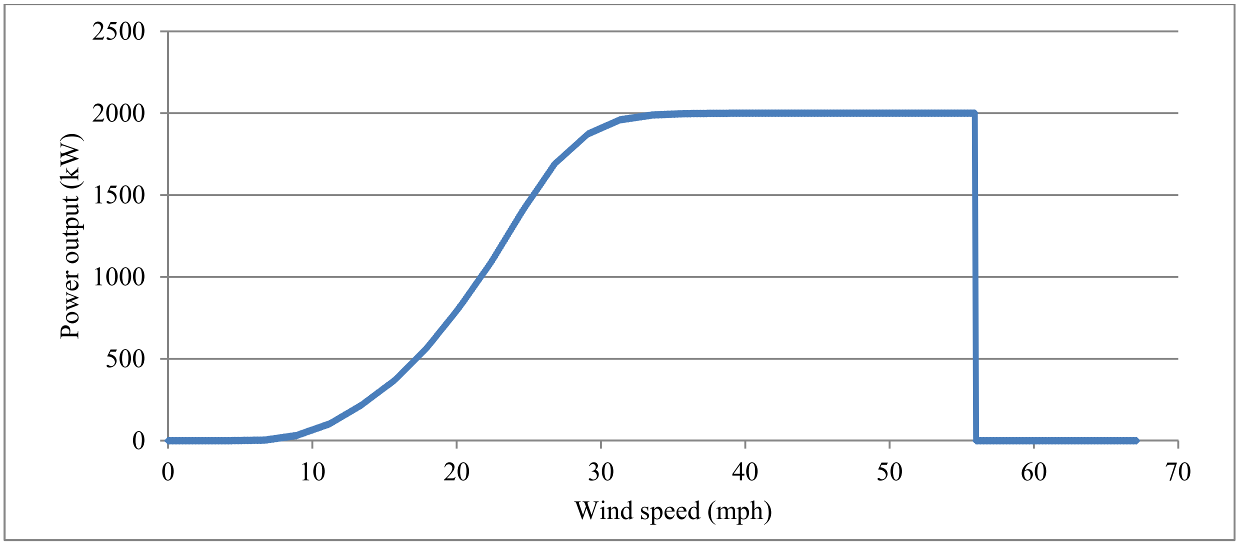


Figure 3.12 Power curve of Lagerwey LW72-2000kW [13]

The energy estimated by different models using Lagerwey LW72-2000kW and Gamesa Eolica G52-850kW can be found in Figure 3.13. The energy output was doubled after using this turbine model. However, the Lagerwey LW72-2000kW turbine is able to harness approximately 26% of the available wind energy as opposed to 24% for Gamesa Eolica G52-850 kW.

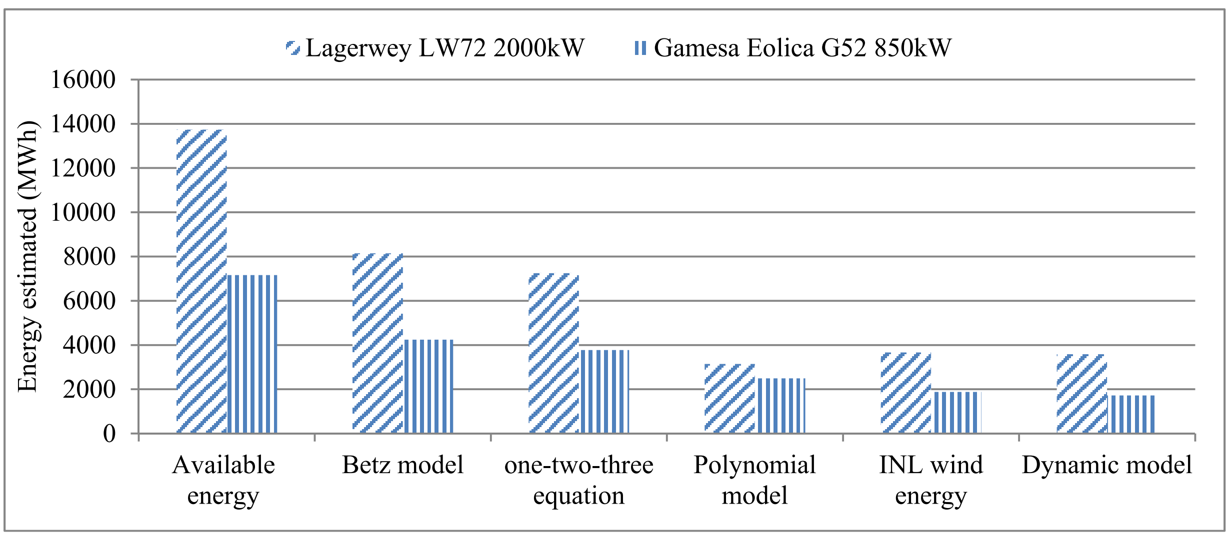


Figure 3.13 Energy estimated by different wind turbine model

3.1.7 Other range gate results

The results of the dynamic model for RG2, RG3, RG4 for mid-lake deployment at a delay time of 1 min are presented in Figure 3.14. The turbine model is Gamesa Eolica G52 850kW. The time period is the mid-lake plateau deployment. RG5 and RG6 were set at altitudes of 150 m and 175 m respectively during mid-lake deployment of the buoy. They were set to test the capabilities of the vindicator sensor but significant amount of data could not be collected by these two range gates. Therefore, no analysis was performed on these.

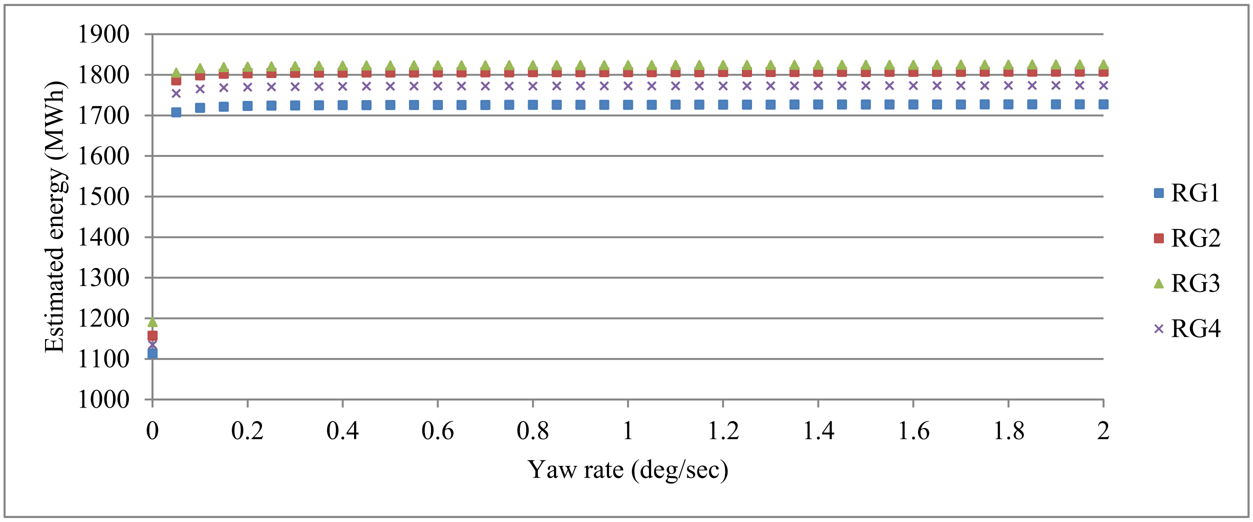


Figure 3.14 Energy estimated at different range gate

It can be seen that the energy estimated increased as the altitude increased. However, the increase was not that significant. The reason for this was that at higher altitudes (75m~125m) the wind speed did not increase that much in this region. The energy output at RG4 was also lower than other range gates. Because the wind speed slowed down at RG4 as seen from Table 3.6. The average wind speeds of the mid-lake deployment for the range gates are presented in Table 3.6. Other deployment results are presented in Appendix B.

Table 3.6 Average wind speeds at different range gates

Range Gate	Altitude(m)	Wind speed (mph)
RG1	75	19.07
RG2	90	19.64
RG3	105	19.83
RG4	125	19.55

Range Gate	Altitude(m)	Wind speed (mph)
RG5	150	18.56
RG6	175	19.07

3.1.8 Effect of time step of data set

A similar study was performed with the 30 sec, 2 min, 5min and 10 min averaged data set. The time frame and the turbine model were similar to the 1 min analysis. The results can be found in Figure 3.15. Theoretically shorter time averaged data set will have more accurate estimation. As we see from the figure the energy estimated varied only less than 2 % with the change of different averaged time.

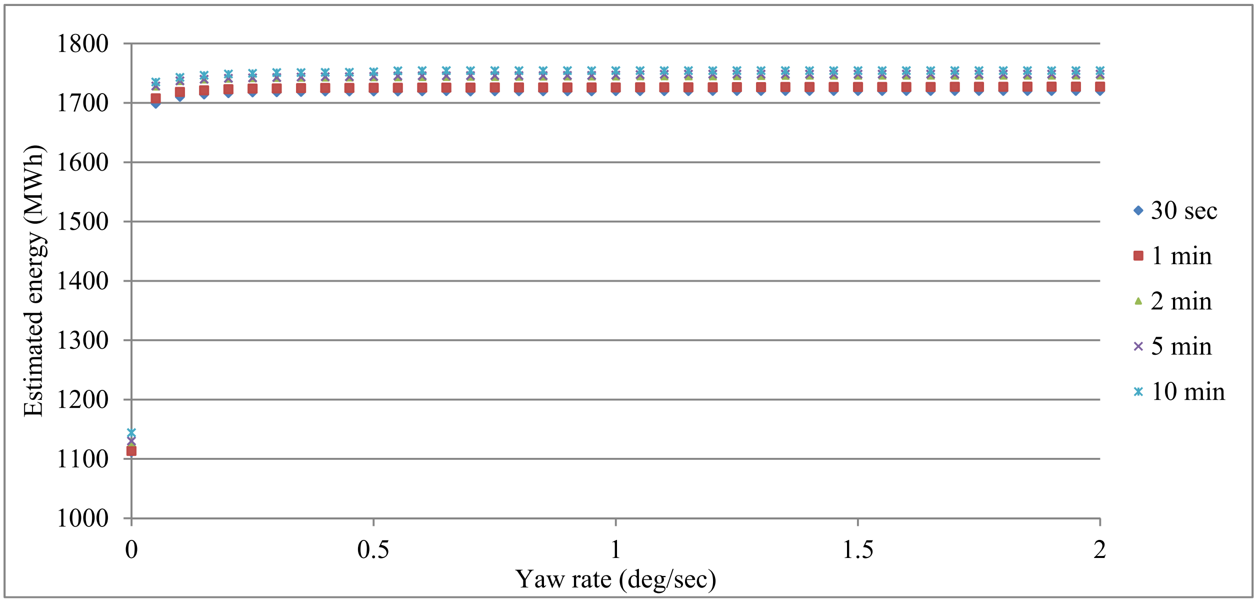


Figure 3.15 Comparison of estimated energy with different time averaged data set

The reason of this increased energy can be explained. At same yaw rate the time taken for the turbine to align itself with the prevailing wind is same for all. Therefore, the yaw error remains minimum for the rest of the delay time. In longer time step the duration of this minimum yaw rate region is longer than shorter time period which results in overestimation in the case of longer time period.

3.1.9 Capacity factor

The capacity factor of a wind farm is the ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full nameplate capacity during operational time.

The capacity factor is generally calculated over a year to include the seasonal variations on the wind. It is normally presented for the total plant. Therefore, the capacity factor reported on one individual turbine and for a partial wind data for the location can be misleading. It can, however, easily be calculated from the results by the following formula.

$$Capacity\ factor = \frac{Energy\ generated\ by\ the\ turbine}{\substack{Energy\ generated\ by\ the\ turbine\ if\ it \\ operates\ at\ rated\ capacity\ for\ the\ entire\ time\ period}} \quad (22)$$

The capacity factors of a single Gamesa Eolica G52 850kW during this time period at different altitudes are presented in Table 3.7. The other deployment results are presented in Appendix B.1.

Table 3.7 Capacity factor at different range gate for Gamesa Eolica G52 850kW

Range Gate	Altitude (m)	Energy output (MWh)	Nameplate capacity (kW)	Capacity factor
RG1	75	1707.732224	850	37.9%
RG2	90	1786.540252	850	39.3%
RG3	105	1805.26632	850	39.7%
RG4	125	1754.083151	850	38.5%

3.1.10 Other deployments

Similar analysis was performed for other locations. For other locations the same turbine model: Gamesa Eolica G52-850kW was used. The detailed results are presented in Appendix B.

3.2 Data representation

3.2.1 Wind rose

The two major data representation techniques that were used in this study were the wind rose and the frequency distribution. Both are a kind of representation of data segregated in bins. If the data set is the wind speed or wind direction segregated by the bin parameter of prevailing wind direction then it is called the wind rose. If the data set is wind speed segregated by the bin parameter of wind speed it is called the frequency distribution.

The wind rose is the graphical representation of the average wind speed or average duration of wind in any particular range of direction. Therefore, two types of wind rose were generated for the data set: the average wind speed in every direction bin and the duration of wind in any direction bin. The bin size was 10 degrees. For computation, a MATLAB script was developed based on the algorithm presented in Methodology. To generate the wind roses MS Excel® was used using the data calculated by MATLAB. The plot type was radar type plot available in MS Excel.

The wind roses of mid-lake deployment can be found in Figure 3.16 and Figure 3.17. 10 min averaged data sets were used to generate these wind roses. The data was collected at a height of 75 m. The wind roses at a height of 90 m for other deployments can be found in Appendix B.2, B.3, and B.4.

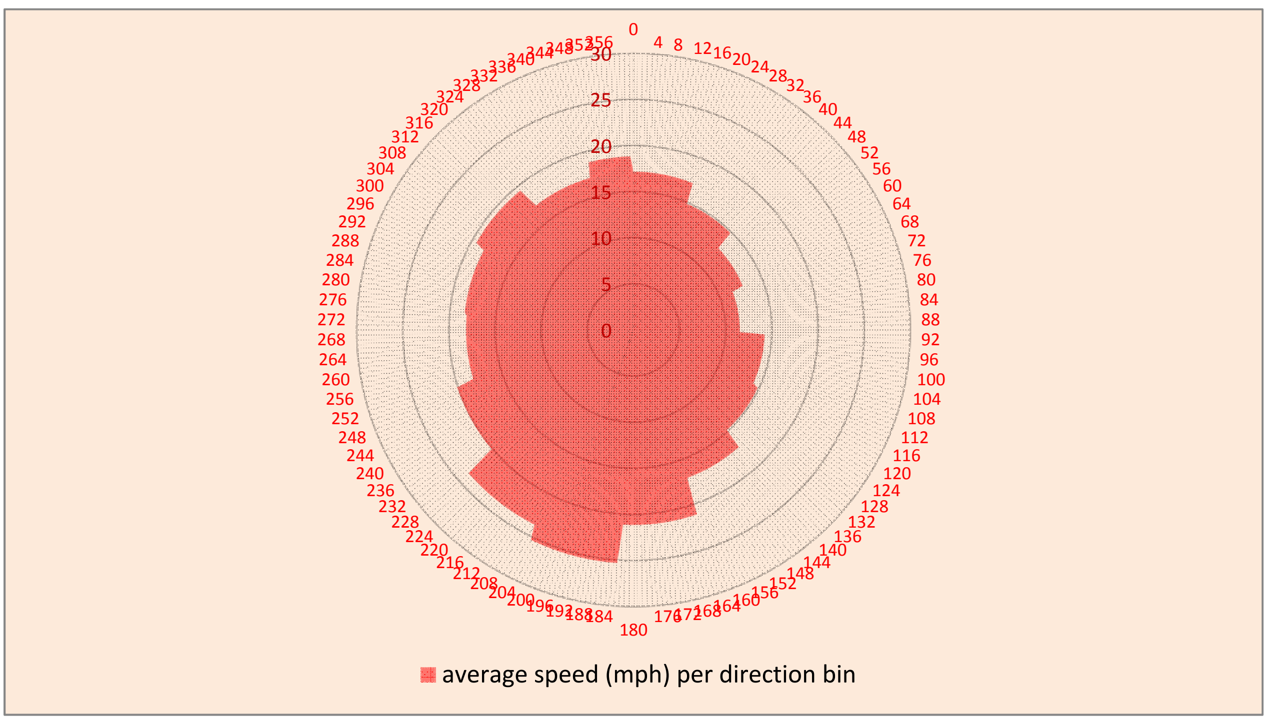


Figure 3.16 Wind rose of averaged speed per direction bin

The wind rose is helpful to determine the predominant wind direction of that location during the time period. The seasonal changes in wind direction and wind speed of a location can be found by comparing the wind roses of different seasons.

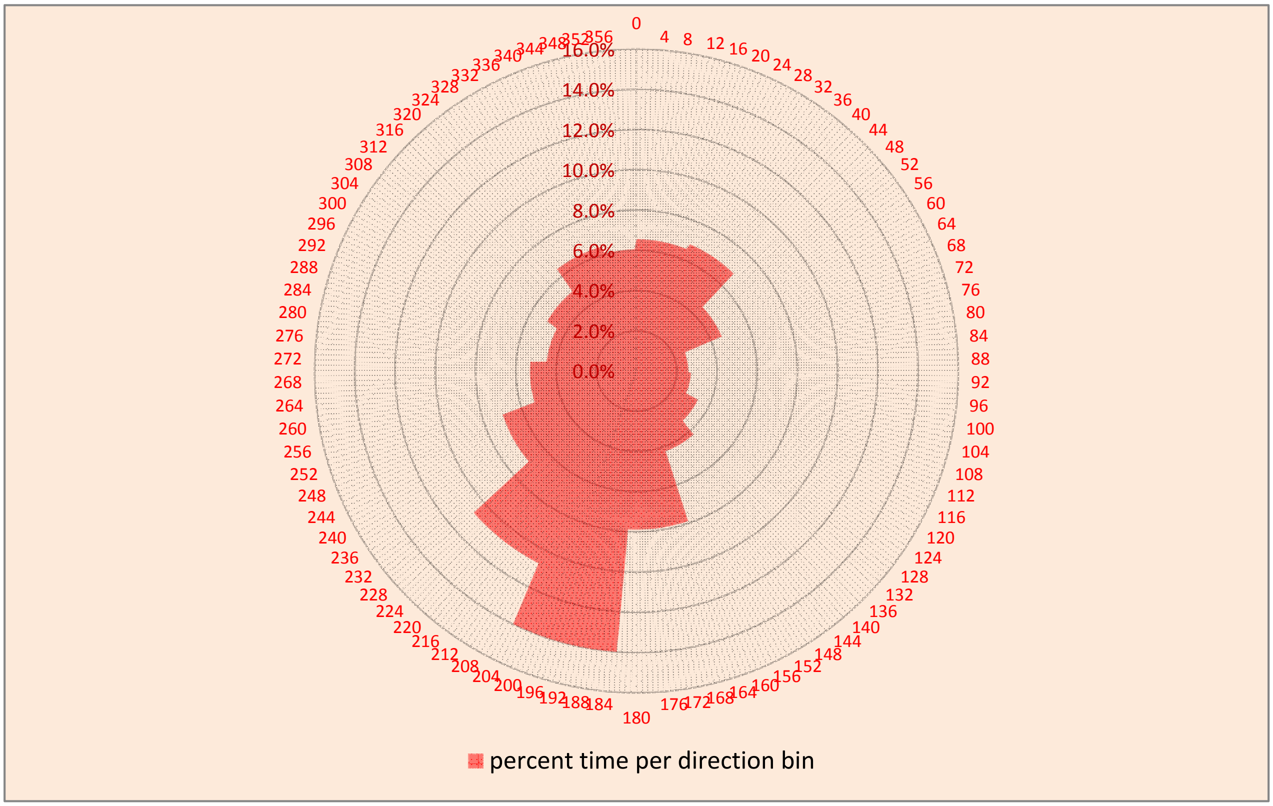


Figure 3.17 Wind rose of fraction time per direction bin

3.2.2 Frequency distribution

Frequency distribution is also calculated by a MATLAB script based on the algorithm presented in Figure 2.7. Unlike the wind rose this plot is more helpful for longer time period of data. The frequency distribution of the RG1 data during the mid-lake deployment is shown in Figure 3.18.

Some interesting information can be found Figure 3.18. First, the typical wind frequency curve follows Weibull or Rayleigh distribution curve. Frequency distribution provides a qualitative result of the data. By knowing the distribution parameters for that location the wind regime can also be predicted for long range energy mapping. However, to estimate the Weibull parameters of that location more than 1~5 years of wind data set is required to remove any seasonal bias. Due to the lack of data these parameters could not be estimated.

Another important feature of frequency distribution is that it shows the wind speeds at which the wind blows most of the time at that location. Therefore, while choosing a turbine for a given location this information can be very helpful as we have seen before. The turbine should have an operating speed which matches the wind speed at which the wind blows most of the time. This way the turbine can harness most of the energy from that location.

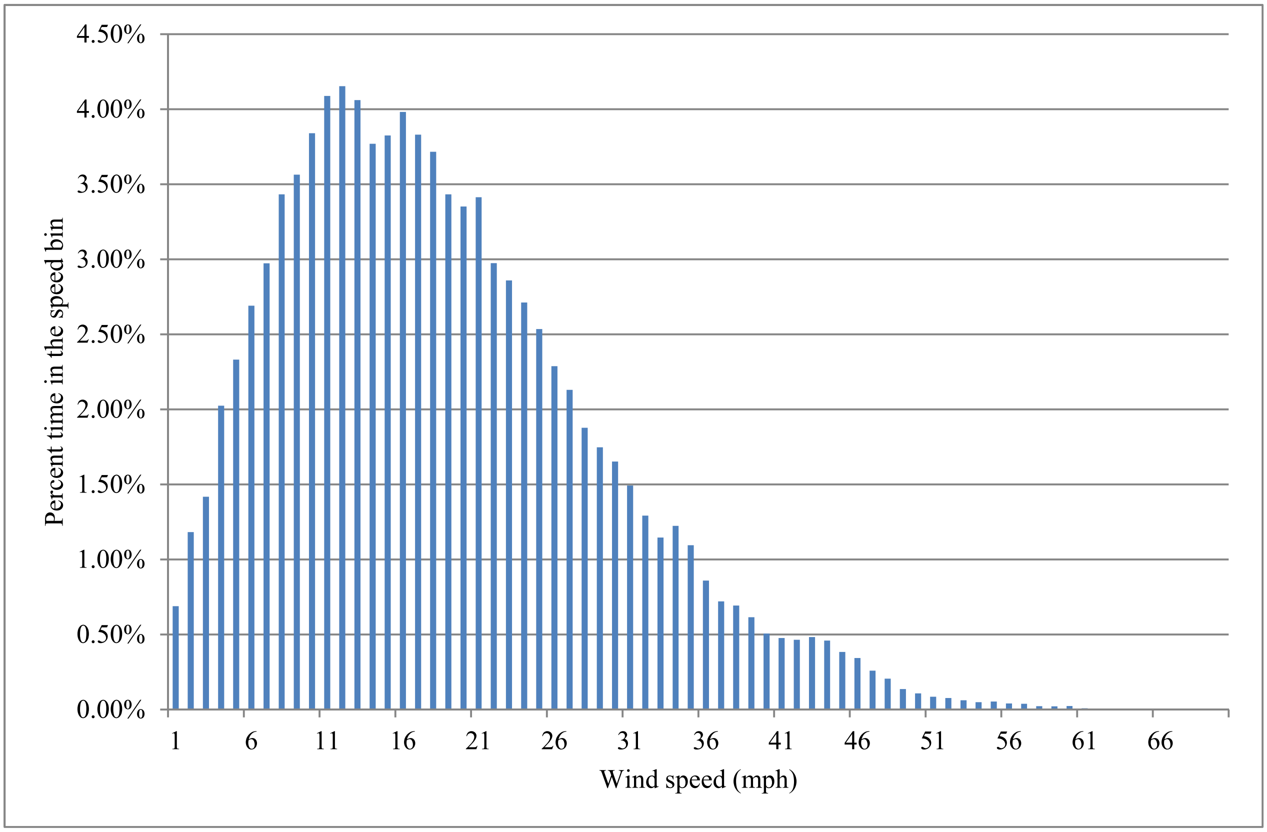


Figure 3.18 Frequency distribution of RG 1

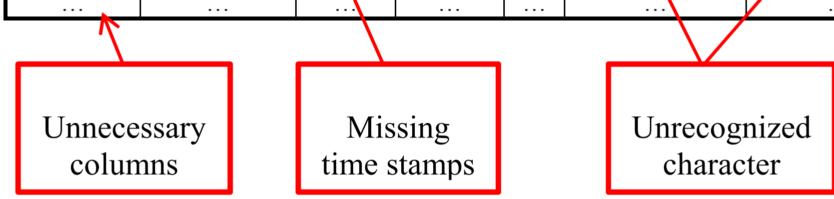
3.3 Data Preprocessing

3.3.1 1 Hz data set

A sample unrefined data set can be found in Table 3.8. The problems with the data set are also marked in the figure.

Table 3.8 Unrefined data set example

DataDBID	DataTimeStamp	ModbusNodeID	SerialNumber	…	WindSpeedHor3MinRG1	WindSpeedHor10MinRG1	WindDirHorRG1	WindDirHor3MinRG1	…
…	…	…	…	…	…	…	…	…	…
1768a1…	1:28:02 PM	1	8	…	4	-4.4	0	0	…
d6068c…	1:28:09 PM	1	8	…	2	-4.8	0	0	…
12695…	1:28:10 PM	1	8	…	1.5	Â	0	0	…
17d8c…	1:28:11 PM	1	8	…	Â	-6.6	0	0	…
…	…	…	…	…	…	…	…	…	…



From the unrefined data table the problems were identified as:

1. Unnecessary columns: These were deleted in the refined 1 Hz data set.
2. Missing time stamps: The missing time stamps were filled with NaN values to work with MATLAB codes.
3. The unrecognized characters were replaced by NaN values also.

A refined 1 Hz data set is presented in Table 3.9.

Table 3.9 Refined 1 Hz data example

DataTimeStamp	ModbusNodeID	SerialNumber	…	WindSpeedHor3MinRG1	WindSpeedHor10MinRG1	WindDirHorRG1	WindDirHor3MinRG1	…
…	…	…	…	…	…	…	…	…
1:28:02 PM	1	8	…	4	-4.4	0	0	…
1:28:03 PM	NaN	NaN	…	NaN	NaN	NaN	NaN	…
1:28:04 PM	NaN	NaN	…	NaN	NaN	NaN	NaN	…
1:28:05 PM	NaN	NaN	…	NaN	NaN	NaN	NaN	…
1:28:06 PM	NaN	NaN	…	NaN	NaN	NaN	NaN	…
1:28:07 PM	NaN	NaN	…	NaN	NaN	NaN	NaN	…
1:28:08 PM	NaN	NaN	…	NaN	NaN	NaN	NaN	…
1:28:09 PM	1	8	…	2	-4.8	0	0	…
1:28:10 PM	1	8	…	1.5	NaN	0	0	…
1:28:11 PM	1	8	…	NaN	-6.6	0	0	…
…	…	…	…	…	…	…	…	…

3.3.2 Time averaged data set

The refined 1 Hz data set then used to generate the time averaged data set. Data were averaged over 30 sec, 1 min, 2 min, 5 min, and 10 min time period. A sample output of the averaged data set can be found in Table 3.10. The standard deviations were also calculated for any possible future work with this data set.

Table 3.10 Time averaged data set example (30 sec)

DataTimeStamp	RG1 Speed	RG1 Direction	RG2 Speed	…	RG1wind speed Standard deviation	RG1wind direction Standard deviation	RG2wind speed Standard deviation	…
…	…	…		…	…	…	…	…
1:28:00 PM	NaN	NaN	NaN	…	NaN	NaN	NaN	…
1:28:30 PM	8	163	8.2	…	0.002	0.005	0.002	…
1:29:00 PM	8.2	165	8.4	…	0.004	0.004	0.003	…
1:29:30 PM	8.3	159	8.5	…	0.054	0.024	0.004	…
1:30:00 PM	6.7	168	6.6	…	0.126	0.095	0.097	…
1:30:30 PM	NaN	NaN	NaN	…	NaN	NaN	NaN	…
1:31:00 PM	3	140	3.1	…	NaN	NaN	NaN	…
1:28:09 PM	2.6	138	2.8	…	0.003	0.005	0.004	…
1:28:10 PM	4.1	163	4.36	…	0.004	0.002	0.003	…
1:28:11 PM	1	154	1.1	…	0.008	0.004	0.006	…
…	…	…		…	…	…	…	…

Chapter 4

4.1 Conclusion

This project was conducted to assess the wind potential over Lake Michigan. The wind data were collected at 1 Hz frequency at six different altitudes within the range of 55m-175m at different locations over the entire project period. The data were collected by state-of-art LIDAR sensor mounted on an unmanned buoy named Wind Sentinel that was developed by AXYS Technologies, Inc., Sydney, British Columbia, Canada.

A thorough literature review was performed to develop an accurate methodology to analyze the collected wind data and assess the wind potential over Lake Michigan. From the literature review it was found that the publicly available estimation techniques overestimate the energy output because of not considering the effect of yaw error and dynamic yaw motion in the estimation process. Therefore, a dynamic mathematical model capable of considering the yaw error and dynamic yaw motion in the estimation technique was developed.

This model required a quality controlled continuous stream of daily data set. However, the collected data were at 1 Hz frequency and had some issues such as missing data and time stamps, unnecessary columns, and unrecognized characters in the data set. A refining module for this unrefined data set was developed to address these issues. An averaging module was also developed to average the data set over 30 sec, 1 min, 2 min, 5 min, and 10 min to observe the effect of data set frequency on the energy output. To represent the dominant wind direction and time duration of wind blowing in different wind directions, a wind rose generating model was developed. A wind frequency generating module was also developed.

The dynamic model was developed in such a way that the effect of yaw control can be included or disregarded in the calculation. If the yaw error is disregarded then the results should be same as the INL wind energy model. The dynamic model was validated by comparing a test data set results with the INL wind energy model. For validation process the effect of yaw error was not considered and the dynamic model generated same results as the INL wind energy model with the same data set which confirms the validity of the MATLAB code developed.

The effect of the two important parameters of the dynamic model, yaw rate and delay time, on the energy output was analyzed. The results suggested that the turbine generated more energy if the yaw rate of the turbine increased. Up to 0.05 deg/sec yaw rate the energy increased sharply. Later the increase was not that significant. The effect of delay time was quite unpredictable. The only conclusion that can be drawn is that the turbine generated highest energy at the minimum delay time which is equal to the time step of the data set.

The findings of the dynamic model were then compared with the INL wind energy model. The INL wind energy model overestimated the output energy. The amount of overestimate depends on the time frame of data as the energy is dependent on the time frame of the data set. For the mid-lake deployment the INL energy model overestimated the output energy by 7% at 75 m altitude. The reason for this was that the INL energy did not consider the yaw misalignment in the energy estimation. The dynamic model results were also compared with the other estimation techniques. The results showed that the turbine used for calculation (Gamesa Eolica G52-850 kW) could harness about 24% of the available wind energy during the mid-lake deployment at 75 m of hub height. The other locations and hub height results were also very close to this.

The dynamic model was a turbine specific estimation technique like INL wind energy model, polynomial model, and one two three equation model. To observe the effect of turbine model on the estimated output energy another turbine, Lagerwey LW72-2000 kW, was used. The energy output was doubled by using this turbine because the turbine was larger in size and had higher rated power output. However, the turbine harnessed about 26% of the available wind energy. The effect of the time step of the data set was also analyzed by using different time averaged data set. The results showed that longer time averaged data sets overestimated energy by small amounts.

The capacity factors of the turbine used in dynamic model (Gamesa Eolica G58-850 kW) were also calculated. The capacity factor varied from 35%~40% for different altitudes and different deployment locations. Note that, the capacity factor calculated was only for one turbine. A wind farm consists of a large of number of wind turbines. Some of those wind turbines may have a lower capacity factor than the other turbines in that wind farm due to maintenance and unavailability of wind resource. While calculating the capacity factor of the entire wind farm the capacity factors of individual turbines are averaged. Therefore, for entire wind farm the capacity factor is generally lower than the capacity factor of an individual turbine. The wind roses provided a good representation of the prevailing wind direction and wind speed. The frequency distributions for different deployments and different altitudes were also generated.

The dynamic yaw control model predicted that the potential energy output from the Gamesa Eolica G58-850 kW would be about 7% lower than the prediction of the INL wind energy model for the mid-lake deployment of the Wind Sentinel. Of course it does not take into account the power that goes into the dynamic control of the turbine.

4.2 Suggested future work

As seen from the results and discussion section it is not possible to truly align the turbine with the prevailing wind. This results in a loss in energy output. A possible solution for this can be the prediction of the wind direction by utilizing the previous wind direction pattern. A time series can be formed to estimate the wind direction for the coming few seconds. Several mathematical estimation techniques can be used such as artificial neural networking (ANN), machine learning approach, etc. Another solution can be sensing the wind direction upstream of the wind turbine using LIDAR technology. NREL (National Renewable Energy Laboratory) has performed a field test of such kind of technology [18].

The estimated energy by different turbines can be used to perform a cost analysis. By knowing the installation and running cost of different turbine models a cost analysis can be performed to find the best cost effective turbine for any location.

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Appendix A

A.1 Dynamic model

```
%last updated on 17 March 2013 %% final version 2.5

clear;
clc;
close all;
clear all;
% turbine parameters and importing the turbine data
rgn2_spd=8.9;%mph
rgn2_thrsold=8;
rgn3_spd=31.3;%mph
rgn3_thrsold=18;
cut_out=47;
[trbn_data trbn_text]=xlsread('turbine_data.xlsx');
turbine=17;
trbn_power=trbn_data(:,turbine+1);
trbn_speed=trbn_data(:,1);
% for different delay time the data was calculated
for freq=30:30:300
     % saving the results
    freq_s=num2str(freq);
     dtd=['30 sec yaw rate results for 30 sec (lake shore):
',freq_s,' secs.txt'];
     diary(dtd)
     diary on
     disp(freq)
    data_freq=30;

    sumcounter=0;
    f_sumcounter=0;
     % for different yaw rate the results are calculated
     for yaw_rate_per_sec=0:.05:2
          disp(yaw_rate_per_sec)
          yaw_rate=yaw_rate_per_sec*data_freq;% will be changed
in different data set
          dt_freq=data_freq; % data frequency
          ratio=freq/dt_freq;
          reply='y';
          if isempty(reply)
               reply='y';
          end
          if reply=='y'
               dynamic_decision=1;
          else
```

```
               dynamic_decision=2;
          end
          daily_energy=zeros(500,1);
          wind_data_length=86400/dt_freq;
          loop_counter=1;
          for file_name=734811:734868
               file_date=datestr(file_name,29); % ISO format
date
               import_file=['GVSU-Vindicator-30-sec-
',file_date,'.csv'];
               dir_data=dir;
               dir_index=[dir_data.isdir];
               file_list={dir_data(~dir_index).name};
               decision=strcmp(import_file,file_list);
               decision=sum(decision);
               if decision==1
                    str=['Importing file: ',import_file];
                    file=importdata(import_file);

     dynamic_trbn_direction=zeros((86400/dt_freq),6);
                    % if dynamic model activated
                    if dynamic_decision==1
                         c=3; % wind direction column
                         for i=1:6

     dynamic_trbn_direction(1,i)=file(1,c); %initial value
                              c=c+2;
                         end
                         for c=2:2:12
                              for i=1:(86400/dt_freq)
                              file(i,c)=file(i,c)*2.2369;
%conversion to mph
                              end
                         end
                         n=1;
                         for c=2:2:12
                              j=1;
                              k=1;
                              l=1;
                              for i=2:ratio:(86400/dt_freq)


                                   if file(i,c)<=rgn2_spd ||
file(i,c)>cut_out || isnan(file(i,c)) % region 1 and 4
                                for l=i:i+ratio
```

```
dynamic_trbn_direction(l,n)=dynamic_trbn_direction(l-1,n); % no
change in turbine orientation
                                end
                                   elseif (file(i,c)>=rgn2_spd
&& file(i,c)<rgn3_spd)||(file(i,c)>rgn3_spd &&
file(i,c)<=cut_out) % region 2 & 3
                                if file(i,c)>=rgn2_spd &&
file(i,c)<rgn3_spd
                                    thrsold=rgn2_thrsold;
                                else
                                    thrsold=rgn3_thrsold;
                                end
                                        error=file(i-1,c+1)-
dynamic_trbn_direction(i-1,n); %checking yaw error
                                        if abs(error)<thrsold
                                    for l=i:i+ratio

dynamic_trbn_direction(l,n)=dynamic_trbn_direction(l-1,n); % if
yaw error is less than accepted value then no change in turbine
orientation
                                    end
                                        elseif
abs(error)>=thrsold % activated yaw rotation
                                             if error<0 % for
clock wise rotation
                                        sign=1;
                                    else
                                        sign=2;
                                    end
                                    m=1;
                                    % step 1
                                    if yaw_rate>abs(error)

dynamic_trbn_direction(i,n)=file(i-1,c+1); % if yaw movement is
larger than error then the turbine will stop at the angle of
wind direction
                                    else

dynamic_trbn_direction(i,n)=dynamic_trbn_direction(i-1,n)+(-
1)^sign*yaw_rate;
                                    end
                                    % step 2
                                    if ratio==2
                                        error=file(i,c+1)-
dynamic_trbn_direction(i,n);
                                        if yaw_rate>abs(error)
```

```
dynamic_trbn_direction(i+1,n)=file(i,c+1); % if yaw movement is larger than error then the turbine will stop at the angle of wind direction
                                        else

dynamic_trbn_direction(i+1,n)=dynamic_trbn_direction(i,n)+(-1)^sign*yaw_rate;
                                        end
                                    end
                                    if ratio>2

                                       error=file(i,c+1)-dynamic_trbn_direction(i,n);


limiter=floor(abs(error/yaw_rate));% how many time steps is needed for the correction of yaw

                                       if limiter>=ratio || isnan(limiter) || isinf(limiter)
                                           limiter=ratio-2;
                                       end
                                        if limiter>=1 && isinf(limiter)==0 && i<=86400/dt_freq
                                            for l=i+1:i+limiter

dynamic_trbn_direction(l,n)=dynamic_trbn_direction(l-1,n)+(-1)^sign*yaw_rate*m;

dynamic_trbn_direction(l,n)=error_correction(dynamic_trbn_direction(l,n));
                                            end
                                        end
                                    end
                                    %step 3
                                    if ratio>2
                                      for l=i+limiter+1:i+ratio-1

dynamic_trbn_direction(l,n)=dynamic_trbn_direction(l-1,n);

dynamic_trbn_direction(l,n)=error_correction(dynamic_trbn_direction(l,n));
                                      end
                                    end
```

```
                                end
                                m=1;
                        end
                        j=j+1;
                    end
                    n=n+1;
                    end
                        %toc
                        if
length(dynamic_trbn_direction)>(86400/dt_freq) % deleting the
end values
                            for
i=1:(length(dynamic_trbn_direction)-(86400/dt_freq))

dynamic_trbn_direction(length(dynamic_trbn_direction),:)=[];
                            end
                        end
                        % if dynamic model not activated
                    elseif dynamic_decision==2
                        for c=2:2:12
                            for i=1:(86400/dt_freq)
                            file(i,c)=file(i,c)*2.2369;
%conversion to mph
                            end
                        end
                        cl=1;
                        for c=3:2:14
                            for r=1:(86400/dt_freq)

dynamic_trbn_direction(r,cl)=file(r,c);
                            end
                            cl=cl+1;
                        end
                    end
                    % yaw error
                    d=zeros((86400/dt_freq),6);
                    s=zeros((86400/dt_freq),6);
                    cl=1;

                    for c=2:2:13
                         for i=1:(86400/dt_freq)
                              s(i,cl)=file(i,c);% wind speed mph
                              d(i,cl)=file(i,c+1); % wind
direction
                         end
                    cl=cl+1;
                    end
```

```
                    for c=1:6
                         for i=1:(86400/dt_freq)
                              if d(i,c) == 90
                                   d(i,c)=NaN;
                              end
                         end
                    end
                    error=d-dynamic_trbn_direction;
                %nancounter
                nancounter=isnan(s);
                sumcounter=sum(nancounter);
                    energy=zeros((86400/dt_freq),6);
                    for c=1:6
                         for i=1:(86400/dt_freq)
                              s(i,c)=s(i,c)*cosd(error(i,c)); %
resolved wind speed
                              for j=1:length(trbn_data)
                                   if
(round(s(i,c)*10)/10)==trbn_data(j,1) % finding the value in
turbine file

     energy(i,c)=trbn_data(j,turbine+1)*data_freq;
                                   end
                              end
                         end
                    end
                    for i=1:6

     daily_energy(loop_counter,i)=sum(energy(:,i))/(3600000);

                    end
               end
               loop_counter=loop_counter+1;
          end
          %fprintf('\n')
          for i=1:6
               total_energy=sum(daily_energy(:,i));
               fprintf('Total_energy_for_the_time_period:_RG%d:
%f MWh\n',i,total_energy)
        end
        f_sumcounter=f_sumcounter+sumcounter;
          fprintf('\n')
     end
     diary off
end
```

A.2 Other models

A.1.1 Other models

```
% Unit of energy: MWh

clear;
clc;
close all;
freq=30;
density=1.155;
power=zeros((86400/freq),6);
energy=zeros(6,1);
total_energy=zeros(6,1);
avg_spd=zeros(6,1);
avg_array=[];
loop_counter=1;
dtd='Other model results diff turbine.txt';
diary(dtd)
diary on
%disp('Import the Wind data file.....');
for file_name=734811:734868
    file_date=datestr(file_name,29); % ISO format date
    import_file=['GVSU-Vindicator-30-sec-',file_date,'.csv'];
    dir_data=dir;
    dir_index=[dir_data.isdir];
    file_list={dir_data(~dir_index).name};
    decision=strcmp(import_file,file_list);
    decision=sum(decision);
    if decision==1
        str=['Importing file: ',import_file];
        %disp(str)
        tic
        file=importdata(import_file);
        %toc
        j=1;
        for c=2:2:12
            for i=1:(86400/freq)
                power(i,j)=file(i,c).^3.*0.5.*density; % W
            end
            j=j+1;
        end
        i=1;
        for c=2:2:12
            avg_spd(i)=nanmean(file(:,c)); % m/s
            i=i+1;
        end
```

```
        for i=1:6

energy(i)=nansum(power(:,i)).*freq./3600./1000./1000.*pi*58^2/4;
%MWh/m2
        end
        total_energy=total_energy+energy;
        avg_array=[avg_array avg_spd];
        loop_counter=loop_counter+1;
    end
end
% average wind speed
fprintf('Average wind speed:\n');
avg_spd=nanmean(avg_array,2);
for i=1:6
    fprintf('RG%d Average speed: %.3f m/s \n',i,(avg_spd(i)));
%energy is multiplied by area of LW58-850
end
fprintf('\n');
% energy available for G52-850
fprintf('Energy available:\n');
for i=1:6
    fprintf('RG%d Energy (for G58-850): %.3f MWh
\n',i,(total_energy(i))); %energy is multiplied by area of LW58-
850
end
fprintf('\n');
% betz analysis
betz_energy=total_energy.*0.593;
fprintf('Betz model:\n');
for i=1:6
    fprintf('RG%d Energy (for G58-850): %.3f MWh
\n',i,(betz_energy(i))); %energy is multiplied by area of G58-
850
end
fprintf('\n');
% one-two-three equation
fprintf('Energy generation (one-two-three equation model):\n');
one_two_three=(density/1.18)*(2*58/3)^2.*(avg_spd).^3; %in W
one_two_three=one_two_three./1000000*(60/3600); % in MWh/min
one_two_three=one_two_three.*24.*60.*(loop_counter-1);
for i=1:6
    fprintf('RG%d Energy (for LW58-850) : %.3f MWh
\n',i,one_two_three(i)); %energy is multiplied by area of G52-
850
end
diary off
```

A.1.2 Polynomial model

```
% Unit of energy: MWh
clear;
clc;
close all;
freq=60;
density=1.155;
power=zeros((86400/freq),6);
energy=zeros(6,1);
total_energy=zeros(6,1);
avg_spd=zeros(6,1);
avg_array=[];
loop_counter=0;
diary('Polynomial results NOAA.txt')
diary on
%disp('Import the Wind data file.....');
for file_name=734873:734967
    file_date=datestr(file_name,29); % ISO format date
    import_file=['GVSU-Vindicator-1-min-',file_date,'.csv'];
    dir_data=dir;
    dir_index=[dir_data.isdir];
    file_list={dir_data(~dir_index).name};
    decision=strcmp(import_file,file_list);
    decision=sum(decision);
    if decision==1
        str=['Importing file: ',import_file];
        %disp(str)
        tic
        file=importdata(import_file);
        %toc
        j=1;
        for c=2:2:12
            for i=1:(86400/freq)
                power(i,j)=power_function(file(i,c)); % kW
            end
            j=j+1;
        end
        for i=1:6
            energy(i)=nansum(power(:,i))*60/1000/3600; %MWh/m2
        end
        total_energy=total_energy+energy;
    end
end
fprintf('polynomial model:\n');
for i=1:6
```

```
    fprintf('RG%d Energy (for G58-850): %.3f MWh
\n',i,(total_energy(i))); %energy is multiplied by area of G58-
850
end
fprintf('\n');
diary off
```
____

```
function
power_output=power_function_inl(wind_speed,wind_set_values,turbi
ne_power)
% remember! output is in kW

wind_speed=round(wind_speed*2.2369*10)/10; %conversion to mph
row=find(wind_set_values==wind_speed);
power_output=turbine_power(row);
if isempty(row)
    power_output=0;
end
```

A.1.3 INL wind energy

```
% Unit of energy: MWh
clear;
clc;
close all;
freq=60;
density=1.155;
power=zeros((86400/freq),6);
energy=zeros(6,1);
total_energy=zeros(6,1);
avg_spd=zeros(6,1);
avg_array=[];
loop_counter=0;
[trbn_data trbn_text]=xlsread('turbine_data.xlsx');
turbine=17;
trbn_power=trbn_data(:,turbine+1);
trbn_speed=trbn_data(:,1);
disp('Import the Wind data file.....');
diary on
diary('INL results for 1 min.txt')
for file_name=734997:735240
    file_date=datestr(file_name,29); % ISO format date
    import_file=['GVSU-Vindicator-1-min-',file_date,'.csv'];
    dir_data=dir;
    dir_index=[dir_data.isdir];
    file_list={dir_data(~dir_index).name};
```

```
    decision=strcmp(import_file,file_list);
    decision=sum(decision);
    if decision==1
        str=['Importing file: ',import_file];
        disp(str)
        tic
        file=importdata(import_file);
        toc
        j=1;
        for c=2:2:12
            for i=1:(86400/freq)

power(i,j)=power_function_inl(file(i,c),trbn_speed,trbn_power);
% kW
            end
            j=j+1;
        end
        for i=1:6
            energy(i)=nansum(power(:,i))*60/1000/3600; %MWh/m2
        end
        total_energy=total_energy+energy;
    end
end
fprintf('INL wind energy:\n');
for i=1:6
    fprintf('RG%d Energy (for G52-850kW): %.3f MWh
\n',i,(total_energy(i)));
end
fprintf('\n');
diary off
```

```
function power_output=power_function(wind_speed)
% remember! output is in kW

cut_in=8.9;% mph
rated_speed=18;% mph
cut_out=47;% mph
rated_power=850; % in kW
m=2;
wind_speed=wind_speed*2.2369; %conversion to mph
if wind_speed<cut_in || wind_speed>cut_out
    power_output=0;
elseif wind_speed>rated_speed && wind_speed<cut_out
    power_output=rated_power;
elseif wind_speed>=cut_in && wind_speed<=rated_speed
```

```
    power_output=(wind_speed^m-cut_in^m)/(rated_speed^m-
cut_in^m)*rated_power;
elseif isnan(wind_speed)
    power_output=0;
end
```

A.2 One second refining module

```
%% One second data refining module
clear all;
clc;
close all;

% file progress graphics handler
h=waitbar(0,'Files Processing...');
step=0;
steps=395; %number of daily data files

% logging of the results
dt=date;
dtd=['Log-w1.1-',dt,'.txt'];
diary(dtd)
diary on

% data file processing in range
for file_name=734783:735224
     % importing the unrefined raw data file
    file_date_s=datestr(file_name,29); % ISO format date
    import_file=[file_date_s,'.csv'];
    check_file=['GVSU-Vindicator-Refined-',file_date_s,'.csv'];
    file_date=file_name;
     % looking for the data file in the directory and checking
for the file is already prcessed or not
    dir_data=dir;
    dir_index=[dir_data.isdir];
    file_list={dir_data(~dir_index).name};
    decision=strcmp(import_file,file_list);
    decision1=strcmp(check_file,file_list);
    decision=sum(decision);
    decision1=sum(decision1);
    str=['Importing file: ',import_file];
    disp(str)

    if decision==1 && decision1~=1
        %% Importing the unrefined 1 sec data
        file=importdata(import_file,',',1);
        date=file.textdata(:,2); % Time stamp
        date(1)=[]; % deleting the column header
```

```
        st_date=file_date; % initial date

        % Creating a time stamp
        date_stamp=linspace(st_date,(st_date+1-1.1574e-
005),86400); % creating the time stamp (numerical value)
        date_stamp_s=datestr(date_stamp,31); % converting the
numerical time stamp
        date_stamp_s=cellstr(date_stamp_s); % converting the
HH:MM:SS strings array to cell array to make them queriable
        date_stamp_s=strtrim(date_stamp_s); % Trimming the white
space from the front and back from the string values

        % Data assign
          limit=size(file.data,2);
        column_n=zeros(86400,limit); % creating new array for
storing the refined data
        length_of_data=length(date);
        sttr=date(length_of_data);

          % checking the last time stamp for check
        dsp=['Last time stamp is',sttr];
        disp('For checking purpose:')
        disp(dsp)

        % Comparing the time stamps and adding NaN values in
missing time stamps
        for i=1:86400
               find1=strcmp(date_stamp_s(i),date); % comparing
the time stamp from data file with the created time stamp
               k=find(find1>0);
                    if isempty(k)==0
                              column_n(i,:)=file.data(k,:);
                    else % adding NaN values if the time stamp
is missing
                              column_n(i,:)=NaN;
                    end
          end

        % Output
        day_of_data=st_date;
        date_f=datenum(day_of_data);
        date_data=datestr(date_f,1);
        date_f=file_date;
        date_stamp_f=linspace(date_f,(date_f+1-1.1574e-
005),86400)';
        file_date=date_f;
        file_date=datenum(file_date);
```

```
        filename=['GVSU-Vindicator-Refined-
',file_date_s,'.csv'];
        answer=[date_stamp_f column_n];
        csvwrite(filename,answer); % writing a csv file for the
refined data set
        str=[import_file,': File Processed Successfully !'];
        disp (str)
    else
         str=[import_file,': File not found !'];
         disp(str)
    end
    step=step+1;
    waitbar(step/steps)
end
close(h)
diary off
```

A.3 Averaging module

```
% file progress graphics handler
h=waitbar(0,'Files Processing...');
step=0;
steps=441;

% logging of the results
dt=date;
dtd=['Average-Log-5-min-',dt,'.txt'];
diary(dtd)
diary on

% data file processing in range
for file_name=734783:735224

     % importing the 1 Hz file
    file_date=datestr(file_name,29); % ISO format date
    import_file=['GVSU-Vindicator-Refined-',file_date,'.csv'];
    check=['GVSU-Vindicator-5-min-',file_date,'.csv'];
    dir_data=dir;
    dir_index=[dir_data.isdir];
    file_list={dir_data(~dir_index).name};
    decision=strcmp(import_file,file_list);

     % looking for the data file in the directory and checking
for the file is already prcessed or not
    decision1=strcmp(check,file_list);
    decision=sum(decision);
    decision1=sum(decision1);
    str=['Importing file: ',import_file];
```

```
    disp(str)
    if decision==1 && decision1~=1
          file=importdata(import_file);
          counter=1;
          pivot=300; % the averaging time in seconds
          temp=zeros(pivot,1);
          x=1;
          number=86400/pivot; % number of data points per day
          avg=zeros(number,6); % average value
          std=zeros(number,6); % standard deviation value
          limit=size(file,2);
        column=[];
        y=1;
            for i=2:8:limit
                column(:,y)=file(:,i); % taking in the wind
speed and other data
                y=y+2;
            end
        y=2;
            for i=5:8:limit
                column(:,y)=file(:,i); % taking in the wind
speed and other data
            end
        for y=2:2:12
            for i=1:86400
                if column(i,y)<0
                    column(i,y)=column(i,y)+360;
                end
            end
        end
        column_n=zeros(86400,12); % creating new array for
storing the refined data
        length_of_data=length(date);
        nansin=[];
        nancos=[];
          %% Calculation
          for c=1:2:11
               x=1;
               for i=1:86400
                    if counter<=pivot
                         temp(counter)=column(i,c); % creating a
temporary block of data for calculation
                         counter=counter+1;
                         if counter>pivot
                              if sum(isnan(temp))<(pivot/2) %
checking for availablity of 50% sample size
                                   avg(x,c)=nanmean(temp);
```

```
                                   std(x,c)=nanstd(temp);
                                   x=x+1;
                                   counter=1;
                              else
                                   avg(x,c)=NaN;
                                   std(x,c)=NaN;
                                   x=x+1;
                                   counter=1;
                              end
                         end
                    end
               end
          end
          for c=2:2:12
               x=1;
               for i=1:86400
                    if counter<=pivot
                         temp(counter)=column(i,c); % creating a
temporary block of data for calculation
                         counter=counter+1;
                         if counter>pivot
                              if sum(isnan(temp))<(pivot/2) %
checking for availablity of 50% sample size

     nansin=nansum(sin(temp*pi/180));

     nancos=nansum(cos(temp*pi/180));

     avg(x,c)=atan2(nansin,nancos)*180/pi;
                                   nan_check=isnan(avg(x,c));
                                   if nan_check==1
                                        avg(x,c)=NaN;
                                   else
                                        if avg(x,c)>=0 &&
avg(x,c)<=90
                                             avg(x,c)=90-
avg(x,c);
                                             elseif avg(x,c)>90
&& avg(x,c)<=180
                                             avg(x,c)=360-
(avg(x,c)-90);
                                             elseif avg(x,c)<0
&& avg(x,c)>=-180

     avg(x,c)=abs(avg(x,c))+90;
                                        end
                                   end
```

```
                                    std(x,c)=nanstd(temp);
                                    x=x+1;
                                    counter=1;
                               else
                                    avg(x,c)=NaN;
                                    std(x,c)=NaN;
                                    x=x+1;
                                    counter=1;
                               end
                          end
                     end
                end
           end
        date_f=file_name; % excel time format
        date_stamp_f=linspace(date_f,(date_f+1-1.1574e-
005*pivot),86400/pivot)';
        filename=['GVSU-Vindicator-5-min-',file_date,'.csv'];
        answer=[date_stamp_f avg std];
        csvwrite(filename,answer); % writing a csv file for the
refined data set
        str=[import_file,': File Processed Successfully !'];
        disp (str)
     else
          str=[import_file,': File not found !'];
          disp(str)
    end
    step=step+1;
    waitbar(step/steps)
end
close(h)
diary off
```

A.4 Wind rose

```
clear;
clc;
close all;

file=uiimport;
%trbn(:,2)=csvread('powercurves.csv',2,17,[2,17,673,17]);
%trbn(:,1)=csvread('powercurves.csv',2,0,[2,0,673,0]);
res=600; % data frequency in seconds
tme=zeros(16,1);
sum_energy=zeros(16,1);
spd_clmn=1;
```

```
dir_clmn=spd_clmn+6;
db=22.5;
last_data_point=length(file.data(:,spd_clmn));
direction_bin=0:22.5:360;
tmp=[];
bin_avg=zeros(16,1);
bin_counter=zeros(16,1);
%% converting the wind speed in mph unit
for i=1:last_data_point
    file.data(i,spd_clmn)=file.data(i,spd_clmn)*2.23693629;
end
for dir_bin_number=1:16
    for i=1:last_data_point
        if file.data(i,dir_clmn)>=direction_bin(dir_bin_number)
&& file.data(i,dir_clmn)<=direction_bin(dir_bin_number+1)
            tmp=[tmp file.data(i,spd_clmn)];

bin_counter(dir_bin_number)=bin_counter(dir_bin_number)+1;
        end
        tmp(1)=NaN;
        bin_avg(dir_bin_number)=nanmean(tmp);
    end
    tmp=[];
end
bin_counter;
bin_avg;
counter=0;
x=1;
rose_avg=zeros(360,1);
for i=1:360
    rose_avg(i)=bin_avg(x);
    rose_count(i)=bin_counter(x);
    counter=counter+1;
    if counter==23
        x=x+1;
        counter=0;
    end
end
rose_time_percent=rose_count'./last_data_point;
```

A.5 Frequency distribution

```
% frequency distribution
clear;
clc;
close all;
freq=60;
```

```
histogram=zeros(70,6);
final_histogram=zeros(70,6);
percentile=zeros(70,6);
total_time=zeros(1,6);
dtd='frequency distribution';
diary(dtd)
diary on
for file_name=734873:734967
    file_date=datestr(file_name,29); % ISO format date
    import_file=['GVSU-Vindicator-1-min-',file_date,'.csv'];
    dir_data=dir;
    dir_index=[dir_data.isdir];
    file_list={dir_data(~dir_index).name};
    decision=strcmp(import_file,file_list);
    decision=sum(decision);
    if decision==1
        file=importdata(import_file);
        i=1;
        for c=2:2:12
            temp=file(:,c)*2.2369;
            temp(isnan(temp))=[];
            histogram(:,i)=histc(temp,1:70);
            i=i+1;
        end
        final_histogram=final_histogram+histogram;
    end
end
for i=1:6
    total_time(i)=nansum(final_histogram(:,i));
    percentile(:,i)=final_histogram(:,i)./total_time(i);
end
csvwrite('frequency distribution percentile of time midlake
locaiton.txt',percentile);
bar(percentile(:,1));
```

Appendix B

B.1 Lake Muskegon deployment results

Table B.1 Summary of results of different range gates

Range Gate	Altitude (m)	Average wind speed (mph)	Energy output (MWh)	Capacity factor
RG1	55	12.69	79.198585	13.9%
RG2	60	13.22	87.530522	15.3%
RG3	75	14.38	106.80838	18.7%
RG4	90	15.33	122.574758	21.5%
RG5	110	15.92	135.333345	23.7%
RG6	120	16.03	135.945984	23.8%

Table B.2 Energy (MWh) estimated by dynamic model for RG1 (30 sec averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)																			
	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600
0	43.2	40.4	40.4	40.5	40.4	40.4	40.4	40.5	40.4	40.4	42.5	41.1	42.5	41.0	40.5	42.9	42.7	42.3	42.5	41.0
0.05	76.6	72.7	71.5	72.2	72.4	72.1	71.5	72.2	72.4	72.4	72.7	71.2	73.2	73.8	72.0	74.1	74.4	70.5	71.2	70.5
0.1	76.8	73.3	72.7	74.1	72.0	71.8	72.7	74.1	72.0	71.0	74.7	72.2	73.6	75.1	70.7	74.8	73.9	71.0	72.8	72.5
0.15	77.0	73.7	73.1	74.2	72.7	72.0	73.1	74.2	72.7	73.1	73.1	72.1	74.4	73.7	72.2	73.6	72.8	71.5	73.0	71.9
0.2	77.3	74.0	72.8	72.7	72.7	71.7	72.8	72.7	72.7	72.5	73.6	72.4	73.2	74.5	72.3	73.6	73.6	72.0	72.9	73.5
0.25	77.3	73.8	73.1	73.2	72.5	71.2	73.1	73.2	72.5	73.7	73.9	72.4	74.3	73.3	71.9	73.5	74.1	72.2	73.2	73.5
0.3	77.6	73.8	72.0	73.2	72.6	71.9	72.0	73.2	72.6	73.1	73.6	72.7	74.4	73.2	71.9	73.8	74.4	72.0	73.6	74.4
0.35	77.7	73.8	71.7	71.4	72.6	72.1	71.7	71.4	72.6	73.2	73.8	72.7	74.3	74.0	72.4	73.8	74.3	72.3	72.7	73.1
0.4	77.8	73.8	71.0	71.5	72.6	72.1	71.0	71.5	72.6	72.5	73.4	72.6	74.7	73.9	72.9	74.4	74.5	72.4	73.0	72.9
0.45	77.7	73.8	71.2	72.1	71.9	72.2	71.2	72.1	71.9	73.2	73.7	73.4	74.5	73.7	72.4	73.9	74.0	72.4	72.7	73.0
0.5	77.7	74.0	70.7	72.1	72.1	71.9	70.7	72.1	72.1	73.1	73.2	73.6	75.0	73.8	72.8	73.8	74.1	72.7	72.9	73.2
0.55	77.6	74.1	71.3	71.6	72.4	72.4	71.3	71.6	72.4	73.7	73.6	73.2	74.6	74.0	73.3	74.2	73.8	72.4	73.2	74.0
0.6	77.6	74.2	71.0	71.8	72.1	72.5	71.0	71.8	72.1	74.2	73.7	73.4	74.5	73.8	73.1	74.4	74.2	72.6	73.6	74.0
0.65	77.5	74.3	71.6	71.6	72.6	72.4	71.6	71.6	72.6	73.8	73.4	73.2	74.9	73.9	73.1	74.1	74.4	72.8	73.5	73.8
0.7	77.5	74.4	71.0	71.8	72.8	73.0	71.0	71.8	72.8	74.0	73.7	73.3	75.1	74.5	73.8	74.4	74.6	72.7	73.6	73.9
0.75	77.6	74.6	71.7	71.9	72.7	72.9	71.7	71.9	72.7	73.8	73.9	73.1	74.6	74.2	73.9	74.3	74.7	73.3	73.9	73.9
0.8	77.6	74.6	72.0	72.2	72.9	72.8	72.0	72.2	72.9	73.8	74.3	73.2	75.1	74.5	74.0	74.6	74.8	73.5	74.1	74.0
0.85	77.7	74.6	72.0	72.5	73.0	72.8	72.0	72.5	73.0	73.7	74.0	73.3	75.2	74.7	74.3	74.7	75.0	73.4	73.9	74.3
0.9	77.7	74.7	71.8	72.5	72.8	72.7	71.8	72.5	72.8	73.6	73.8	73.4	75.3	74.9	74.2	74.8	75.1	73.5	74.3	74.4
0.95	77.7	74.8	72.1	72.6	73.1	72.8	72.1	72.6	73.1	74.0	74.3	73.6	75.5	74.7	74.4	75.1	75.0	73.6	74.3	74.2
1	77.7	75.0	72.2	72.9	73.4	72.8	72.2	72.9	73.4	74.2	74.3	73.8	75.4	75.0	74.5	74.8	74.8	73.4	74.2	74.2
1.05	77.8	75.2	72.2	73.2	73.4	72.9	72.2	73.2	73.4	74.3	74.6	73.9	75.3	75.1	74.4	74.8	74.9	73.6	74.3	74.3
1.1	77.8	75.2	72.3	73.2	73.5	73.2	72.3	73.2	73.5	74.7	74.6	74.0	75.5	75.0	74.8	74.7	75.3	73.7	74.2	74.3
1.15	77.8	75.2	72.4	73.3	73.5	73.2	72.4	73.3	73.5	74.5	74.8	74.0	75.2	74.9	74.3	74.9	75.0	73.6	74.2	74.5
1.2	77.8	75.2	72.3	73.4	73.6	73.7	72.3	73.4	73.6	74.9	74.7	73.9	75.3	75.2	74.5	74.8	74.9	73.8	74.1	74.8
1.25	77.8	75.3	72.4	73.4	73.8	73.6	72.4	73.4	73.8	74.6	74.6	74.0	75.4	75.1	74.5	75.1	75.0	73.7	74.3	74.7
1.3	77.8	75.4	72.3	73.5	73.8	73.8	72.3	73.5	73.8	74.6	74.6	74.1	75.5	75.0	74.4	75.0	75.0	73.6	74.1	74.7
1.35	77.8	75.5	72.8	73.7	73.9	73.8	72.8	73.7	73.9	74.9	74.5	74.0	75.5	75.2	75.0	75.2	74.8	73.7	73.9	75.1

Yaw Rate (deg/sec)	Delay Time (secs)																			
	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600
1.4	77.8	75.5	72.9	73.9	74.1	73.6	72.9	73.9	74.1	74.6	74.7	74.0	75.9	75.3	74.5	75.4	75.1	73.3	73.9	74.8
1.45	77.7	75.5	72.9	73.7	74.1	73.7	72.9	73.7	74.1	74.6	74.7	73.9	75.4	75.1	74.2	75.2	75.0	73.5	73.9	74.5
1.5	77.8	75.5	73.2	73.9	74.1	73.4	73.2	73.9	74.1	74.8	74.8	74.1	75.9	75.4	74.6	74.9	74.9	73.8	74.0	75.2
1.55	77.8	75.6	73.1	73.9	73.9	73.6	73.1	73.9	73.9	75.0	75.0	74.1	75.8	75.4	75.2	75.4	75.0	74.0	73.9	75.1
1.6	77.7	75.6	73.2	74.0	74.3	73.7	73.2	74.0	74.3	75.0	74.9	74.0	75.8	75.5	74.8	75.4	75.2	74.0	74.1	74.9
1.65	77.7	75.8	73.1	73.9	74.5	73.8	73.1	73.9	74.5	74.9	75.0	73.9	75.5	75.2	74.3	75.2	74.9	73.6	73.6	74.8
1.7	77.7	75.9	73.2	74.2	74.5	73.6	73.2	74.2	74.5	74.8	74.9	74.3	75.5	75.4	74.4	75.3	75.1	73.6	73.5	74.9
1.75	77.7	75.9	73.3	74.3	74.4	73.6	73.3	74.3	74.4	75.0	74.9	74.4	75.7	75.6	74.6	75.4	75.2	73.7	73.7	74.9
1.8	77.7	76.0	73.3	74.3	74.3	73.6	73.3	74.3	74.3	74.9	75.0	74.5	75.9	75.6	75.2	75.7	75.3	74.1	74.1	74.9
1.85	77.7	76.0	73.2	74.3	74.3	73.7	73.2	74.3	74.3	74.8	74.9	74.3	75.7	75.2	75.2	75.7	75.5	74.1	73.9	75.1
1.9	77.7	76.0	73.2	74.3	74.5	73.8	73.2	74.3	74.5	74.7	74.7	73.8	75.6	74.8	74.1	75.3	75.1	73.5	73.8	74.5
1.95	77.7	76.0	73.2	74.1	74.4	73.7	73.2	74.1	74.4	74.5	74.6	74.0	75.2	74.6	73.8	74.7	75.0	73.1	73.3	74.2
2	77.7	76.0	73.3	74.1	74.3	73.9	73.3	74.1	74.3	74.7	74.6	73.9	75.4	74.7	74.1	74.6	74.9	73.5	73.2	74.6

Table B.3 Energy (MWh) estimated by dynamic model for RG2 (30 sec averaged data set)

Yaw Rate (deg/sec)	**Delay Time (secs)**																			
	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600
0	58.3	52.9	52.8	52.9	52.8	52.8	52.8	52.9	52.8	52.9	57.4	53.7	57.3	53.6	52.9	57.7	57.5	56.8	57.1	53.6
0.05	86.4	81.3	79.4	79.9	80.7	79.9	79.4	79.9	80.7	79.8	81.5	80.4	81.3	79.7	81.5	81.9	81.0	77.8	78.4	78.5
0.1	86.1	81.9	80.7	81.9	81.5	79.5	80.7	81.9	81.5	79.0	81.3	79.9	80.5	83.4	80.2	81.4	80.0	79.4	81.8	79.9
0.15	85.8	81.9	80.9	82.7	81.1	80.3	80.9	82.7	81.1	80.1	80.5	80.6	81.7	82.8	79.6	81.8	80.8	80.0	80.8	80.0
0.2	85.7	81.9	80.6	82.0	80.4	80.7	80.6	82.0	80.4	80.6	82.0	80.7	82.5	81.4	79.3	80.9	82.2	80.8	81.0	80.7
0.25	85.7	82.2	80.4	81.1	80.1	78.6	80.4	81.1	80.1	81.6	81.5	80.3	82.3	81.6	80.2	82.4	82.0	80.4	80.9	81.0
0.3	85.8	82.1	80.7	80.5	81.0	80.1	80.7	80.5	81.0	81.3	81.8	80.6	83.1	81.6	80.1	82.1	81.8	80.7	80.9	82.1
0.35	85.9	82.1	79.8	80.1	80.7	79.1	79.8	80.1	80.7	81.3	81.7	80.3	82.4	82.0	80.3	82.2	82.3	80.2	80.8	81.0
0.4	86.0	82.2	80.0	80.5	80.3	79.6	80.0	80.5	80.3	81.1	82.1	80.3	83.1	81.7	80.8	82.4	82.2	80.3	80.6	81.4
0.45	86.0	82.3	79.9	79.9	80.1	79.6	79.9	79.9	80.1	81.5	82.2	80.9	82.9	82.4	80.5	82.5	82.1	80.0	81.0	81.1
0.5	86.1	82.4	79.8	80.1	80.5	80.5	79.8	80.1	80.5	81.5	82.1	81.4	83.0	82.2	80.7	82.1	82.3	80.8	80.7	81.4
0.55	86.1	82.5	80.1	80.6	79.9	80.9	80.1	80.6	79.9	81.7	81.9	81.2	82.9	81.8	81.0	82.5	82.4	80.5	81.4	81.9
0.6	86.2	82.5	79.6	80.8	79.9	80.3	79.6	80.8	79.9	82.2	81.5	81.4	83.2	82.3	80.9	82.6	82.3	80.4	81.4	81.6
0.65	86.2	82.8	79.2	80.8	80.7	80.9	79.2	80.8	80.7	82.0	82.0	81.2	83.3	82.3	81.1	82.3	82.5	80.8	81.6	81.7
0.7	86.4	82.9	79.7	80.7	80.7	80.5	79.7	80.7	80.7	82.1	81.8	81.3	83.6	82.4	81.7	82.7	82.8	81.2	81.6	81.8
0.75	86.4	82.9	79.8	80.8	80.8	81.0	79.8	80.8	80.8	82.0	81.9	81.6	83.8	82.3	81.9	82.9	82.9	81.2	81.5	82.1
0.8	86.5	83.0	80.0	80.6	81.2	81.2	80.0	80.6	81.2	81.9	82.4	81.8	84.0	82.7	82.1	83.3	83.0	81.5	81.8	81.9
0.85	86.5	83.1	79.9	81.0	81.1	81.5	79.9	81.0	81.1	82.0	82.4	81.4	84.4	83.0	82.5	83.3	83.1	81.8	81.7	81.9
0.9	86.5	83.3	80.1	81.2	81.2	81.4	80.1	81.2	81.2	82.0	82.2	81.6	84.2	83.5	82.4	83.6	83.0	81.6	81.8	82.1
0.95	86.6	83.4	80.3	81.4	81.7	81.1	80.3	81.4	81.7	82.2	82.4	81.8	84.4	83.3	82.3	83.6	83.1	81.6	81.9	82.2
1	86.6	83.6	80.4	81.7	81.9	81.5	80.4	81.7	81.9	82.3	82.5	82.1	84.4	83.2	82.5	83.6	83.2	81.9	81.9	82.4
1.05	86.6	83.6	80.4	81.8	81.7	81.3	80.4	81.8	81.7	82.4	83.0	82.1	84.3	83.3	82.4	83.6	83.0	81.6	82.0	82.3
1.1	86.6	83.8	80.6	81.9	82.1	81.4	80.6	81.9	82.1	82.5	83.1	82.3	84.4	83.1	82.5	83.6	83.3	82.0	82.0	82.3
1.15	86.6	83.9	80.6	82.0	82.0	81.5	80.6	82.0	82.0	82.9	83.3	82.0	84.2	83.7	82.5	83.7	83.0	81.7	82.1	82.5
1.2	86.6	84.0	80.6	81.9	82.2	81.8	80.6	81.9	82.2	82.9	83.1	82.3	84.6	83.8	82.6	83.7	83.1	82.0	82.1	82.8
1.25	86.6	84.0	80.5	81.9	82.1	81.8	80.5	81.9	82.1	82.6	83.1	82.1	84.4	83.6	82.5	84.1	83.3	81.9	82.4	82.5
1.3	86.7	84.1	80.7	82.2	82.0	81.9	80.7	82.2	82.0	82.9	83.0	82.4	84.4	83.7	82.6	83.6	82.9	81.7	82.1	82.4
1.35	86.7	84.1	80.9	82.2	82.1	81.9	80.9	82.2	82.1	83.0	83.0	82.2	84.5	83.7	82.8	84.0	83.0	81.9	82.1	82.4

Yaw Rate (deg/sec)	Delay Time (secs)																			
	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600
1.4	86.6	84.2	81.1	82.3	82.6	81.7	81.1	82.3	82.6	82.7	83.1	82.4	84.4	83.8	82.6	84.0	83.0	82.0	82.5	82.4
1.45	86.6	84.2	81.1	82.4	82.4	81.9	81.1	82.4	82.4	82.8	83.1	82.3	84.2	83.6	82.3	84.0	82.8	81.6	82.2	82.6
1.5	86.6	84.3	81.2	82.6	82.6	81.8	81.2	82.6	82.6	83.0	83.3	82.5	84.5	83.8	82.8	84.1	83.0	81.9	81.9	83.2
1.55	86.6	84.4	81.3	82.6	82.5	81.7	81.3	82.6	82.5	83.4	83.2	82.6	84.7	83.8	83.4	84.2	83.0	82.1	82.2	83.1
1.6	86.6	84.5	81.4	82.6	82.7	81.8	81.4	82.6	82.7	83.2	83.4	82.5	84.3	83.9	82.9	84.3	83.0	82.4	82.0	83.1
1.65	86.6	84.5	81.3	82.7	82.9	82.0	81.3	82.7	82.9	83.3	83.5	82.5	84.4	83.5	82.5	84.0	83.5	81.7	81.6	82.7
1.7	86.7	84.6	81.3	82.5	83.0	81.8	81.3	82.5	83.0	83.0	83.2	82.6	84.4	83.8	82.4	84.0	83.5	81.9	81.6	82.9
1.75	86.7	84.6	81.6	82.6	82.8	81.8	81.6	82.6	82.8	83.2	83.5	82.7	84.5	83.9	82.8	84.3	83.9	81.8	82.0	83.3
1.8	86.6	84.7	81.7	82.7	82.9	81.8	81.7	82.7	82.9	83.4	83.5	82.8	84.5	83.9	83.1	84.2	83.9	82.1	82.4	83.0
1.85	86.7	84.8	81.6	82.6	82.6	81.9	81.6	82.6	82.6	83.2	83.1	82.8	84.5	83.9	83.4	84.1	83.7	82.4	82.1	83.2
1.9	86.6	84.7	81.6	82.7	82.7	82.0	81.6	82.7	82.7	83.1	83.2	82.1	84.5	83.4	82.9	84.0	83.4	81.4	81.9	82.7
1.95	86.6	84.7	81.7	82.6	82.7	82.0	81.7	82.6	82.7	83.0	83.0	82.2	84.1	83.1	82.0	83.6	83.4	81.3	81.5	82.4
2	86.7	84.8	81.6	82.5	82.7	82.1	81.6	82.5	82.7	82.9	82.8	82.1	84.2	83.0	82.0	83.6	83.4	81.6	81.7	82.6

Table B.4 Energy (MWh) estimated by dynamic model for RG3 (30 sec averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)																			
	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600
0	71.9	65.1	65.1	65.2	65.1	65.2	65.1	65.2	65.1	65.2	70.6	66.5	70.5	66.4	65.3	71.1	70.8	69.9	70.3	66.3
0.05	105.3	98.5	97.7	97.9	98.7	98.4	97.7	97.9	98.7	98.1	98.8	98.6	99.8	101.2	100.0	100.2	99.1	95.7	96.8	96.4
0.1	105.2	99.4	99.0	99.7	99.0	98.8	99.0	99.7	99.0	98.0	98.9	97.9	100.6	99.4	99.6	100.5	99.7	97.4	99.3	98.1
0.15	105.2	99.9	99.1	101.3	98.8	98.8	99.1	101.3	98.8	98.3	99.7	98.2	99.9	98.8	99.6	100.1	100.8	97.8	99.4	99.2
0.2	105.0	100.5	99.1	99.3	98.6	96.7	99.1	99.3	98.6	100.0	99.5	99.3	100.0	99.8	100.0	100.1	99.7	97.7	98.9	99.4
0.25	105.1	100.6	99.1	99.7	98.3	98.1	99.1	99.7	98.3	99.3	99.8	99.1	100.3	100.5	98.3	101.1	100.6	97.6	99.0	100.1
0.3	105.5	101.0	98.6	99.1	97.8	98.7	98.6	99.1	97.8	99.7	99.5	99.6	101.6	100.5	98.8	101.2	101.1	98.3	99.4	100.7
0.35	105.7	101.3	98.8	98.4	98.8	98.0	98.8	98.4	98.8	100.4	99.8	99.1	101.4	100.9	98.9	101.0	101.0	98.3	99.6	100.3
0.4	106.0	101.4	98.2	99.5	98.2	98.8	98.2	99.5	98.2	99.2	99.9	99.7	101.6	100.8	99.9	102.0	100.9	97.7	99.4	99.9
0.45	106.1	101.5	98.0	98.0	98.8	98.2	98.0	98.0	98.8	99.9	99.8	99.3	101.8	101.0	99.0	101.0	100.8	97.9	98.9	99.5
0.5	106.1	101.5	98.1	98.2	98.6	99.2	98.1	98.2	98.6	100.0	100.2	99.8	101.8	101.4	98.6	101.2	100.9	98.2	98.8	100.5
0.55	106.0	101.3	97.8	98.5	98.7	98.9	97.8	98.5	98.7	100.5	100.3	99.6	101.7	101.1	99.3	101.3	100.8	97.6	99.6	100.0
0.6	105.9	101.3	98.1	97.8	98.2	98.7	98.1	97.8	98.2	101.1	100.6	99.5	101.8	101.3	99.5	101.3	101.4	98.1	99.9	100.7
0.65	105.8	101.4	98.5	98.1	98.4	98.6	98.5	98.1	98.4	100.8	100.4	100.0	101.9	101.5	99.5	101.0	101.3	98.4	99.7	100.4
0.7	105.7	101.5	98.4	98.8	99.0	98.8	98.4	98.8	99.0	100.9	100.1	100.0	102.3	100.8	99.7	101.9	101.5	98.1	100.2	100.5
0.75	105.7	101.6	97.9	98.9	99.1	98.7	97.9	98.9	99.1	101.7	100.4	100.1	102.1	101.3	100.2	102.5	101.3	98.5	100.3	100.6
0.8	105.6	101.7	98.4	99.0	99.2	99.2	98.4	99.0	99.2	101.7	100.6	100.2	102.5	101.8	100.5	102.3	102.1	98.7	100.4	100.7
0.85	105.5	101.6	98.5	99.4	99.6	99.5	98.5	99.4	99.6	101.2	101.4	100.3	102.3	102.3	100.9	102.6	101.7	99.0	100.4	100.6
0.9	105.6	101.8	98.9	99.8	99.7	99.7	98.9	99.8	99.7	101.3	100.9	100.6	102.6	101.9	100.7	102.7	101.3	99.3	100.1	100.8
0.95	105.6	101.9	99.0	99.6	99.8	99.7	99.0	99.6	99.8	101.3	101.7	100.5	103.0	102.2	101.1	102.9	101.6	99.0	100.5	101.3
1	105.7	102.2	98.9	99.7	100.3	100.1	98.9	99.7	100.3	101.1	101.4	100.8	103.1	102.2	101.1	102.7	101.9	99.5	101.0	101.1
1.05	105.7	102.2	99.0	100.1	100.2	100.0	99.0	100.1	100.2	101.5	101.6	100.9	103.2	102.5	101.0	103.0	102.1	99.5	100.4	100.7
1.1	105.8	102.2	98.7	100.3	100.2	100.0	98.7	100.3	100.2	101.3	101.7	101.0	103.2	103.4	101.1	102.8	101.9	99.7	100.6	101.0
1.15	105.8	102.2	99.2	100.4	100.4	100.0	99.2	100.4	100.4	101.5	101.7	101.1	103.1	102.7	101.1	103.0	102.0	99.4	100.6	100.8
1.2	105.9	102.3	99.2	100.8	100.5	100.2	99.2	100.8	100.5	101.8	101.7	101.3	103.4	102.7	101.2	103.2	102.0	99.7	100.9	101.1
1.25	105.9	102.4	99.8	100.5	100.7	100.3	99.8	100.5	100.7	102.1	101.8	101.2	103.4	102.9	101.2	103.1	101.9	99.3	101.1	101.5
1.3	106.0	102.4	99.6	100.6	100.7	100.3	99.6	100.6	100.7	101.8	102.1	101.2	103.5	102.6	101.0	103.2	101.6	99.3	100.5	100.9
1.35	106.0	102.5	100.1	100.8	100.7	100.2	100.1	100.8	100.7	101.7	101.8	101.4	103.4	103.1	100.9	103.0	101.6	99.3	101.0	100.9

Yaw Rate (deg/sec)	Delay Time (secs)																			
	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600
1.4	106.0	102.6	100.4	101.0	100.7	100.0	100.4	101.0	100.7	101.9	101.8	101.4	103.4	103.1	101.2	103.2	101.7	99.1	100.8	101.4
1.45	106.0	102.6	100.2	101.3	100.9	100.1	100.2	101.3	100.9	101.7	102.0	101.2	103.5	102.7	101.2	103.1	101.5	99.1	100.3	101.4
1.5	106.0	102.6	100.5	101.4	101.1	100.4	100.5	101.4	101.1	102.0	102.0	101.4	103.7	103.1	100.8	103.2	101.6	99.4	100.5	101.8
1.55	105.9	102.8	100.5	101.3	100.9	100.4	100.5	101.3	100.9	102.4	102.1	101.6	103.6	103.2	101.2	103.2	101.9	99.7	100.7	101.5
1.6	105.9	102.8	100.6	101.5	101.2	100.4	100.6	101.5	101.2	102.6	102.1	101.5	103.4	102.9	101.3	103.1	102.3	99.7	100.6	101.8
1.65	105.9	102.9	100.5	101.4	101.1	100.6	100.5	101.4	101.1	102.1	102.2	101.3	103.4	102.8	100.9	103.3	101.4	99.3	100.1	101.5
1.7	105.9	103.0	100.7	101.5	100.9	100.7	100.7	101.5	100.9	102.0	102.0	101.3	103.2	103.2	101.0	103.2	101.9	99.5	100.3	101.9
1.75	105.9	103.0	101.0	101.6	101.1	100.7	101.0	101.6	101.1	102.5	102.3	101.7	103.6	103.2	101.2	103.1	102.3	99.7	100.5	102.1
1.8	105.9	103.1	101.0	101.5	101.3	100.8	101.0	101.5	101.3	102.3	102.3	101.9	103.5	103.0	101.5	103.2	102.2	100.2	101.0	101.7
1.85	105.9	103.2	100.9	101.3	101.1	100.9	100.9	101.3	101.1	102.2	102.2	101.6	103.6	102.7	101.7	103.4	102.3	99.6	100.8	101.6
1.9	106.0	103.3	100.9	101.5	101.1	100.9	100.9	101.5	101.1	102.3	102.1	101.3	103.6	102.8	101.8	102.6	101.9	99.2	100.3	101.8
1.95	105.9	103.3	101.0	101.5	101.0	100.7	101.0	101.5	101.0	101.7	101.7	101.0	103.0	102.1	100.9	102.8	101.8	98.8	99.5	101.3
2	106.0	103.3	101.0	101.5	101.1	100.6	101.0	101.5	101.1	101.7	101.7	101.2	103.0	102.5	101.1	102.8	102.0	98.8	99.8	100.9

Table B.5 Energy (MWh) estimated by dynamic model for RG4 (30 sec averaged data set)

Yaw Rate (deg/sec)	**Delay Time (secs)**																			
	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600
0	81.0	73.7	73.7	73.7	73.6	73.8	73.7	73.7	73.6	73.7	79.6	75.2	79.4	75.1	74.0	80.1	79.8	78.8	79.2	75.0
0.05	121.9	114.1	113.6	112.5	113.6	113.3	113.6	112.5	113.6	112.7	114.0	112.9	114.2	112.8	111.2	115.8	115.4	114.4	113.9	111.1
0.1	121.4	114.4	114.8	114.4	115.2	113.7	114.8	114.4	115.2	112.4	113.2	113.1	116.4	114.1	112.3	114.4	114.0	115.3	113.6	110.6
0.15	120.9	114.2	114.8	114.6	111.9	113.5	114.8	114.6	111.9	111.8	115.6	114.4	115.1	113.7	114.1	114.3	114.9	112.6	112.6	111.7
0.2	120.5	114.3	114.5	114.8	113.9	112.3	114.5	114.8	113.9	111.9	114.6	113.3	114.6	114.2	113.2	114.5	114.3	113.5	113.8	113.8
0.25	120.4	114.8	113.5	114.2	112.1	113.4	113.5	114.2	112.1	112.4	114.1	114.4	114.9	114.8	112.5	116.0	114.3	112.8	113.5	113.1
0.3	120.5	115.1	112.8	114.0	112.2	112.9	112.8	114.0	112.2	113.5	114.7	114.1	115.1	115.2	113.2	115.0	114.4	112.9	114.2	114.3
0.35	120.4	115.3	111.4	113.6	111.2	113.2	111.4	113.6	111.2	113.4	113.8	114.0	115.9	115.3	114.0	116.6	114.6	113.0	114.6	114.2
0.4	120.5	115.6	112.6	113.2	112.5	112.4	112.6	113.2	112.5	113.6	114.0	114.5	114.8	115.1	114.3	116.4	114.6	112.4	114.2	113.8
0.45	120.6	115.6	111.6	113.3	111.8	112.1	111.6	113.3	111.8	113.9	114.4	114.0	115.4	115.4	113.5	115.9	114.4	112.3	114.2	114.3
0.5	120.7	115.5	111.9	113.0	113.1	112.9	111.9	113.0	113.1	114.2	113.7	115.1	115.4	115.6	113.7	115.4	114.7	112.4	113.6	114.3
0.55	120.7	115.6	111.9	112.9	112.8	112.7	111.9	112.9	112.8	115.0	114.5	114.6	115.8	115.5	114.0	116.0	114.6	111.9	113.7	114.4
0.6	120.6	115.6	112.3	112.4	113.0	113.2	112.3	112.4	113.0	114.8	114.5	114.3	116.1	115.2	114.2	115.7	114.8	112.7	114.5	114.6
0.65	120.6	115.6	112.7	113.2	113.3	113.2	112.7	113.2	113.3	114.8	114.4	114.7	116.1	115.4	113.4	115.9	115.0	112.9	114.8	114.7
0.7	120.6	115.6	112.2	113.4	113.3	113.2	112.2	113.4	113.3	115.0	114.6	114.8	116.0	115.2	114.2	116.6	115.6	112.7	114.6	115.2
0.75	120.5	115.7	112.5	113.6	113.8	114.0	112.5	113.6	113.8	115.0	114.6	114.6	116.3	116.0	114.9	116.5	115.6	113.0	114.8	115.1
0.8	120.5	115.8	112.5	114.5	114.1	113.8	112.5	114.5	114.1	114.8	114.7	114.6	116.5	116.2	115.1	117.0	115.4	113.4	115.1	115.2
0.85	120.4	115.9	112.6	114.7	114.3	113.7	112.6	114.7	114.3	115.4	114.6	114.6	116.9	116.4	115.5	117.0	115.2	113.3	115.2	115.1
0.9	120.4	116.0	112.3	114.3	114.0	113.7	112.3	114.3	114.0	115.5	114.9	114.9	116.7	116.5	115.6	117.1	115.2	113.7	115.3	115.1
0.95	120.4	116.1	113.0	114.6	114.3	114.0	113.0	114.6	114.3	116.2	115.0	115.1	117.1	116.4	115.9	117.0	115.3	113.8	115.7	116.0
1	120.4	116.2	113.1	114.7	114.6	114.3	113.1	114.7	114.6	116.4	115.0	115.0	117.3	116.8	115.9	117.3	115.6	114.0	115.4	115.6
1.05	120.4	116.3	113.1	114.8	114.8	114.7	113.1	114.8	114.8	116.2	115.1	115.4	117.2	116.8	116.0	116.9	115.7	113.9	115.7	115.7
1.1	120.5	116.5	113.5	115.1	114.7	114.6	113.5	115.1	114.7	116.1	115.7	115.4	117.4	117.0	116.0	117.3	115.7	113.9	115.3	115.8
1.15	120.5	116.7	113.6	115.2	115.0	114.5	113.6	115.2	115.0	116.8	115.7	115.6	117.7	117.0	115.9	117.3	116.0	114.2	115.5	115.6
1.2	120.5	116.8	113.8	115.5	115.0	114.1	113.8	115.5	115.0	116.6	116.0	115.5	117.6	117.5	115.9	117.1	116.2	114.1	115.4	115.6
1.25	120.6	116.8	113.7	115.4	114.7	114.5	113.7	115.4	114.7	116.7	116.2	115.8	117.7	116.9	116.2	117.5	116.3	114.3	115.6	115.9
1.3	120.6	116.9	113.5	115.5	115.2	114.5	113.5	115.5	115.2	116.9	116.1	115.9	117.6	117.2	115.5	117.5	115.9	114.3	115.3	115.8
1.35	120.6	117.1	113.8	115.5	115.1	114.5	113.8	115.5	115.1	117.1	116.1	115.9	118.0	117.6	115.9	117.5	116.0	114.4	115.7	115.4

Yaw Rate (deg/sec)	Delay Time (secs)																			
	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600
1.4	120.6	117.1	113.8	115.7	115.1	114.6	113.8	115.7	115.1	116.9	116.2	116.4	118.1	117.1	116.0	117.7	115.9	114.3	115.6	116.4
1.45	120.6	117.1	113.9	116.0	115.1	114.9	113.9	116.0	115.1	117.1	116.4	115.8	118.0	117.2	115.9	117.8	115.7	114.0	115.2	115.7
1.5	120.6	117.2	114.3	116.0	115.3	114.8	114.3	116.0	115.3	117.0	116.0	115.9	118.0	117.5	115.6	117.4	115.6	114.5	115.3	116.3
1.55	120.6	117.3	114.5	115.9	115.3	114.9	114.5	115.9	115.3	117.4	116.5	116.0	118.2	117.8	115.6	117.7	116.0	114.8	115.9	116.2
1.6	120.7	117.3	114.6	116.0	115.5	114.8	114.6	116.0	115.5	117.1	116.3	116.1	118.1	117.2	116.0	117.7	116.1	114.4	115.8	116.4
1.65	120.7	117.4	114.6	116.2	115.7	114.9	114.6	116.2	115.7	117.1	116.5	115.8	118.0	117.3	116.3	117.7	115.9	114.4	115.6	116.1
1.7	120.7	117.4	114.8	116.2	115.6	115.1	114.8	116.2	115.6	117.0	116.1	115.5	118.0	117.4	116.0	117.6	115.9	114.7	115.3	116.4
1.75	120.7	117.5	115.1	116.2	115.8	115.2	115.1	116.2	115.8	117.1	116.4	115.7	118.2	117.7	115.9	117.9	116.0	114.5	115.5	116.2
1.8	120.7	117.6	115.3	116.1	115.5	115.2	115.3	116.1	115.5	117.3	116.4	115.8	118.3	117.7	116.1	118.0	116.2	114.8	115.8	116.3
1.85	120.7	117.7	115.2	116.1	115.5	115.3	115.2	116.1	115.5	117.0	116.6	116.3	118.0	117.4	116.4	118.2	116.1	114.4	115.9	116.4
1.9	120.8	117.9	114.9	116.2	115.4	115.1	114.9	116.2	115.4	116.7	116.1	115.7	118.0	117.0	116.3	117.6	115.6	114.0	115.7	115.6
1.95	120.7	117.9	114.7	116.1	115.3	114.9	114.7	116.1	115.3	116.6	115.9	115.7	117.7	116.8	115.8	117.3	115.5	113.7	115.1	115.6
2	120.8	118.0	114.7	116.2	115.4	115.2	114.7	116.2	115.4	116.8	115.9	115.6	117.3	117.1	116.1	117.0	115.6	113.6	114.6	115.5

Table B.6 Energy (MWh) estimated by dynamic model for RG5 (30 sec averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)																			
	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600
0	85.1	77.9	77.8	78.0	77.8	77.9	77.8	78.0	77.8	78.0	83.8	79.4	83.6	79.3	78.2	84.3	84.0	83.0	83.4	79.1
0.05	132.2	125.2	123.7	122.5	123.7	124.7	123.7	122.5	123.7	125.3	125.2	121.1	127.2	124.8	124.4	123.7	123.5	122.1	121.9	121.3
0.1	133.0	126.2	125.0	122.3	126.2	123.0	125.0	122.3	126.2	123.9	124.3	120.6	125.7	123.6	122.5	124.7	124.4	122.2	122.4	121.9
0.15	132.8	126.0	125.1	122.4	124.2	123.0	125.1	122.4	124.2	124.0	123.7	121.1	125.5	123.4	122.6	125.0	123.5	121.6	123.0	122.0
0.2	132.6	125.7	122.0	121.8	123.1	121.5	122.0	121.8	123.1	124.9	123.3	122.5	125.3	122.8	121.6	125.6	123.9	120.8	123.3	122.5
0.25	132.6	125.8	123.0	122.2	122.3	120.8	123.0	122.2	122.3	124.2	123.4	122.7	125.3	123.4	122.9	125.3	124.1	122.6	123.5	123.2
0.3	132.4	125.5	122.2	122.2	121.6	121.6	122.2	122.2	121.6	122.9	124.8	122.9	125.3	122.9	123.7	124.8	124.6	122.1	123.8	123.6
0.35	132.2	125.2	120.9	122.7	121.7	122.2	120.9	122.7	121.7	122.7	124.5	123.2	125.1	123.8	123.2	125.5	124.7	122.9	123.7	122.6
0.4	132.0	125.2	122.3	122.6	122.6	121.1	122.3	122.6	122.6	123.8	124.0	124.0	125.4	123.4	123.3	125.0	124.7	122.8	123.3	122.3
0.45	131.6	125.1	123.4	122.7	123.1	121.6	123.4	122.7	123.1	123.7	124.1	123.2	125.7	124.4	123.2	124.7	124.4	122.2	123.3	122.5
0.5	131.4	125.0	122.3	122.7	123.1	121.4	122.3	122.7	123.1	124.2	124.3	124.2	125.7	123.6	123.9	124.7	124.6	122.2	123.0	122.7
0.55	131.3	125.1	120.8	122.6	123.6	122.3	120.8	122.6	123.6	124.3	124.7	124.1	125.2	124.4	123.9	124.9	124.3	122.2	123.5	122.8
0.6	131.0	125.2	121.4	122.9	123.4	122.1	121.4	122.9	123.4	124.7	124.4	124.3	125.1	124.1	123.9	125.2	124.2	122.1	123.9	123.2
0.65	130.8	125.2	122.0	123.4	124.3	122.4	122.0	123.4	124.3	125.2	124.6	124.3	124.5	124.5	124.2	125.4	124.2	122.6	123.9	123.6
0.7	130.8	125.2	122.6	123.3	123.3	123.2	122.6	123.3	123.3	125.0	124.4	124.2	124.8	124.5	124.2	125.4	124.5	122.8	124.3	123.5
0.75	130.7	125.3	121.4	123.9	123.3	122.9	121.4	123.9	123.3	124.9	124.4	123.8	125.2	124.4	124.5	125.9	125.2	123.0	123.9	123.8
0.8	130.6	125.4	122.3	123.8	124.1	122.9	122.3	123.8	124.1	124.9	124.8	124.3	125.1	124.5	124.8	125.9	125.3	123.0	124.3	124.3
0.85	130.5	125.5	122.0	124.1	124.2	123.0	122.0	124.1	124.2	124.3	125.0	123.7	125.7	125.3	124.7	126.0	125.1	123.2	124.1	124.0
0.9	130.5	125.7	122.6	124.1	124.4	123.5	122.6	124.1	124.4	125.0	125.3	124.2	126.2	125.4	125.3	126.5	125.5	123.8	124.3	124.1
0.95	130.5	125.9	122.7	123.9	124.8	123.5	122.7	123.9	124.8	125.4	125.0	124.6	126.1	125.6	125.5	126.4	125.1	123.3	124.4	124.1
1	130.6	126.0	122.5	124.0	124.2	123.8	122.5	124.0	124.2	125.4	125.2	124.6	126.7	125.7	125.5	126.3	125.4	123.6	124.5	124.6
1.05	130.6	126.2	123.1	124.3	124.8	123.9	123.1	124.3	124.8	125.5	125.5	124.8	126.2	125.6	125.5	126.5	125.4	123.8	124.7	124.1
1.1	130.6	126.4	122.6	124.6	124.4	123.8	122.6	124.6	124.4	125.8	125.7	124.8	126.8	125.7	125.6	126.7	125.5	123.7	124.4	124.3
1.15	130.6	126.5	122.8	124.9	124.6	124.0	122.8	124.9	124.6	125.8	126.2	124.9	126.5	126.1	125.7	126.8	125.6	124.1	124.4	124.3
1.2	130.6	126.7	123.3	124.7	124.6	123.8	123.3	124.7	124.6	125.7	125.8	125.1	127.1	125.8	126.0	126.8	125.8	123.9	124.2	124.3
1.25	130.6	126.8	123.2	125.3	124.7	124.0	123.2	125.3	124.7	126.0	125.9	124.9	127.0	125.7	125.7	126.9	125.7	123.6	124.5	124.3
1.3	130.6	127.0	123.2	125.3	124.8	124.0	123.2	125.3	124.8	126.3	126.2	125.8	126.7	125.7	125.4	127.0	126.1	123.6	124.6	124.5
1.35	130.6	127.1	123.4	125.2	124.8	124.1	123.4	125.2	124.8	126.2	126.1	125.2	127.2	126.1	125.9	126.8	125.7	124.5	124.5	124.7

Yaw Rate (deg/sec)	Delay Time (secs)																			
	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600
1.4	130.6	127.2	123.4	125.6	125.0	123.9	123.4	125.6	125.0	126.3	126.5	125.3	127.0	125.9	125.7	126.8	125.6	123.8	124.9	124.4
1.45	130.6	127.2	123.4	125.5	124.9	124.3	123.4	125.5	124.9	126.1	126.4	125.4	126.5	125.4	125.5	126.8	125.6	124.1	124.5	124.4
1.5	130.6	127.2	123.7	125.5	125.0	124.3	123.7	125.5	125.0	126.1	126.1	125.6	126.9	125.9	125.6	127.0	125.8	124.1	124.8	124.7
1.55	130.7	127.3	123.8	125.5	125.0	124.7	123.8	125.5	125.0	126.3	126.5	125.3	127.0	126.4	125.8	127.0	125.7	124.8	124.4	124.5
1.6	130.7	127.3	124.0	125.9	124.9	124.7	124.0	125.9	124.9	126.4	126.0	125.2	127.2	126.2	126.0	126.9	125.7	124.1	124.8	124.4
1.65	130.7	127.3	124.3	125.9	125.0	124.8	124.3	125.9	125.0	126.1	126.2	125.4	126.8	125.7	125.7	126.7	125.6	124.1	124.6	124.6
1.7	130.7	127.4	124.2	125.7	125.2	124.7	124.2	125.7	125.2	126.1	126.3	125.6	127.0	125.9	125.5	127.0	125.8	123.9	124.6	123.9
1.75	130.7	127.4	124.4	125.7	125.4	124.8	124.4	125.7	125.4	126.3	126.5	125.5	127.0	126.0	125.8	127.2	126.0	124.1	125.2	124.8
1.8	130.7	127.5	124.4	125.8	125.2	124.8	124.4	125.8	125.2	126.2	126.7	125.8	127.4	126.2	125.9	127.2	125.9	125.0	125.1	124.8
1.85	130.7	127.6	124.4	126.0	125.1	124.8	124.4	126.0	125.1	126.1	126.5	125.3	127.3	126.7	125.9	127.2	125.8	124.1	125.3	124.5
1.9	130.7	127.6	124.4	126.0	125.2	124.8	124.4	126.0	125.2	126.0	126.3	125.1	126.9	125.8	125.9	126.7	125.5	123.8	124.3	124.5
1.95	130.7	127.8	124.4	125.7	125.0	124.7	124.4	125.7	125.0	126.0	125.6	125.0	126.5	125.5	125.0	126.8	125.0	123.6	123.9	123.8
2	130.7	127.8	124.3	125.9	124.9	124.8	124.3	125.9	124.9	125.8	125.5	124.9	126.4	125.2	125.2	126.8	125.0	122.8	124.0	124.6

Table B.7 Energy (MWh) estimated by dynamic model for RG6 (30 sec averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)																			
	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600
0	84.3	77.8	77.6	77.8	77.7	77.7	77.6	77.8	77.7	77.8	82.9	78.9	83.0	78.7	77.9	83.5	83.2	82.3	82.7	78.8
0.05	133.6	127.1	125.4	125.7	125.7	125.8	125.4	125.7	125.7	124.9	124.7	124.2	125.3	125.6	125.4	124.9	126.8	123.2	122.3	120.8
0.1	134.3	128.1	127.0	126.5	124.4	125.3	127.0	126.5	124.4	126.6	123.2	122.8	125.3	124.9	124.0	125.8	124.3	122.0	124.6	122.4
0.15	134.2	128.1	126.9	125.0	123.1	121.9	126.9	125.0	123.1	125.5	124.3	125.7	123.7	126.5	125.6	125.3	126.0	122.3	124.3	123.2
0.2	134.2	127.8	126.0	123.9	123.5	121.1	126.0	123.9	123.5	124.5	123.4	124.7	125.8	124.6	124.8	126.2	126.4	122.7	124.5	124.1
0.25	134.2	127.5	125.8	124.1	123.1	121.5	125.8	124.1	123.1	125.3	124.3	124.6	126.3	125.8	125.0	126.4	127.2	122.5	124.8	124.0
0.3	134.0	127.4	125.0	123.5	123.0	121.8	125.0	123.5	123.0	124.6	124.7	125.1	125.7	124.5	124.6	126.2	126.6	123.3	124.9	124.4
0.35	133.8	127.1	125.0	124.6	123.6	122.3	125.0	124.6	123.6	124.3	125.1	125.1	125.8	124.7	125.2	127.2	126.7	123.6	125.4	123.8
0.4	133.5	127.0	123.5	124.1	124.5	122.9	123.5	124.1	124.5	124.6	125.6	125.6	125.9	125.6	125.2	126.5	126.2	124.0	124.7	123.3
0.45	133.3	126.7	123.2	124.3	124.2	122.8	123.2	124.3	124.2	125.7	125.0	125.2	126.5	125.7	124.8	126.6	126.0	124.2	124.8	124.0
0.5	133.1	126.6	122.6	124.0	123.3	123.2	122.6	124.0	123.3	125.2	125.5	125.4	126.7	125.9	124.9	126.5	126.8	123.6	125.3	123.5
0.55	133.0	126.8	123.2	124.0	123.4	123.5	123.2	124.0	123.4	126.0	126.5	125.0	126.2	125.2	124.8	126.5	126.0	124.0	125.5	124.3
0.6	132.8	126.9	123.9	124.0	122.9	123.0	123.9	124.0	122.9	125.8	126.0	124.9	126.1	125.2	125.2	126.6	125.6	123.7	125.5	124.7
0.65	132.7	127.0	123.2	124.0	123.6	123.2	123.2	124.0	123.6	126.1	126.1	125.4	126.4	126.2	125.6	127.1	126.5	124.5	125.2	125.3
0.7	132.5	127.1	123.5	124.4	124.1	123.1	123.5	124.4	124.1	125.8	125.6	125.2	126.4	126.2	125.6	127.4	126.6	124.6	125.3	124.6
0.75	132.4	127.2	123.3	125.0	124.2	123.8	123.3	125.0	124.2	126.0	125.4	125.0	125.7	125.9	125.8	127.4	126.3	124.9	125.6	124.9
0.8	132.3	127.3	124.1	125.5	124.4	123.8	124.1	125.5	124.4	125.8	126.0	124.9	126.5	126.3	126.0	127.6	126.6	124.9	125.7	125.1
0.85	132.1	127.4	123.9	125.2	124.4	124.0	123.9	125.2	124.4	125.7	126.0	125.2	126.5	126.4	126.3	127.5	126.8	124.9	125.8	125.1
0.9	132.1	127.6	123.9	125.3	124.9	123.9	123.9	125.3	124.9	125.7	125.9	125.5	127.0	126.5	126.2	128.2	127.0	125.0	125.6	124.7
0.95	132.0	127.7	124.0	125.7	125.3	124.6	124.0	125.7	125.3	126.1	126.3	125.7	127.2	126.9	126.5	127.9	126.8	125.0	125.7	125.2
1	132.0	127.9	124.0	125.6	125.1	124.5	124.0	125.6	125.1	126.1	126.7	125.7	127.6	127.2	126.4	128.0	127.3	125.0	125.7	125.2
1.05	132.0	127.8	123.8	125.9	125.5	124.8	123.8	125.9	125.5	126.4	126.6	125.7	127.5	127.0	126.8	128.4	127.0	125.2	125.7	125.4
1.1	132.0	128.0	123.6	126.1	125.7	124.8	123.6	126.1	125.7	126.7	126.8	125.9	128.1	127.0	126.8	128.4	126.8	124.7	125.4	125.3
1.15	132.0	128.2	123.9	126.1	125.9	125.4	123.9	126.1	125.9	126.7	127.0	126.1	128.0	127.1	127.0	128.3	126.8	125.3	125.3	125.8
1.2	132.0	128.5	124.1	126.6	125.7	125.5	124.1	126.6	125.7	126.9	127.1	126.1	128.5	127.1	127.6	128.9	126.9	125.1	125.8	126.0
1.25	132.0	128.6	124.3	126.6	125.6	125.3	124.3	126.6	125.6	127.4	127.2	126.3	128.1	127.0	127.4	128.8	127.4	124.8	125.9	125.6
1.3	132.0	128.6	124.8	126.5	125.8	125.4	124.8	126.5	125.8	127.3	127.2	126.4	128.2	127.1	127.3	128.7	127.1	125.0	126.0	125.5
1.35	132.1	128.7	124.6	126.5	125.9	125.1	124.6	126.5	125.9	127.3	127.3	126.5	128.1	127.3	127.6	128.9	127.4	125.2	125.8	126.3

Yaw Rate (deg/sec)	Delay Time (secs)																			
	30	60	90	120	150	180	210	240	270	300	330	360	390	420	450	480	510	540	570	600
1.4	132.0	128.9	124.8	126.9	126.0	125.3	124.8	126.9	126.0	127.4	127.2	126.3	128.1	127.0	127.3	128.8	127.6	124.8	125.9	126.1
1.45	132.0	129.0	124.9	126.6	126.2	125.2	124.9	126.6	126.2	127.3	127.3	126.2	127.9	126.9	126.7	128.5	127.3	125.4	125.4	126.0
1.5	132.0	129.0	125.3	127.0	126.2	125.4	125.3	127.0	126.2	127.3	127.4	126.1	128.3	126.9	127.5	128.7	127.3	125.3	125.8	126.0
1.55	132.0	129.0	125.2	127.1	126.4	125.3	125.2	127.1	126.4	127.4	127.4	126.2	128.5	127.3	127.3	129.1	127.5	125.8	125.6	126.0
1.6	132.0	129.1	125.4	127.2	126.2	125.7	125.4	127.2	126.2	127.5	127.6	126.2	128.3	127.6	127.6	128.9	127.6	125.2	125.9	126.2
1.65	132.0	129.2	125.2	127.3	126.3	125.9	125.2	127.3	126.3	127.8	127.6	126.4	127.9	127.2	126.9	128.4	127.0	125.6	125.8	125.8
1.7	132.0	129.2	125.6	127.3	126.5	125.6	125.6	127.3	126.5	127.8	127.1	126.0	128.1	127.3	126.8	128.5	127.4	125.1	126.1	125.9
1.75	132.0	129.2	125.7	127.4	126.6	125.7	125.7	127.4	126.6	127.6	127.3	126.3	128.2	127.3	127.5	128.8	127.9	125.5	125.8	126.1
1.8	132.0	129.3	125.8	127.4	126.3	125.7	125.8	127.4	126.3	127.6	127.3	126.5	128.6	127.3	127.2	129.2	127.9	125.4	126.1	125.8
1.85	132.0	129.3	126.0	127.4	126.5	125.9	126.0	127.4	126.5	127.7	127.3	126.4	128.8	127.9	127.5	128.7	127.4	125.5	125.9	126.3
1.9	132.0	129.5	126.0	127.5	126.6	126.0	126.0	127.5	126.6	127.3	127.2	126.6	128.1	127.3	127.0	128.5	126.7	125.0	125.6	125.6
1.95	132.0	129.5	125.9	127.2	126.4	125.6	125.9	127.2	126.4	127.4	126.5	125.9	127.9	126.5	126.4	128.2	126.6	124.5	125.2	125.0
2	132.0	129.6	125.9	127.2	126.2	125.9	125.9	127.2	126.2	127.1	126.5	126.0	128.1	126.4	126.6	128.2	126.6	124.1	125.3	125.6

Table B.8 Energy (MWh) estimated by dynamic model for RG1 (1 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)									
	60	120	180	240	300	360	420	480	540	600
0	46.4	44.7	45.4	45.1	45.7	45.9	45.1	46.2	45.9	45.7
0.05	79.2	75.3	75.1	75.8	76.0	75.2	75.4	75.9	73.5	76.6
0.1	79.4	77.6	74.3	76.1	73.2	76.6	76.3	76.8	75.2	75.5
0.15	79.7	77.5	76.0	73.9	75.5	75.3	75.5	76.3	76.5	75.9
0.2	79.9	77.5	75.7	74.9	75.0	74.5	75.7	76.4	77.3	75.6
0.25	79.8	77.5	75.2	74.3	75.5	74.9	75.4	77.8	76.5	75.0
0.3	79.7	77.7	74.8	74.2	75.9	74.8	76.0	77.7	76.3	75.6
0.35	79.6	77.8	75.2	75.1	76.3	75.7	75.7	77.8	77.1	75.7
0.4	79.6	77.8	75.0	75.6	76.1	75.6	75.9	78.1	77.0	75.4
0.45	79.6	77.9	76.4	75.9	75.7	76.2	75.6	78.2	77.0	75.6
0.5	79.5	78.0	76.1	76.3	76.1	76.1	76.0	77.9	77.2	75.8
0.55	79.5	78.0	76.4	76.4	76.2	76.6	75.9	78.0	76.8	75.8
0.6	79.4	78.0	76.3	76.0	76.2	76.5	76.3	77.5	77.1	76.0
0.65	79.3	78.1	76.7	76.2	76.9	76.6	75.8	78.2	77.1	76.1
0.7	79.3	78.2	76.6	76.2	76.7	76.7	75.8	77.6	77.1	76.1
0.75	79.3	78.3	76.9	76.5	77.1	76.8	76.0	78.2	77.7	76.4
0.8	79.3	78.3	77.0	76.7	77.0	77.1	76.0	77.9	77.3	76.6
0.85	79.3	78.2	77.0	76.9	77.1	77.0	76.3	78.0	77.0	76.7
0.9	79.3	78.3	77.1	77.2	76.7	77.4	76.7	78.3	77.7	76.8
0.95	79.3	78.5	77.1	77.3	77.0	77.4	76.2	78.5	77.2	76.6
1	79.4	78.6	76.8	77.1	76.7	77.4	76.6	77.8	77.5	76.1
1.05	79.5	78.6	77.1	77.1	76.8	77.7	76.5	78.1	77.4	76.4
1.1	79.5	78.6	77.3	77.2	76.7	77.8	76.8	78.3	77.6	76.3
1.15	79.5	78.7	77.5	77.0	77.1	77.7	76.5	78.4	77.4	76.3
1.2	79.6	78.7	77.6	77.3	76.6	77.5	76.4	78.2	77.0	76.3
1.25	79.6	78.8	77.6	77.3	76.9	77.5	76.1	77.8	76.8	76.6
1.3	79.7	78.9	77.8	77.3	77.0	77.6	76.3	78.0	77.1	77.0
1.35	79.8	78.9	77.9	77.3	76.8	77.9	76.4	78.2	77.6	76.9
1.4	79.8	79.1	78.0	77.4	77.0	78.0	76.5	78.3	77.4	76.8
1.45	79.8	79.0	78.1	77.5	77.3	77.9	76.5	78.2	77.6	76.4
1.5	79.8	79.0	77.9	77.6	77.1	77.4	76.5	77.5	77.1	76.4
1.55	79.9	79.0	77.7	77.3	76.9	77.5	76.4	77.8	77.0	76.4
1.6	79.9	79.0	77.7	77.5	77.0	77.5	76.4	77.8	77.3	76.6
1.65	80.0	79.1	77.7	77.5	77.1	77.4	76.4	78.2	77.5	76.5
1.7	80.2	79.1	77.8	77.7	77.3	77.5	76.5	78.4	77.6	76.9
1.75	80.3	79.2	78.0	77.8	77.6	77.8	76.8	78.7	77.9	77.2
1.8	80.4	79.3	78.2	78.1	77.9	78.1	77.1	79.0	78.6	77.4
1.85	80.5	79.4	78.5	78.3	78.1	78.3	77.3	79.2	78.5	77.8
1.9	80.5	79.4	78.4	78.2	77.9	77.9	77.4	79.4	77.6	77.8
1.95	80.5	79.5	78.3	78.1	77.7	77.9	76.9	79.0	77.8	77.6
2	80.5	79.5	78.4	78.1	78.0	77.8	76.7	78.6	77.6	77.3

Table B.9 Energy (MWh) estimated by dynamic model for RG2 (1 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)									
	60	120	180	240	300	360	420	480	540	600
0	60.9	58.6	59.7	59.1	60.0	60.3	59.1	60.8	60.3	60.0
0.05	87.5	83.0	83.0	83.4	84.6	83.5	84.9	84.5	81.5	83.4
0.1	87.7	85.3	82.0	83.6	83.8	82.7	83.3	84.1	83.3	83.5
0.15	87.7	85.6	82.5	82.8	83.4	83.6	83.8	85.8	83.7	83.7
0.2	88.1	85.5	83.5	83.9	85.0	83.5	83.4	85.1	84.8	84.7
0.25	88.2	85.8	83.0	83.5	83.1	83.2	83.5	86.7	84.7	84.0
0.3	88.2	85.9	83.0	83.2	83.9	84.3	83.7	86.8	84.9	83.9
0.35	88.3	86.1	83.2	84.0	84.6	84.6	84.4	86.8	85.3	84.0
0.4	88.3	86.2	84.0	84.3	84.7	84.4	84.6	86.5	85.5	84.1
0.45	88.4	86.3	84.4	85.0	84.7	85.2	84.1	86.7	85.6	84.1
0.5	88.4	86.5	84.3	85.2	84.9	84.9	84.7	86.9	85.4	83.7
0.55	88.4	86.5	85.0	85.0	84.6	86.0	84.5	86.7	85.3	84.0
0.6	88.4	86.5	85.5	85.1	85.0	85.4	84.6	86.9	85.9	84.5
0.65	88.4	86.6	84.7	85.4	85.5	85.4	84.4	86.9	85.4	84.7
0.7	88.4	86.6	84.6	85.2	85.5	85.8	84.7	86.7	85.8	84.5
0.75	88.5	86.8	85.4	85.6	85.4	85.7	84.6	87.1	86.2	84.9
0.8	88.5	86.8	85.5	85.7	85.3	86.1	84.8	87.1	86.1	85.0
0.85	88.5	86.9	85.8	86.1	85.6	86.1	85.0	87.3	85.9	85.0
0.9	88.5	87.0	85.7	85.9	85.5	86.3	85.5	87.4	86.6	85.2
0.95	88.6	87.1	85.6	86.2	85.9	86.2	85.0	87.6	86.0	84.9
1	88.6	87.2	85.7	85.7	85.5	86.3	85.3	86.9	86.2	84.5
1.05	88.7	87.3	85.7	85.9	85.8	86.4	85.3	87.0	86.0	84.6
1.1	88.7	87.3	85.9	85.8	85.7	86.2	85.4	87.3	86.5	84.7
1.15	88.7	87.4	86.1	86.0	86.1	86.2	85.1	87.6	86.1	84.7
1.2	88.7	87.4	86.4	86.0	85.7	86.3	84.9	87.0	85.6	84.6
1.25	88.8	87.5	86.3	86.0	85.6	86.2	84.9	86.6	85.5	84.8
1.3	88.9	87.6	86.4	86.0	85.7	86.3	85.2	87.0	85.8	85.1
1.35	88.9	87.8	86.6	86.2	85.8	86.7	85.5	87.2	86.5	85.1
1.4	89.0	87.9	86.7	86.1	85.9	86.6	85.3	87.3	86.2	85.0
1.45	89.0	87.8	86.6	86.4	86.1	86.5	84.8	87.4	86.3	85.4
1.5	89.0	87.9	86.4	86.2	86.1	86.5	85.0	86.5	85.8	84.8
1.55	89.1	87.9	86.3	86.0	85.8	86.2	85.1	86.8	85.7	84.6
1.6	89.1	87.9	86.3	86.1	85.8	86.4	85.2	86.8	85.8	84.7
1.65	89.2	87.9	86.3	86.2	86.0	86.1	85.3	87.2	86.0	84.6
1.7	89.4	88.0	86.5	86.4	86.2	86.3	85.3	87.5	86.2	84.9
1.75	89.5	88.1	86.7	86.6	86.5	86.6	85.7	87.7	86.5	85.3
1.8	89.6	88.2	87.0	87.1	86.8	87.0	86.0	87.9	87.2	85.6
1.85	89.7	88.3	87.1	87.1	87.0	87.2	86.1	88.0	87.5	86.0
1.9	89.7	88.3	87.0	87.0	86.8	86.7	86.0	88.4	86.6	86.0
1.95	89.7	88.4	87.0	86.9	86.5	86.7	85.7	87.7	86.5	85.8
2	89.7	88.4	87.1	86.9	86.8	86.8	85.2	87.4	86.2	85.5

Table B.10 Energy (MWh) estimated by dynamic model for RG3 (1 min averaged data set)

Yaw Rate (deg/sec)	**Delay Time (secs)**									
	60	120	180	240	300	360	420	480	540	600
0	75.4	71.9	73.4	72.7	73.9	74.3	72.9	75.0	74.4	73.9
0.05	106.8	100.5	101.7	101.3	102.1	102.0	100.8	103.6	101.2	100.5
0.1	107.0	101.9	101.6	103.8	101.3	102.3	102.8	105.3	102.9	102.8
0.15	107.4	103.2	100.8	101.2	103.9	103.3	102.0	104.2	104.0	101.9
0.2	107.8	104.0	102.2	101.4	102.7	103.4	102.6	106.1	104.4	102.8
0.25	108.2	104.3	100.4	102.0	101.9	102.4	103.0	106.3	104.5	102.6
0.3	108.2	104.4	102.5	102.2	102.8	102.9	103.1	106.1	104.6	102.2
0.35	108.2	104.7	102.2	102.9	103.3	102.6	102.7	105.2	105.2	103.1
0.4	108.2	104.9	103.0	102.9	102.9	103.0	103.9	105.7	104.4	102.9
0.45	108.1	105.2	103.1	103.1	103.3	103.1	103.4	105.9	104.7	102.8
0.5	108.1	105.5	103.4	103.5	103.5	102.9	103.9	106.1	104.9	102.5
0.55	108.1	105.5	103.6	103.8	103.7	104.6	103.7	106.2	104.6	102.8
0.6	108.1	105.6	104.1	104.0	104.0	103.8	103.5	106.1	104.6	103.2
0.65	108.1	105.6	104.4	104.1	104.4	104.0	103.8	106.2	104.2	103.7
0.7	108.0	105.7	104.3	104.2	104.4	104.6	104.0	106.1	105.0	103.1
0.75	108.0	105.8	104.5	104.3	104.6	104.0	104.0	106.5	104.9	103.5
0.8	108.0	105.8	104.8	104.7	104.4	104.7	104.2	106.5	105.0	103.8
0.85	108.0	106.0	104.7	104.8	104.6	104.8	104.2	106.5	104.9	104.1
0.9	108.0	106.1	104.8	105.0	104.4	104.8	104.5	106.4	105.2	104.1
0.95	108.1	106.2	105.1	104.9	104.6	104.8	104.4	106.6	105.6	103.8
1	108.1	106.2	104.8	104.6	104.4	104.7	104.2	106.7	104.3	103.8
1.05	108.1	106.3	104.8	104.8	104.8	104.6	104.4	106.3	104.3	103.5
1.1	108.1	106.3	105.1	104.6	104.8	104.8	104.4	106.5	104.9	103.4
1.15	108.2	106.3	105.4	104.6	105.2	104.6	104.4	106.4	104.7	103.3
1.2	108.2	106.4	105.5	104.6	104.3	104.4	104.0	106.0	104.3	103.4
1.25	108.3	106.6	105.5	104.3	104.6	104.6	104.2	105.8	104.5	103.8
1.3	108.4	106.7	105.7	104.6	104.9	105.0	104.3	106.1	104.3	104.3
1.35	108.5	106.8	106.0	104.6	105.1	105.2	104.6	106.3	104.8	103.9
1.4	108.6	106.8	105.8	104.7	105.4	105.1	104.9	106.4	105.2	103.8
1.45	108.6	106.9	105.7	104.7	105.1	105.1	104.5	106.3	104.9	104.0
1.5	108.6	107.0	105.5	104.8	105.2	104.7	103.9	106.0	104.7	103.3
1.55	108.7	107.0	105.4	104.7	104.9	104.4	104.0	105.6	104.1	103.1
1.6	108.8	107.1	105.5	104.8	104.9	104.2	104.1	105.7	104.1	103.0
1.65	108.9	107.1	105.6	104.9	105.1	104.0	104.1	105.8	104.3	102.9
1.7	109.0	107.3	105.7	105.0	105.3	104.3	104.5	106.1	104.7	103.3
1.75	109.2	107.4	105.7	105.3	105.6	104.8	104.9	106.4	104.8	103.7
1.8	109.3	107.5	105.9	105.6	105.9	105.3	105.1	106.7	105.5	104.1
1.85	109.4	107.6	106.0	105.9	105.8	105.4	105.5	107.2	105.8	104.6
1.9	109.4	107.7	106.0	105.8	105.8	105.5	105.4	107.4	105.3	104.9
1.95	109.4	107.7	106.0	105.7	105.6	105.0	104.9	106.7	105.0	104.3

Yaw Rate (deg/sec)	Delay Time (secs)									
	60	120	180	240	300	360	420	480	540	600
2	109.4	107.7	106.3	105.7	105.8	105.1	104.6	106.4	104.9	104.7

Table B.11 Energy (MWh) estimated by dynamic model for RG4 (1 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)									
	60	120	180	240	300	360	420	480	540	600
0	84.3	80.5	82.3	81.5	82.8	83.2	81.6	83.9	83.3	82.8
0.05	122.6	115.9	116.3	115.5	116.8	115.6	118.1	120.9	115.8	116.3
0.1	122.1	116.3	115.8	116.5	116.7	118.0	115.5	120.6	116.0	119.0
0.15	121.6	116.7	118.2	116.9	117.6	115.9	116.0	119.4	116.3	116.8
0.2	122.1	117.8	115.0	116.0	116.4	117.3	116.3	120.4	118.1	117.3
0.25	122.4	118.4	114.9	116.2	115.9	117.1	116.4	119.5	117.6	115.9
0.3	122.9	118.6	115.4	116.2	115.5	116.8	116.8	119.4	117.8	116.4
0.35	123.0	119.1	115.5	116.6	116.2	117.6	116.9	120.0	119.7	116.6
0.4	122.8	119.4	115.9	117.1	116.5	117.3	117.4	120.5	119.6	116.1
0.45	122.8	119.7	116.9	116.9	116.7	117.7	118.5	120.3	119.3	116.4
0.5	122.8	120.1	117.2	117.2	117.6	118.6	118.3	120.0	119.8	116.6
0.55	122.8	120.4	117.5	116.9	117.8	118.5	118.4	120.1	120.0	116.4
0.6	122.8	120.7	118.9	118.1	118.0	119.1	118.6	120.4	119.6	116.4
0.65	122.8	120.9	118.9	118.6	118.4	118.6	118.3	120.6	119.4	117.2
0.7	122.9	120.9	118.6	118.6	118.9	119.1	118.3	120.8	120.0	116.7
0.75	122.9	120.8	118.7	118.6	118.9	118.9	118.6	121.0	119.6	117.6
0.8	123.0	120.8	118.8	119.6	119.1	119.0	118.6	121.4	120.0	117.9
0.85	123.0	120.9	119.0	119.3	118.8	119.5	118.9	120.9	119.6	117.9
0.9	123.1	121.0	119.6	119.1	118.7	119.4	119.2	121.0	120.1	117.8
0.95	123.1	121.0	119.6	118.9	119.1	119.0	119.1	121.4	120.1	118.1
1	123.1	121.0	119.3	118.9	119.0	118.6	119.2	121.0	119.4	117.2
1.05	123.2	121.1	119.5	119.1	119.2	118.9	119.2	121.3	119.5	117.3
1.1	123.3	121.1	119.6	119.3	119.2	119.1	119.3	121.1	120.4	117.5
1.15	123.3	121.1	119.8	119.2	119.2	119.4	119.0	120.7	119.6	117.7
1.2	123.4	121.2	120.0	119.2	119.5	119.0	118.9	120.6	119.1	117.0
1.25	123.5	121.4	120.2	119.1	119.0	118.8	118.6	120.9	119.5	117.2
1.3	123.6	121.5	120.6	119.1	119.4	119.1	119.0	121.1	119.8	117.3
1.35	123.7	121.7	120.9	119.4	119.5	119.0	119.4	121.1	120.0	117.4
1.4	123.7	121.8	120.9	119.5	119.7	119.1	119.4	121.1	120.2	117.6
1.45	123.7	121.8	120.8	119.5	119.6	119.4	118.6	120.6	119.2	117.5
1.5	123.7	122.0	120.4	119.4	119.5	118.8	118.4	120.0	119.3	116.6
1.55	123.8	122.0	120.4	119.5	119.3	118.3	118.5	119.9	118.9	116.6
1.6	123.9	122.1	120.4	119.6	119.4	118.3	118.7	120.1	119.1	117.0
1.65	124.0	122.2	120.4	119.7	119.5	118.3	118.9	120.3	119.3	117.4
1.7	124.2	122.3	120.6	119.9	119.5	118.6	119.3	120.7	119.8	117.6

Yaw Rate (deg/sec)	Delay Time (secs)									
	60	120	180	240	300	360	420	480	540	600
1.75	124.3	122.4	120.9	120.3	119.8	119.1	119.7	121.1	120.2	118.1
1.8	124.4	122.5	121.0	120.6	120.0	119.5	120.1	121.6	120.8	118.2
1.85	124.5	122.5	121.3	120.8	120.2	119.8	120.1	121.7	120.9	118.2
1.9	124.5	122.6	121.0	120.7	120.5	119.9	119.4	121.9	120.1	118.3
1.95	124.5	122.6	120.9	120.5	120.0	119.5	119.0	121.5	119.4	117.9
2	124.5	122.6	121.0	120.7	119.9	119.7	118.8	121.0	119.8	118.1

Table B.12 Energy (MWh) estimated by dynamic model for RG5 (1 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)									
	60	120	180	240	300	360	420	480	540	600
0	88.5	84.7	86.5	85.7	87.0	87.4	85.8	88.1	87.5	87.0
0.05	135.3	128.1	127.9	125.6	128.3	128.6	127.0	129.5	125.6	126.9
0.1	135.5	128.5	127.0	127.2	127.0	128.1	125.7	129.2	127.8	125.9
0.15	134.8	127.9	127.7	124.6	127.0	126.5	127.3	128.1	127.6	125.9
0.2	134.7	128.1	125.2	125.9	125.9	128.4	127.0	129.0	127.2	125.1
0.25	134.4	128.4	124.7	125.4	124.5	126.7	126.3	129.6	128.7	125.6
0.3	134.3	128.9	124.9	126.1	125.7	127.1	125.9	129.7	128.5	126.1
0.35	134.2	129.3	125.4	126.4	126.4	128.0	125.6	129.7	128.9	126.4
0.4	133.9	129.7	126.6	126.4	126.0	127.7	127.0	130.0	129.0	126.2
0.45	133.8	130.0	126.0	127.5	126.5	128.1	127.3	129.9	129.5	126.3
0.5	133.7	130.0	126.5	128.0	127.4	128.6	127.9	129.6	129.7	126.6
0.55	133.6	130.4	127.1	128.5	127.8	129.1	128.0	129.9	129.6	126.2
0.6	133.5	130.7	127.9	128.8	127.9	129.3	127.8	130.1	129.6	127.0
0.65	133.4	130.7	127.6	128.3	128.3	128.6	127.8	130.5	129.4	126.6
0.7	133.3	130.8	127.7	128.5	128.1	128.9	127.6	130.6	129.4	126.6
0.75	133.3	130.6	128.5	129.0	128.0	128.9	127.8	130.8	129.8	127.1
0.8	133.2	130.6	128.7	129.0	128.6	129.5	127.9	131.1	129.9	127.5
0.85	133.1	130.7	128.9	129.3	128.4	129.0	127.9	131.0	129.8	127.1
0.9	133.1	130.8	128.8	129.4	128.6	129.2	128.6	130.9	130.3	127.4
0.95	133.0	131.2	129.2	129.5	128.6	129.4	128.2	130.9	130.2	127.4
1	133.1	131.3	129.3	129.8	128.4	128.8	128.3	130.8	129.4	126.9
1.05	133.1	131.4	129.2	129.5	128.8	129.0	128.6	130.9	130.0	126.8
1.1	133.1	131.4	129.8	129.8	128.8	129.0	128.9	130.8	129.9	127.2
1.15	133.1	131.4	129.5	129.7	129.0	129.2	128.3	130.6	130.2	126.7
1.2	133.1	131.5	130.1	129.8	129.0	128.8	127.8	130.5	129.2	126.7
1.25	133.2	131.7	130.4	129.6	129.0	129.0	128.1	130.5	129.3	126.8
1.3	133.3	131.8	130.3	129.9	129.0	129.5	128.6	130.9	129.5	127.0
1.35	133.4	132.2	130.5	129.7	129.2	129.8	129.2	131.1	129.8	127.3
1.4	133.4	132.1	130.7	129.8	129.1	129.2	129.0	131.5	129.6	127.5
1.45	133.4	132.1	130.3	130.0	128.9	129.3	128.3	130.7	129.2	126.8

Yaw Rate (deg/sec)	Delay Time (secs)									
	60	120	180	240	300	360	420	480	540	600
1.5	133.5	132.1	130.1	129.7	128.5	128.9	127.8	130.4	129.2	126.2
1.55	133.6	132.2	130.1	129.8	128.5	128.7	127.8	130.5	128.5	126.2
1.6	133.7	132.2	130.1	129.9	128.6	128.7	127.9	130.7	128.7	126.6
1.65	133.9	132.3	130.1	130.1	128.8	128.9	128.2	130.9	129.5	126.8
1.7	134.1	132.4	130.4	130.4	129.0	129.2	128.3	131.3	129.3	127.4
1.75	134.3	132.5	130.6	130.7	129.3	129.7	128.9	131.7	129.8	127.8
1.8	134.4	132.6	130.9	130.9	129.8	130.2	129.4	132.0	130.3	128.3
1.85	134.5	132.7	131.1	131.0	129.8	129.9	129.6	132.0	130.6	128.7
1.9	134.5	132.7	130.7	131.0	129.8	130.1	129.1	131.8	129.7	128.1
1.95	134.5	132.7	130.7	130.6	129.5	129.7	128.4	131.3	129.4	127.0
2	134.5	132.7	131.0	130.5	129.5	129.4	127.9	131.4	129.2	127.4

Table B.13 Energy (MWh) estimated by dynamic model for RG6 (1 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)									
	60	120	180	240	300	360	420	480	540	600
0	88.2	84.7	86.3	85.6	86.7	87.1	85.8	87.8	87.2	86.7
0.05	135.9	129.4	129.1	128.1	128.9	129.5	127.7	130.0	127.8	126.0
0.1	135.9	130.2	128.7	127.7	128.3	126.8	124.6	129.2	127.9	127.2
0.15	135.6	129.4	126.7	127.3	128.1	126.2	126.3	129.3	128.0	127.5
0.2	135.2	129.4	128.6	128.6	126.9	128.6	125.9	129.8	129.0	126.2
0.25	135.0	129.7	127.1	127.1	126.0	127.1	126.7	130.3	128.6	126.0
0.3	135.0	129.7	126.2	127.8	128.2	128.3	127.5	130.9	129.4	127.0
0.35	134.8	130.1	126.2	127.8	127.7	127.4	127.1	131.0	129.6	128.4
0.4	134.6	130.5	126.0	127.9	126.9	128.3	128.3	131.1	129.6	127.3
0.45	134.5	131.1	126.9	129.5	127.6	129.7	128.8	131.2	130.1	127.6
0.5	134.4	131.2	126.9	129.6	128.3	129.7	129.4	130.6	130.0	127.9
0.55	134.4	131.4	127.5	129.2	128.5	129.9	129.4	130.8	130.0	128.1
0.6	134.4	131.7	128.5	130.0	129.3	129.9	129.1	131.1	130.2	128.2
0.65	134.3	131.7	129.6	130.4	129.5	129.7	129.2	131.5	130.1	128.4
0.7	134.2	131.7	128.9	130.2	129.2	129.6	129.3	131.4	130.3	128.1
0.75	134.1	131.7	129.6	130.5	129.2	129.6	129.4	131.7	130.5	128.2
0.8	134.1	131.8	129.8	130.5	129.3	130.1	129.8	132.0	130.8	128.6
0.85	134.1	132.0	130.2	130.8	129.4	129.9	130.3	131.9	130.9	128.2
0.9	134.0	132.0	130.6	131.2	129.7	130.0	130.5	132.5	131.4	128.6
0.95	134.0	132.4	130.7	131.4	129.6	130.2	130.3	132.0	130.8	128.3
1	134.0	132.4	130.6	131.2	129.5	130.0	130.3	131.8	130.9	127.8
1.05	134.0	132.5	130.7	131.1	129.7	130.0	130.4	132.0	130.4	127.9
1.1	134.0	132.4	130.9	131.1	130.0	130.3	130.8	132.2	131.0	128.4
1.15	134.0	132.5	130.9	131.0	129.8	130.2	130.4	132.0	130.9	127.8
1.2	134.1	132.6	131.2	131.0	129.6	130.0	130.2	131.5	130.4	127.8

Yaw Rate (deg/sec)	Delay Time (secs)									
	60	120	180	240	300	360	420	480	540	600
1.25	134.2	132.7	131.1	131.0	129.9	130.2	130.4	132.0	130.2	127.9
1.3	134.3	132.8	131.3	131.0	130.2	130.3	130.7	132.6	130.7	128.4
1.35	134.3	133.0	131.4	131.0	130.7	130.5	131.0	132.5	130.6	129.0
1.4	134.4	133.1	131.9	130.9	130.6	130.8	130.8	132.5	131.3	128.9
1.45	134.4	133.1	131.4	131.4	130.3	130.1	130.2	132.1	130.6	128.5
1.5	134.4	133.1	131.4	131.3	129.6	130.0	129.3	131.6	129.9	127.5
1.55	134.5	133.1	130.9	130.9	129.4	129.8	129.6	131.9	129.3	127.0
1.6	134.7	133.2	131.0	131.0	129.5	129.9	129.8	132.1	129.4	127.3
1.65	134.9	133.3	131.1	131.2	129.7	130.2	130.1	132.3	129.8	127.7
1.7	135.1	133.4	131.3	131.5	130.0	130.7	130.4	132.8	130.0	128.1
1.75	135.3	133.5	131.6	131.9	130.3	131.0	131.0	133.2	130.8	128.6
1.8	135.4	133.6	132.0	132.1	130.7	131.4	131.6	133.7	131.0	129.3
1.85	135.5	133.7	132.0	132.2	130.8	131.9	131.8	133.8	131.4	129.9
1.9	135.5	133.7	131.7	132.3	130.8	131.4	131.0	133.5	131.2	129.6
1.95	135.5	133.7	131.8	131.8	130.9	130.4	130.7	132.7	131.0	128.7
2	135.5	133.8	131.8	131.9	130.8	130.4	130.3	132.3	130.5	128.6

Table B.14 Energy (MWh) estimated by dynamic model for RG1 (2 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)				
	120	240	360	480	600
0	56.6	55.5	56.7	55.6	56.5
0.05	80.6	78.9	79.5	77.4	79.8
0.1	80.9	79.0	78.3	75.4	79.6
0.15	81.4	80.0	78.6	77.8	78.6
0.2	81.7	80.2	80.4	78.1	79.5
0.25	81.9	80.7	80.4	80.2	79.8
0.3	82.0	80.8	80.2	80.0	80.4
0.35	81.9	81.1	80.5	79.9	80.8
0.4	81.8	81.4	81.0	80.4	80.4
0.45	81.8	81.1	81.2	80.0	80.7
0.5	81.9	81.2	81.4	80.1	81.0
0.55	82.0	81.3	81.5	80.2	81.1
0.6	82.0	81.6	81.5	80.2	81.3
0.65	82.2	81.8	82.0	80.3	81.5
0.7	82.4	82.2	82.0	80.7	81.4
0.75	82.4	82.3	81.5	80.6	81.1
0.8	82.5	82.3	81.3	80.1	81.1
0.85	82.7	82.4	81.6	80.3	81.3
0.9	83.0	82.6	82.1	80.9	81.9
0.95	83.1	82.9	82.7	81.4	82.0

Yaw Rate (deg/sec)	Delay Time (secs)				
	120	240	360	480	600
1	83.1	82.9	82.2	81.3	81.7
1.05	83.1	82.9	82.2	81.3	81.7
1.1	83.2	82.9	82.1	81.3	81.8
1.15	83.2	82.9	82.1	81.4	81.9
1.2	83.3	83.0	82.1	81.4	82.2
1.25	83.6	83.3	82.3	81.8	82.5
1.3	83.8	83.5	82.6	82.2	82.9
1.35	84.1	83.8	83.0	82.9	83.5
1.4	84.3	84.1	83.7	83.0	83.7
1.45	84.4	84.3	83.5	82.7	83.7
1.5	84.4	84.2	83.5	82.3	83.2
1.55	84.4	84.1	83.3	82.3	83.0
1.6	84.4	84.1	83.1	82.2	82.8
1.65	84.4	84.0	83.0	82.0	82.6
1.7	84.4	83.9	83.0	81.9	82.5
1.75	84.4	83.8	83.0	81.9	82.4
1.8	84.4	83.8	83.0	81.9	82.3
1.85	84.4	83.8	83.0	81.9	82.3
1.9	84.4	83.8	83.1	82.0	82.4
1.95	84.4	83.8	83.1	82.0	82.5
2	84.4	83.8	83.1	81.9	82.5

Table B.15 Energy (MWh) estimated by dynamic model for RG2 (2 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)				
	120	240	360	480	600
0	65.4	64.2	65.6	64.3	65.4
0.05	89.4	86.8	87.5	85.4	86.5
0.1	89.7	87.5	88.6	84.2	87.9
0.15	90.4	88.4	87.7	86.5	87.2
0.2	90.5	88.8	89.7	87.8	89.1
0.25	90.7	89.1	89.3	87.2	89.1
0.3	90.8	89.2	89.2	88.6	89.8
0.35	90.8	89.6	89.2	88.8	89.9
0.4	90.9	90.1	89.9	89.0	89.5
0.45	91.0	90.2	90.2	88.8	89.6
0.5	91.2	89.9	90.4	88.8	90.0
0.55	91.3	89.9	90.5	88.8	89.7
0.6	91.3	90.4	90.4	88.9	90.0
0.65	91.5	90.6	91.1	89.1	89.7
0.7	91.7	91.0	91.4	89.5	90.0

Yaw Rate (deg/sec)	Delay Time (secs)				
	120	240	360	480	600
0.75	91.8	91.2	90.7	89.5	89.9
0.8	91.9	91.2	90.7	88.9	89.6
0.85	92.1	91.4	91.0	89.2	89.7
0.9	92.4	91.6	91.4	89.8	90.2
0.95	92.5	91.8	91.8	90.2	90.5
1	92.5	91.9	91.3	90.2	90.5
1.05	92.6	91.8	91.3	90.3	90.1
1.1	92.6	91.8	91.2	90.2	90.1
1.15	92.6	91.8	91.3	90.3	90.2
1.2	92.7	91.9	91.4	90.3	90.8
1.25	92.9	92.2	91.7	90.7	91.1
1.3	93.2	92.4	92.0	91.2	91.5
1.35	93.5	92.7	92.4	91.8	92.1
1.4	93.7	93.1	93.0	92.0	92.6
1.45	93.8	93.3	92.9	91.6	92.2
1.5	93.8	93.2	92.8	91.1	91.9
1.55	93.8	93.2	92.6	91.1	91.5
1.6	93.8	93.1	92.4	91.0	91.5
1.65	93.8	93.0	92.3	90.9	91.3
1.7	93.8	92.9	92.2	90.8	91.1
1.75	93.8	92.9	92.2	90.7	91.0
1.8	93.8	92.8	92.3	90.7	91.0
1.85	93.8	92.8	92.3	90.8	91.0
1.9	93.8	92.8	92.4	90.9	91.1
1.95	93.8	92.8	92.4	90.8	91.2
2	93.8	92.8	92.4	90.9	91.2

Table B.16 Energy (MWh) estimated by dynamic model for RG3 (2 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)				
	120	240	360	480	600
0	80.1	78.2	80.2	78.3	79.9
0.05	109.4	106.8	107.7	103.4	105.6
0.1	110.1	108.1	107.6	103.1	107.0
0.15	110.6	109.3	109.0	106.0	108.9
0.2	111.0	109.6	108.7	106.7	108.7
0.25	110.9	109.8	108.2	107.7	109.4
0.3	110.8	109.9	108.2	108.0	109.7
0.35	110.9	110.2	109.7	107.5	110.2
0.4	111.0	110.5	109.4	108.2	109.7
0.45	111.2	110.7	110.2	109.1	109.8

Yaw Rate (deg/sec)	Delay Time (secs)				
	120	240	360	480	600
0.5	111.2	110.5	111.1	108.9	109.7
0.55	111.4	110.7	111.4	108.8	109.7
0.6	111.5	110.8	111.3	109.1	110.1
0.65	111.7	111.2	111.7	109.0	110.4
0.7	112.0	111.5	111.3	109.1	110.1
0.75	112.1	111.6	111.1	109.3	110.0
0.8	112.2	111.6	111.2	109.1	110.1
0.85	112.5	111.8	111.5	109.4	110.4
0.9	112.8	112.0	112.0	109.9	110.9
0.95	113.0	112.2	112.2	110.6	111.0
1	113.0	112.2	112.3	110.3	110.1
1.05	113.0	112.2	112.2	110.2	110.3
1.1	113.0	112.2	112.2	110.1	110.4
1.15	113.1	112.2	112.3	110.3	110.4
1.2	113.3	112.4	112.5	110.3	111.2
1.25	113.6	112.7	112.9	110.6	111.7
1.3	113.9	113.0	113.3	110.9	112.3
1.35	114.2	113.3	113.8	111.5	112.7
1.4	114.4	113.6	114.0	111.7	113.2
1.45	114.5	114.0	113.1	111.3	112.7
1.5	114.5	113.8	113.3	111.4	112.7
1.55	114.5	113.7	112.9	111.3	112.3
1.6	114.5	113.6	112.7	111.2	112.2
1.65	114.5	113.5	112.6	111.2	112.0
1.7	114.5	113.4	112.5	111.2	111.9
1.75	114.5	113.3	112.5	111.1	111.8
1.8	114.5	113.2	112.6	111.1	111.8
1.85	114.5	113.2	112.7	111.2	111.8
1.9	114.5	113.2	112.9	111.2	111.8
1.95	114.5	113.2	112.9	111.2	111.8
2	114.5	113.2	112.9	111.2	111.8

Table B.17 Energy (MWh) estimated by dynamic model for RG4 (2 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)				
	120	240	360	480	600
0	89.6	87.6	89.8	87.6	89.4
0.05	125.6	121.7	121.8	118.5	123.2
0.1	125.0	122.6	120.5	117.7	122.5
0.15	124.6	123.1	121.6	120.0	124.0
0.2	125.0	123.4	122.8	122.4	123.0

Yaw Rate (deg/sec)	Delay Time (secs)				
	120	240	360	480	600
0.25	125.6	123.9	123.4	121.8	123.5
0.3	125.7	124.4	123.8	123.1	123.9
0.35	125.8	124.8	124.7	123.3	124.7
0.4	125.8	125.1	125.3	123.4	124.7
0.45	126.0	125.4	126.4	124.3	124.7
0.5	126.1	125.5	126.2	124.1	124.8
0.55	126.2	125.7	126.4	123.8	125.0
0.6	126.3	125.8	126.2	123.9	124.8
0.65	126.7	126.2	126.7	124.2	125.1
0.7	126.9	126.5	126.9	124.3	125.2
0.75	127.0	126.6	126.1	124.0	125.0
0.8	127.2	126.7	126.0	123.9	124.9
0.85	127.7	126.9	126.4	124.2	125.2
0.9	128.1	127.2	127.0	125.0	125.6
0.95	128.2	127.4	127.2	125.7	125.9
1	128.2	127.4	127.3	125.0	125.3
1.05	128.3	127.4	127.3	124.9	125.3
1.1	128.3	127.4	127.4	124.8	125.5
1.15	128.4	127.5	127.5	124.9	125.5
1.2	128.6	127.7	127.8	125.0	125.8
1.25	129.0	128.1	128.2	125.4	126.3
1.3	129.4	128.5	128.7	125.9	127.1
1.35	129.8	128.8	129.2	126.5	127.8
1.4	130.0	129.1	129.5	127.3	128.0
1.45	130.0	129.4	128.9	126.8	127.5
1.5	130.0	129.5	128.5	126.2	127.5
1.55	130.0	129.4	128.4	126.2	127.5
1.6	130.0	129.3	128.2	126.1	127.2
1.65	130.0	129.2	128.1	126.0	127.1
1.7	130.0	129.1	128.0	126.0	127.0
1.75	130.0	129.1	127.9	126.0	126.9
1.8	130.0	129.0	128.0	126.0	126.9
1.85	130.0	129.0	128.2	126.0	126.9
1.9	130.0	129.0	128.3	126.1	126.9
1.95	130.0	129.0	128.3	126.2	126.9
2	130.0	129.0	128.3	126.2	126.9

Table B.18 Energy (MWh) estimated by dynamic model for RG5 (2 min averaged data set)

Yaw Rate (deg/sec)	**Delay Time (secs)**				
	120	240	360	480	600
0	94.1	92.1	94.3	92.2	93.9
0.05	137.8	132.6	132.1	131.1	129.8
0.1	136.8	132.4	130.9	130.4	133.6
0.15	136.4	133.0	130.5	130.0	134.0
0.2	136.2	133.6	131.9	131.5	134.0
0.25	136.2	134.3	133.3	131.6	133.6
0.3	136.1	134.5	133.8	133.6	133.6
0.35	136.2	134.9	133.8	133.3	134.2
0.4	136.3	135.2	134.6	134.0	134.5
0.45	136.6	135.5	135.9	134.2	134.1
0.5	136.6	135.5	135.8	134.1	134.4
0.55	136.8	135.7	136.1	134.4	134.5
0.6	136.9	136.0	136.3	134.1	134.2
0.65	137.1	136.2	136.6	134.6	134.9
0.7	137.3	136.4	136.6	134.5	135.2
0.75	137.4	136.4	136.2	134.2	134.4
0.8	137.6	136.5	135.9	134.1	134.5
0.85	138.0	136.7	136.3	134.3	135.2
0.9	138.3	137.0	136.9	134.9	136.2
0.95	138.4	137.0	137.2	135.5	136.3
1	138.4	137.1	137.5	134.6	135.5
1.05	138.4	137.1	137.5	135.0	136.2
1.1	138.5	137.1	137.5	134.8	135.4
1.15	138.5	137.1	137.6	134.8	135.5
1.2	138.7	137.2	138.0	134.8	135.7
1.25	139.1	137.6	138.3	135.6	136.1
1.3	139.5	138.1	139.0	136.2	137.0
1.35	139.8	138.4	139.4	136.7	137.8
1.4	139.9	138.9	139.8	137.3	138.2
1.45	140.0	139.2	139.4	137.0	137.5
1.5	140.0	139.1	139.0	136.5	136.3
1.55	140.0	139.1	138.4	136.4	136.1
1.6	140.0	139.0	138.2	136.2	136.1
1.65	140.0	138.9	138.0	136.1	135.9
1.7	140.0	138.7	137.9	136.0	135.8
1.75	140.0	138.6	137.8	135.9	135.7
1.8	140.0	138.6	137.9	136.0	135.8
1.85	140.0	138.5	137.9	136.0	136.0
1.9	140.0	138.5	138.0	136.1	136.1
1.95	140.0	138.6	138.0	136.2	136.1

Yaw Rate (deg/sec)	Delay Time (secs)				
	120	240	360	480	600
2	140.0	138.6	138.0	136.2	136.1

Table B.19 Energy (MWh) estimated by dynamic model for RG6 (2 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)				
	120	240	360	480	600
0	94.2	92.5	94.3	92.5	94.0
0.05	139.7	135.6	136.4	131.7	132.5
0.1	139.2	135.3	132.3	131.4	132.7
0.15	138.7	135.8	134.9	133.3	131.5
0.2	138.4	135.5	134.7	132.6	134.8
0.25	138.1	136.1	134.6	133.6	134.2
0.3	137.8	136.1	135.0	134.4	134.9
0.35	137.7	136.5	135.8	134.3	135.4
0.4	137.6	136.6	135.9	134.8	135.4
0.45	137.7	136.6	136.1	135.3	135.7
0.5	137.7	136.6	136.5	135.2	135.4
0.55	137.8	136.7	136.7	135.6	135.3
0.6	137.8	136.9	137.1	135.3	135.8
0.65	138.2	137.1	136.9	135.7	136.2
0.7	138.4	137.3	137.1	136.0	136.4
0.75	138.4	137.3	136.8	135.7	135.9
0.8	138.6	137.4	136.5	135.6	135.7
0.85	138.9	137.7	136.9	135.8	136.2
0.9	139.2	138.0	137.6	136.4	136.9
0.95	139.3	138.2	138.0	136.9	137.1
1	139.3	138.3	137.8	136.0	137.1
1.05	139.4	138.3	137.8	136.4	136.9
1.1	139.4	138.2	137.9	136.3	137.0
1.15	139.5	138.3	138.0	136.3	137.0
1.2	139.7	138.5	138.3	136.2	137.2
1.25	140.0	138.8	138.9	137.0	137.9
1.3	140.4	139.3	139.5	137.7	138.5
1.35	140.7	139.6	139.8	138.0	138.9
1.4	140.9	139.8	140.1	138.1	139.6
1.45	140.9	140.1	139.8	137.9	139.3
1.5	140.9	140.0	139.4	137.7	137.7
1.55	140.9	140.0	139.2	137.5	137.8
1.6	140.9	139.9	139.0	137.3	137.7
1.65	140.9	139.8	138.8	137.2	137.5
1.7	140.9	139.7	138.7	137.1	137.4

Yaw Rate (deg/sec)	Delay Time (secs)				
	120	240	360	480	600
1.75	140.9	139.6	138.6	137.1	137.4
1.8	140.9	139.5	138.7	137.1	137.4
1.85	140.9	139.5	138.8	137.2	137.5
1.9	140.9	139.5	138.8	137.3	137.6
1.95	140.9	139.5	138.9	137.3	137.6
2	140.9	139.5	138.9	137.3	137.6

Table B.20 Energy (MWh) estimated by dynamic model for RG1 (5 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)		Yaw Rate (deg/sec)	Delay Time (secs)	
	300	600		300	600
0	59.1	59.3	1.05	87.3	87.5
0.05	82.9	82.8	1.1	88.0	88.0
0.1	83.6	83.6	1.15	88.3	88.4
0.15	83.5	84.7	1.2	88.4	88.5
0.2	83.7	84.9	1.25	88.4	88.5
0.25	83.9	85.1	1.3	88.4	88.5
0.3	84.4	85.3	1.35	88.4	88.5
0.35	84.7	85.3	1.4	88.4	88.5
0.4	85.1	85.5	1.45	88.4	88.5
0.45	85.1	85.6	1.5	88.4	88.5
0.5	85.4	85.8	1.55	88.4	88.5
0.55	85.8	86.1	1.6	88.4	88.5
0.6	85.9	86.8	1.65	88.4	88.5
0.65	85.9	86.7	1.7	88.4	88.5
0.7	85.9	86.6	1.75	88.4	88.5
0.75	86.0	86.6	1.8	88.4	88.5
0.8	86.0	86.7	1.85	88.4	88.5
0.85	86.0	86.7	1.9	88.4	88.5
0.9	86.0	86.7	1.95	88.4	88.5
0.95	86.2	86.8	2	88.4	88.5
1	86.6	87.1			

Table B.21 Energy (MWh) estimated by dynamic model for RG2 (5 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)		Yaw Rate (deg/sec)	Delay Time (secs)	
	300	600		300	600
0	65.1	65.5	1.05	97.1	96.7
0.05	91.1	91.4	1.1	97.8	97.5

Yaw Rate (deg/sec)	Delay Time (secs)		Yaw Rate (deg/sec)	Delay Time (secs)	
	300	600		300	600
0.1	92.3	92.4	1.15	98.2	98.1
0.15	92.4	93.4	1.2	98.3	98.2
0.2	92.8	93.6	1.25	98.3	98.2
0.25	93.1	93.9	1.3	98.3	98.2
0.3	93.6	94.4	1.35	98.3	98.2
0.35	93.9	94.5	1.4	98.3	98.2
0.4	94.2	94.8	1.45	98.3	98.2
0.45	94.2	94.9	1.5	98.3	98.2
0.5	94.6	95.2	1.55	98.3	98.2
0.55	95.3	95.7	1.6	98.3	98.2
0.6	95.6	95.8	1.65	98.3	98.2
0.65	95.6	95.7	1.7	98.3	98.2
0.7	95.6	95.5	1.75	98.3	98.2
0.75	95.6	95.5	1.8	98.3	98.2
0.8	95.7	95.6	1.85	98.3	98.2
0.85	95.7	95.6	1.9	98.3	98.2
0.9	95.7	95.6	1.95	98.3	98.2
0.95	95.8	95.8	2	98.3	98.2
1	96.3	96.1			

Table B.22 Energy (MWh) estimated by dynamic model for RG3 (5 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)		Yaw Rate (deg/sec)	Delay Time (secs)	
	300	600		300	600
0	79.2	79.4	1.05	118.0	117.8
0.05	111.0	112.0	1.1	118.9	118.6
0.1	112.6	113.0	1.15	119.3	119.2
0.15	112.8	113.9	1.2	119.4	119.3
0.2	113.1	114.2	1.25	119.4	119.3
0.25	113.4	114.4	1.3	119.4	119.3
0.3	113.8	115.2	1.35	119.4	119.3
0.35	114.3	115.3	1.4	119.4	119.3
0.4	114.6	115.5	1.45	119.4	119.3
0.45	114.7	115.5	1.5	119.4	119.3
0.5	115.1	115.8	1.55	119.4	119.3
0.55	116.0	116.4	1.6	119.4	119.3
0.6	116.2	116.8	1.65	119.4	119.3
0.65	116.2	116.7	1.7	119.4	119.3
0.7	116.2	116.4	1.75	119.4	119.3

Yaw Rate (deg/sec)	Delay Time (secs)		Yaw Rate (deg/sec)	Delay Time (secs)	
	300	600		300	600
0.75	116.2	116.4	1.8	119.4	119.3
0.8	116.3	116.4	1.85	119.4	119.3
0.85	116.3	116.4	1.9	119.4	119.3
0.9	116.3	116.4	1.95	119.4	119.3
0.95	116.4	116.6	2	119.4	119.3
1	117.0	117.0			

Table B.23 Energy (MWh) estimated by dynamic model for RG4 (5 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)		Yaw Rate (deg/sec)	Delay Time (secs)	
	300	600		300	600
0	88.7	89.0	1.05	134.0	133.5
0.05	126.1	127.1	1.1	135.0	134.5
0.1	126.8	128.2	1.15	135.4	135.1
0.15	127.9	129.6	1.2	135.4	135.2
0.2	128.2	129.6	1.25	135.4	135.2
0.25	128.5	129.8	1.3	135.4	135.2
0.3	128.8	130.1	1.35	135.4	135.2
0.35	129.6	130.3	1.4	135.4	135.2
0.4	130.0	130.7	1.45	135.4	135.2
0.45	130.0	130.7	1.5	135.4	135.2
0.5	130.7	131.1	1.55	135.4	135.2
0.55	131.7	132.0	1.6	135.4	135.2
0.6	131.9	132.4	1.65	135.4	135.2
0.65	131.9	132.1	1.7	135.4	135.2
0.7	131.9	131.8	1.75	135.4	135.2
0.75	131.9	131.8	1.8	135.4	135.2
0.8	131.9	131.8	1.85	135.4	135.2
0.85	131.9	131.8	1.9	135.4	135.2
0.9	131.9	131.8	1.95	135.4	135.2
0.95	132.1	132.0	2	135.4	135.2
1	132.9	132.6			

Table B.24 Energy (MWh) estimated by dynamic model for RG5 (5 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)		Yaw Rate (deg/sec)	Delay Time (secs)	
	300	600		300	600
0	93.4	93.7	1.05	144.6	143.8
0.05	138.7	136.5	1.1	145.4	144.7
0.1	138.5	137.1	1.15	145.7	145.4

Yaw Rate (deg/sec)	Delay Time (secs)		Yaw Rate (deg/sec)	Delay Time (secs)	
	300	600		300	600
0.15	139.1	138.4	1.2	145.8	145.4
0.2	139.0	138.9	1.25	145.8	145.4
0.25	139.2	139.2	1.3	145.8	145.4
0.3	139.6	139.7	1.35	145.8	145.4
0.35	140.3	140.3	1.4	145.8	145.4
0.4	140.6	140.6	1.45	145.8	145.4
0.45	140.7	140.5	1.5	145.8	145.4
0.5	141.2	141.1	1.55	145.8	145.4
0.55	142.0	142.1	1.6	145.8	145.4
0.6	142.1	142.4	1.65	145.8	145.4
0.65	142.1	142.1	1.7	145.8	145.4
0.7	142.1	141.8	1.75	145.8	145.4
0.75	142.1	141.8	1.8	145.8	145.4
0.8	142.2	141.8	1.85	145.8	145.4
0.85	142.2	141.8	1.9	145.8	145.4
0.9	142.2	141.8	1.95	145.8	145.4
0.95	142.5	142.1	2	145.8	145.4
1	143.3	142.8			

Table B.25 Energy (MWh) estimated by dynamic model for RG6 (5 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)		Yaw Rate (deg/sec)	Delay Time (secs)	
	300	600		300	600
0	93.9	94.1	1.05	145.5	144.7
0.05	140.7	139.4	1.1	146.3	145.7
0.1	139.9	138.6	1.15	146.7	146.4
0.15	140.3	139.7	1.2	146.7	146.5
0.2	140.1	139.9	1.25	146.7	146.5
0.25	140.3	140.2	1.3	146.7	146.5
0.3	140.6	140.8	1.35	146.7	146.5
0.35	141.3	141.1	1.4	146.7	146.5
0.4	141.6	141.3	1.45	146.7	146.5
0.45	141.7	141.4	1.5	146.7	146.5
0.5	142.2	142.1	1.55	146.7	146.5
0.55	143.0	143.0	1.6	146.7	146.5
0.6	143.1	143.3	1.65	146.7	146.5
0.65	143.1	143.0	1.7	146.7	146.5
0.7	143.1	142.6	1.75	146.7	146.5
0.75	143.1	142.5	1.8	146.7	146.5
0.8	143.1	142.5	1.85	146.7	146.5
0.85	143.1	142.6	1.9	146.7	146.5
0.9	143.1	142.6	1.95	146.7	146.5
0.95	143.4	142.8	2	146.7	146.5
1	144.2	143.6			

Table B.26 Energy (MWh) estimated by dynamic model for RG1 (10 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)	Yaw Rate (deg/sec)	Delay Time (secs)
	600		600
0	58.4	1.05	88.5
0.05	82.6	1.1	88.5
0.1	83.1	1.15	88.5
0.15	83.9	1.2	88.5
0.2	84.8	1.25	88.5
0.25	85.3	1.3	88.5
0.3	86.3	1.35	88.5
0.35	86.3	1.4	88.5
0.4	86.3	1.45	88.5
0.45	86.3	1.5	88.5
0.5	86.8	1.55	88.5
0.55	88.1	1.6	88.5
0.6	88.5	1.65	88.5
0.65	88.5	1.7	88.5
0.7	88.5	1.75	88.5
0.75	88.5	1.8	88.5
0.8	88.5	1.85	88.5
0.85	88.5	1.9	88.5
0.9	88.5	1.95	88.5
0.95	88.5	2	88.5
1	88.5		

Table B.27 Energy (MWh) estimated by dynamic model for RG2 (10 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)	Yaw Rate (deg/sec)	Delay Time (secs)
	600		600
0	64.2	1.05	98.1
0.05	90.9	1.1	98.1
0.1	91.6	1.15	98.1
0.15	93.2	1.2	98.1
0.2	94.4	1.25	98.1
0.25	94.8	1.3	98.1
0.3	95.8	1.35	98.1
0.35	95.8	1.4	98.1
0.4	95.8	1.45	98.1
0.45	95.9	1.5	98.1
0.5	96.4	1.55	98.1
0.55	97.7	1.6	98.1
0.6	98.1	1.65	98.1
0.65	98.1	1.7	98.1
0.7	98.1	1.75	98.1
0.75	98.1	1.8	98.1

Yaw Rate (deg/sec)	Delay Time (secs)	Yaw Rate (deg/sec)	Delay Time (secs)
	600		600
0.8	98.1	1.85	98.1
0.85	98.1	1.9	98.1
0.9	98.1	1.95	98.1
0.95	98.1	2	98.1
1	98.1		

Table B.28 Energy (MWh) estimated by dynamic model for RG3 (10 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)	Yaw Rate (deg/sec)	Delay Time (secs)
	600		600
0	77.8	1.05	119.6
0.05	110.9	1.1	119.6
0.1	111.8	1.15	119.6
0.15	113.8	1.2	119.6
0.2	114.9	1.25	119.6
0.25	115.5	1.3	119.6
0.3	116.7	1.35	119.6
0.35	116.8	1.4	119.6
0.4	116.8	1.45	119.6
0.45	116.8	1.5	119.6
0.5	117.5	1.55	119.6
0.55	119.2	1.6	119.6
0.6	119.6	1.65	119.6
0.65	119.6	1.7	119.6
0.7	119.6	1.75	119.6
0.75	119.6	1.8	119.6
0.8	119.6	1.85	119.6
0.85	119.6	1.9	119.6
0.9	119.6	1.95	119.6
0.95	119.6	2	119.6
1	119.6		

Table B.29 Energy (MWh) estimated by dynamic model for RG4 (10 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)	Yaw Rate (deg/sec)	Delay Time (secs)
	600		600
0	87.3	1.05	135.9
0.05	127.5	1.1	135.9
0.1	127.6	1.15	135.9
0.15	129.5	1.2	135.9

Yaw Rate (deg/sec)	Delay Time (secs)	Yaw Rate (deg/sec)	Delay Time (secs)
	600		600
0.2	130.7	1.25	135.9
0.25	131.4	1.3	135.9
0.3	132.7	1.35	135.9
0.35	132.7	1.4	135.9
0.4	132.7	1.45	135.9
0.45	132.8	1.5	135.9
0.5	133.7	1.55	135.9
0.55	135.5	1.6	135.9
0.6	135.9	1.65	135.9
0.65	135.9	1.7	135.9
0.7	135.9	1.75	135.9
0.75	135.9	1.8	135.9
0.8	135.9	1.85	135.9
0.85	135.9	1.9	135.9
0.9	135.9	1.95	135.9
0.95	135.9	2	135.9
1	135.9		

Table B.30 Energy (MWh) estimated by dynamic model for RG5 (10 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)	Yaw Rate (deg/sec)	Delay Time (secs)
	600		600
0	92.2	1.05	145.7
0.05	138.6	1.1	145.7
0.1	138.0	1.15	145.7
0.15	139.2	1.2	145.7
0.2	140.2	1.25	145.7
0.25	141.0	1.3	145.7
0.3	142.1	1.35	145.7
0.35	142.1	1.4	145.7
0.4	142.2	1.45	145.7
0.45	142.4	1.5	145.7
0.5	143.4	1.55	145.7
0.55	145.4	1.6	145.7
0.6	145.7	1.65	145.7
0.65	145.7	1.7	145.7
0.7	145.7	1.75	145.7
0.75	145.7	1.8	145.7

Yaw Rate (deg/sec)	Delay Time (secs)	Yaw Rate (deg/sec)	Delay Time (secs)
	600		600
0.8	145.7	1.85	145.7
0.85	145.7	1.9	145.7
0.9	145.7	1.95	145.7
0.95	145.7	2	145.7
1	145.7		

Table B.31 Energy (MWh) estimated by dynamic model for RG6 (10 min averaged data set)

Yaw Rate (deg/sec)	Delay Time (secs)	Yaw Rate (deg/sec)	Delay Time (secs)
	600		600
0	92.8	1.05	146.7
0.05	139.7	1.1	146.7
0.1	139.3	1.15	146.7
0.15	140.5	1.2	146.7
0.2	141.4	1.25	146.7
0.25	142.2	1.3	146.7
0.3	143.3	1.35	146.7
0.35	143.3	1.4	146.7
0.4	143.5	1.45	146.7
0.45	143.6	1.5	146.7
0.5	144.7	1.55	146.7
0.55	146.4	1.6	146.7
0.6	146.7	1.65	146.7
0.65	146.7	1.7	146.7
0.7	146.7	1.75	146.7
0.75	146.7	1.8	146.7
0.8	146.7	1.85	146.7
0.85	146.7	1.9	146.7
0.9	146.7	1.95	146.7
0.95	146.7	2	146.7
1	146.7		

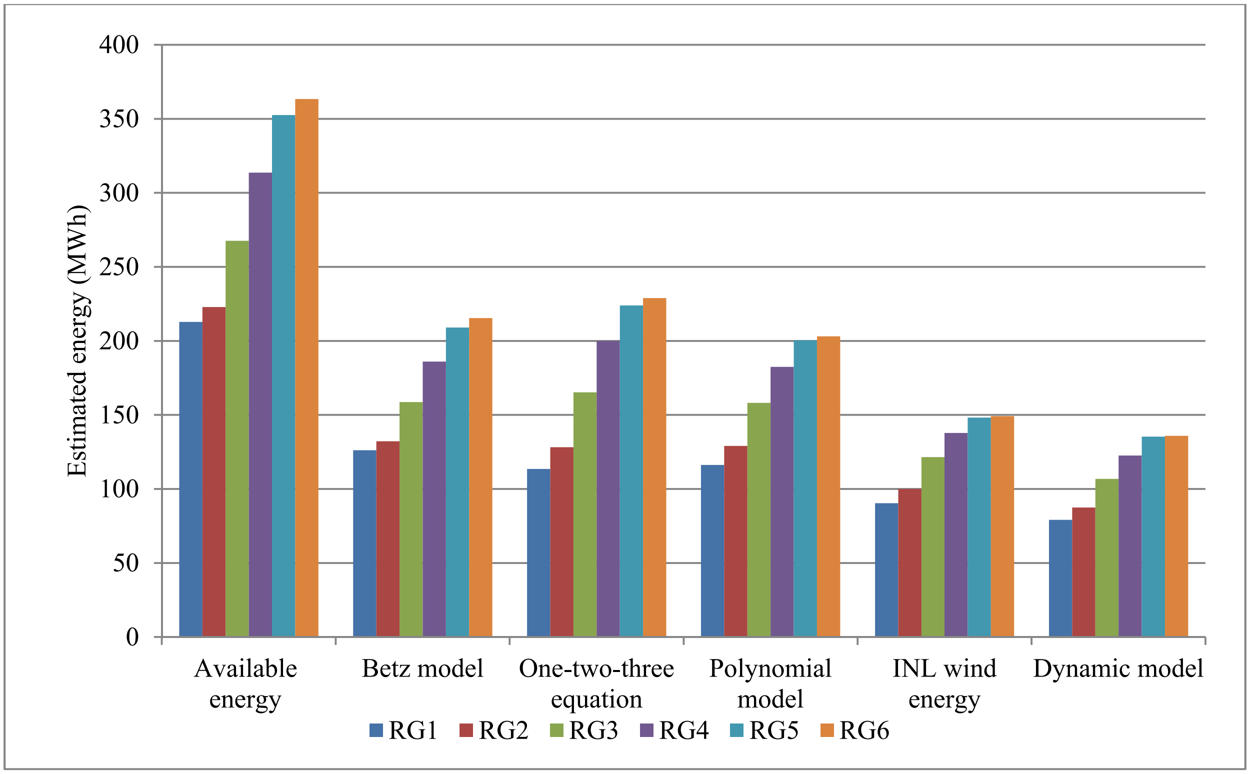

Figure B.1 Comparison of energy estimated by different models (1 min data set)

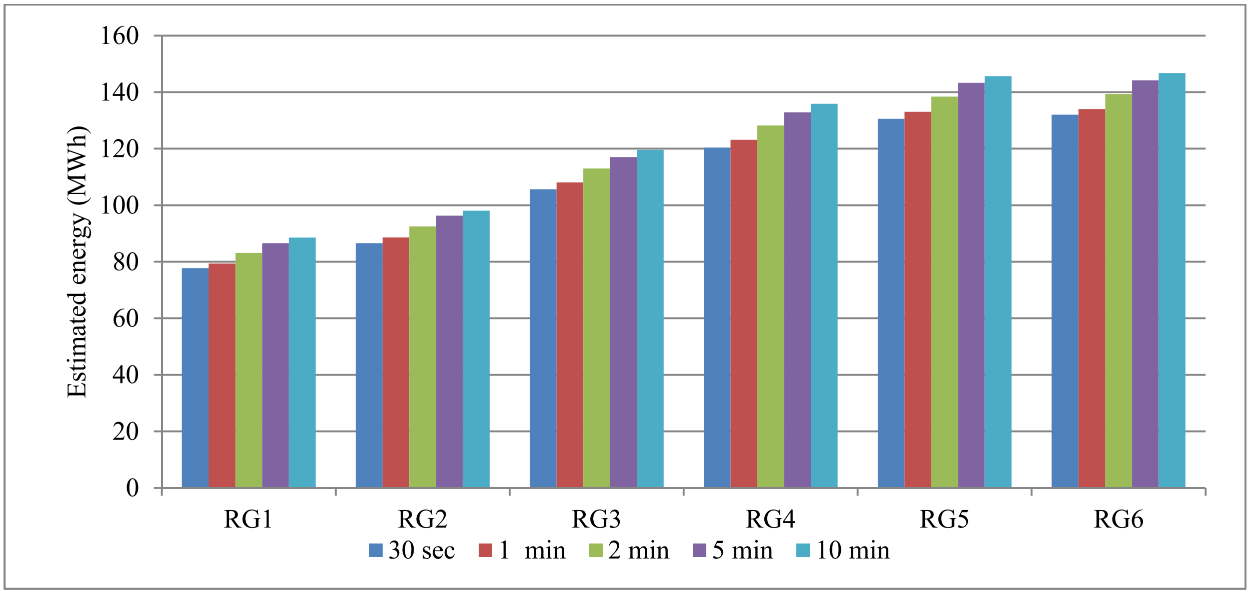

Figure B.2 Comparison of energy estimated by different frequency data sets (yaw rate 1 deg/sec)

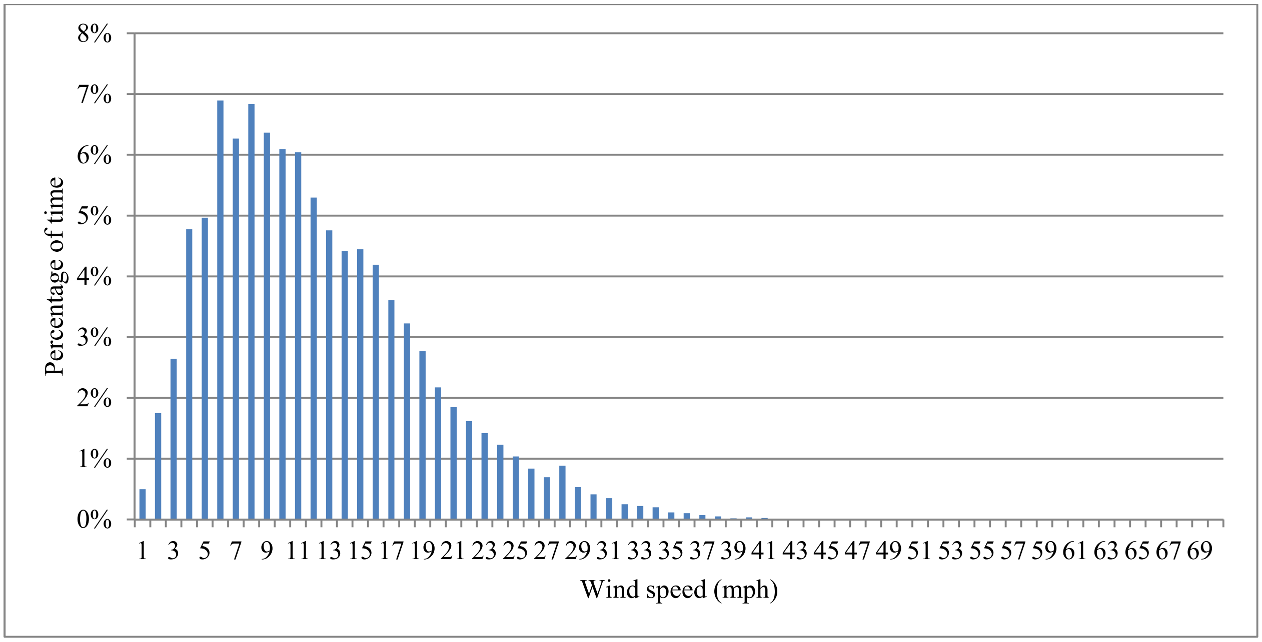

Figure B.3 Frequency distribution at RG1

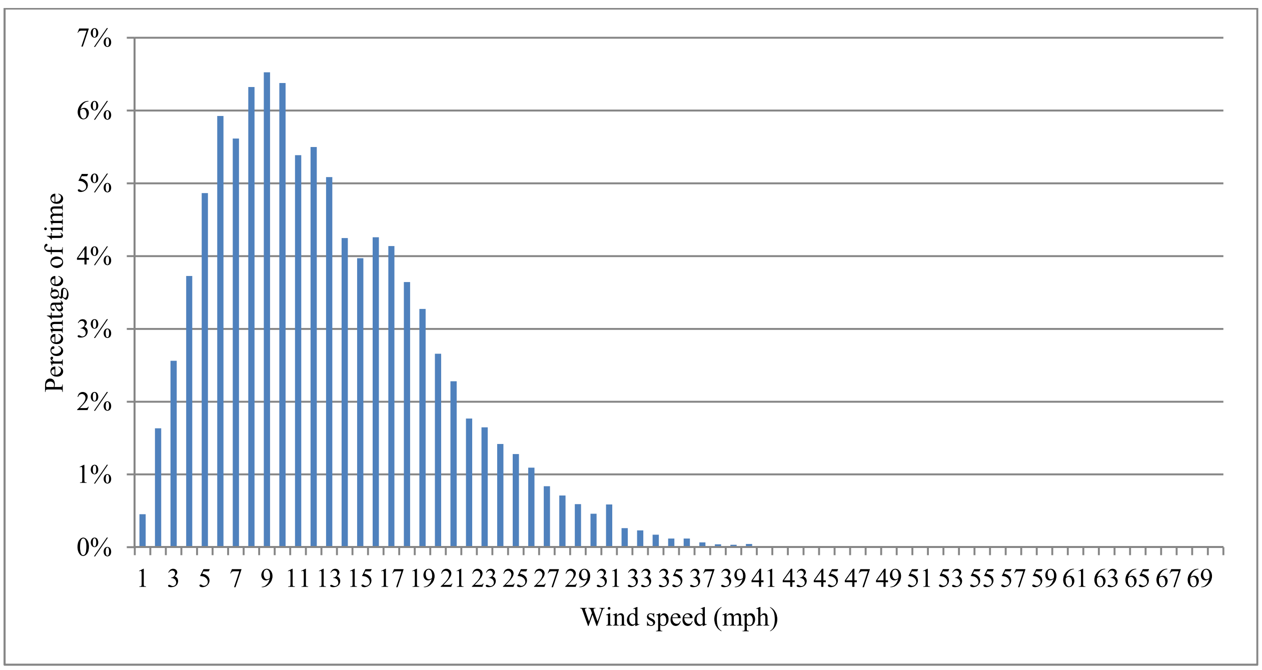

Figure B.4 Frequency distribution at RG2

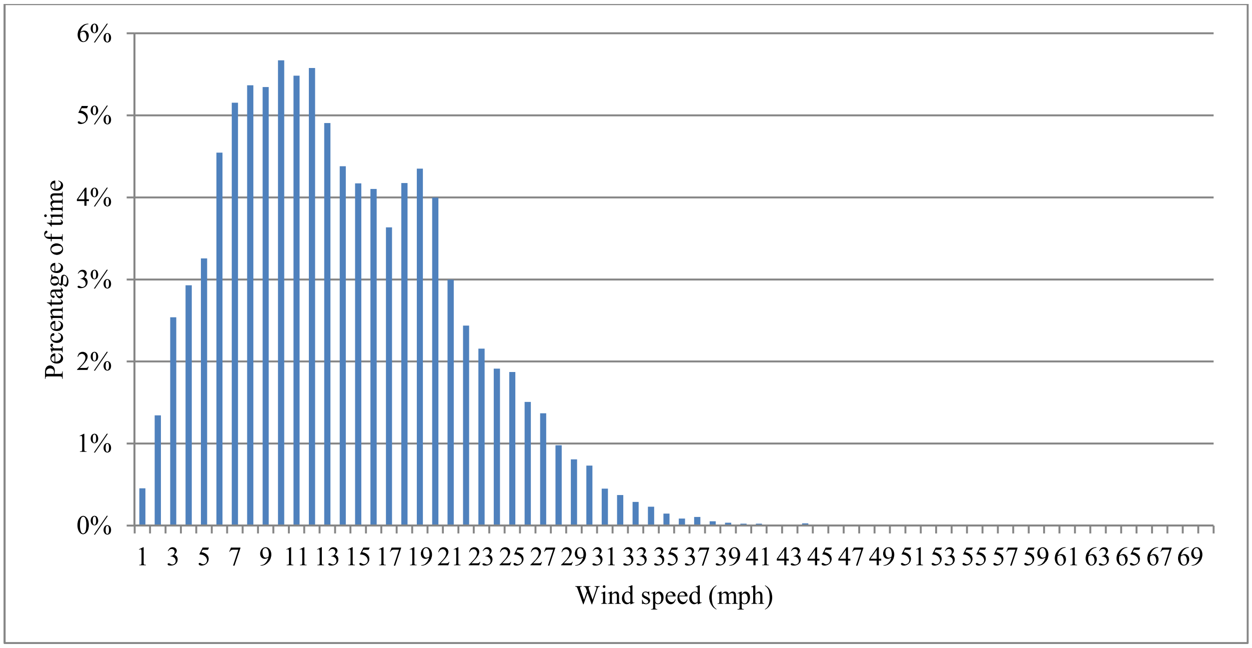

Figure B.5 Frequency distribution at RG3

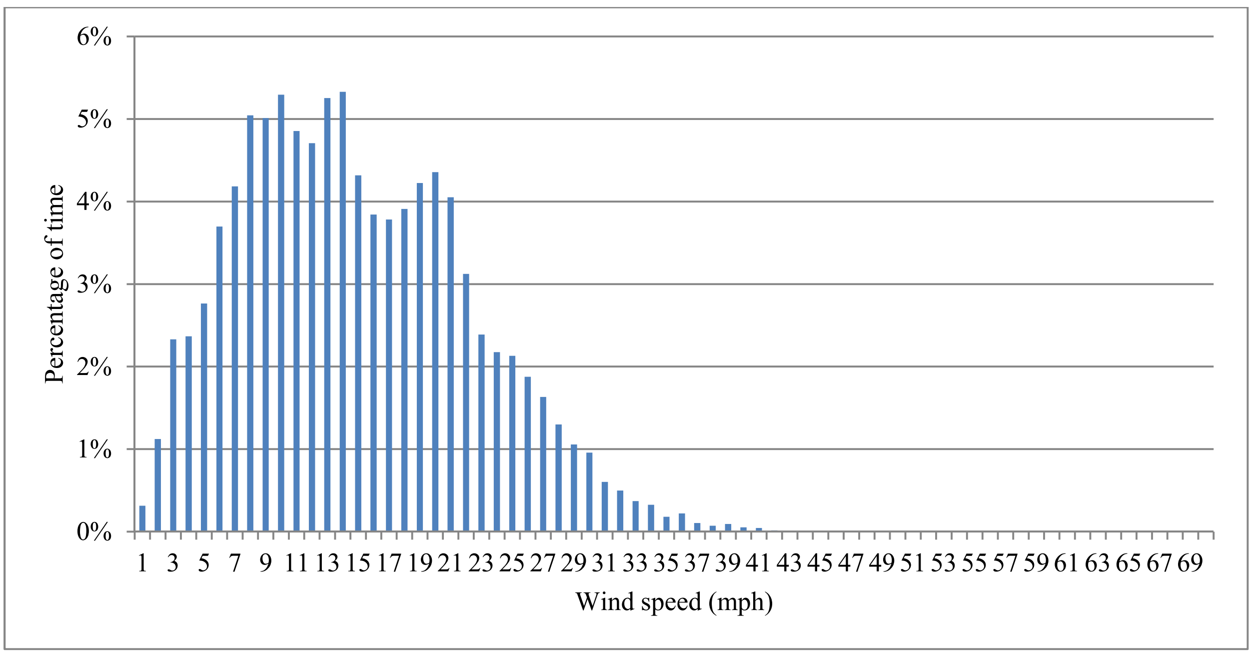

Figure B.6 Frequency distribution at RG4

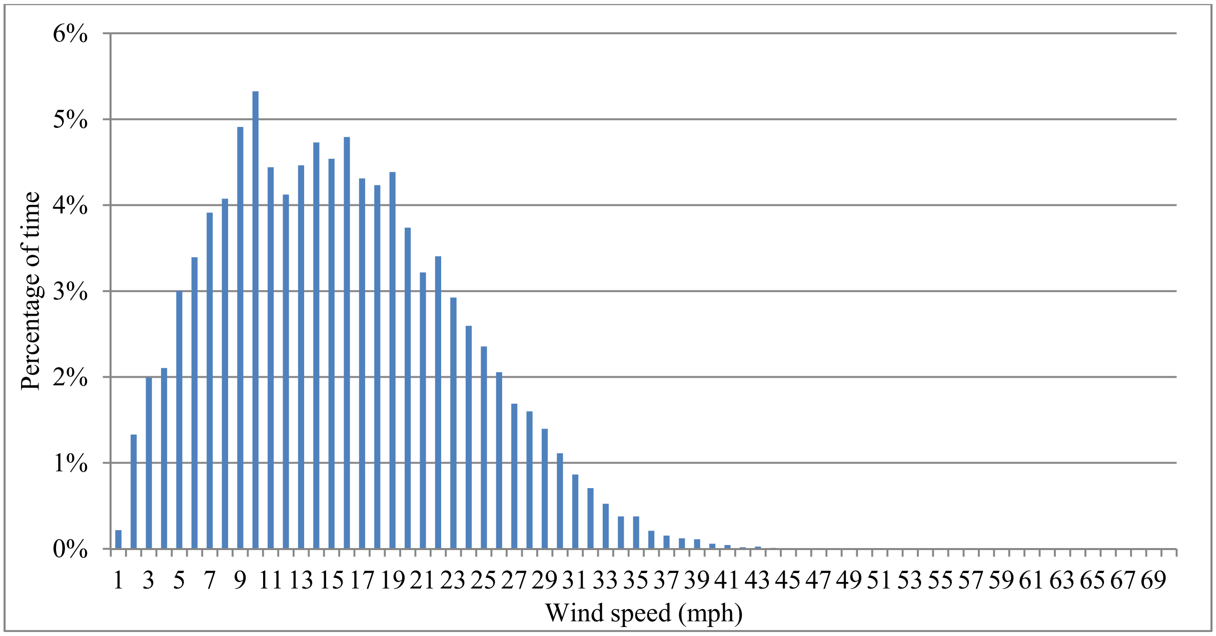

Figure B.7 Frequency distribution at RG5

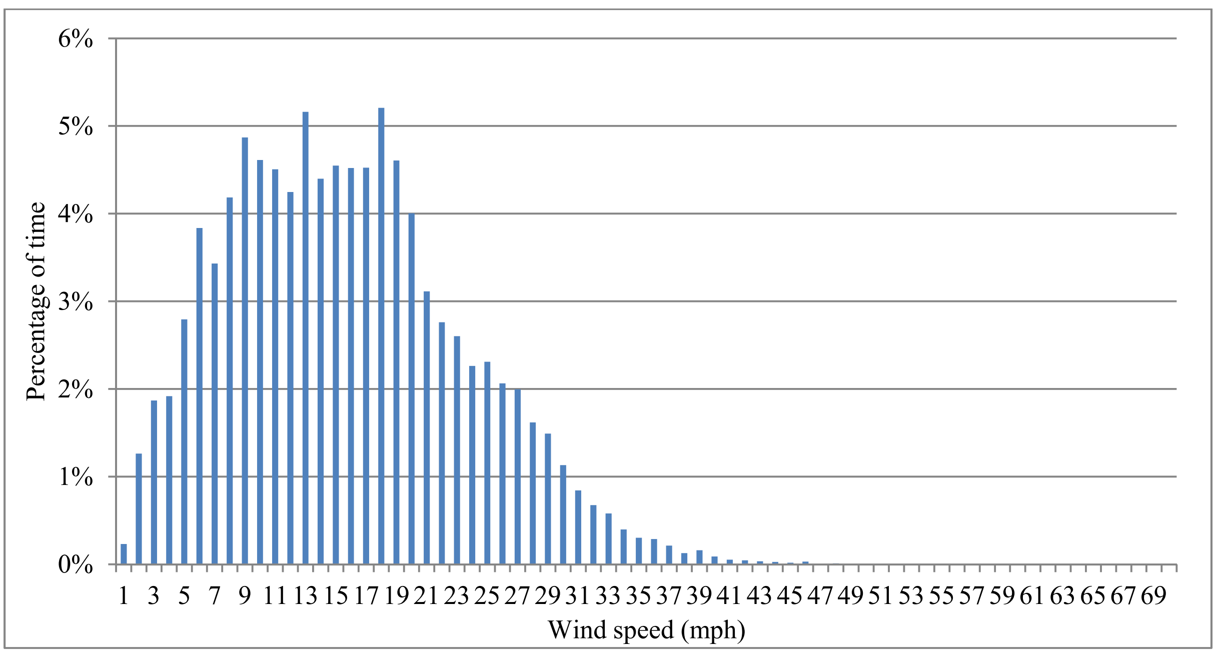

Figure B.8 Frequency distribution at RG6

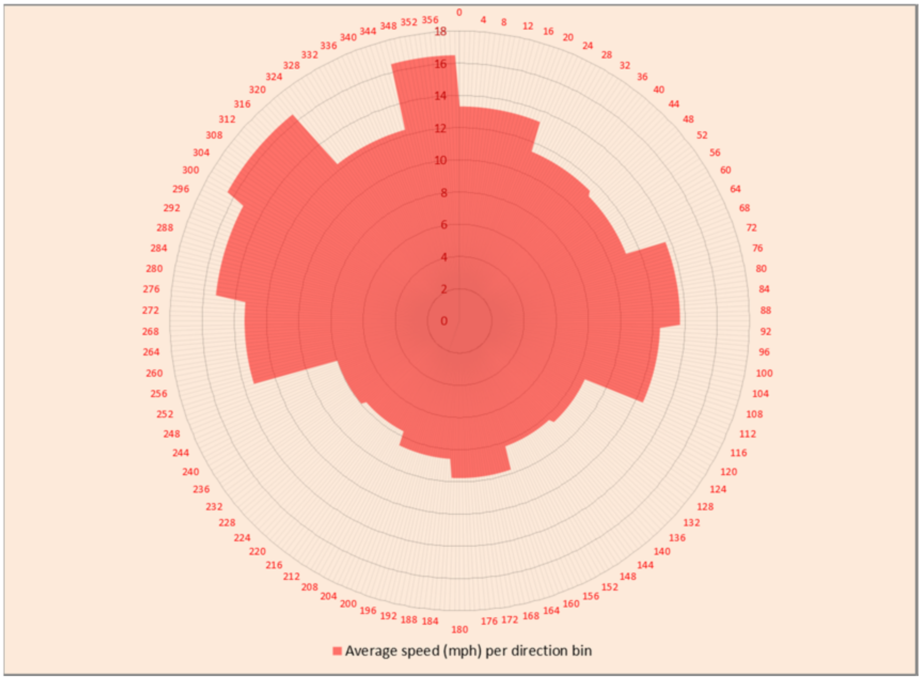

Figure B.9 Wind rose for average speed of RG1

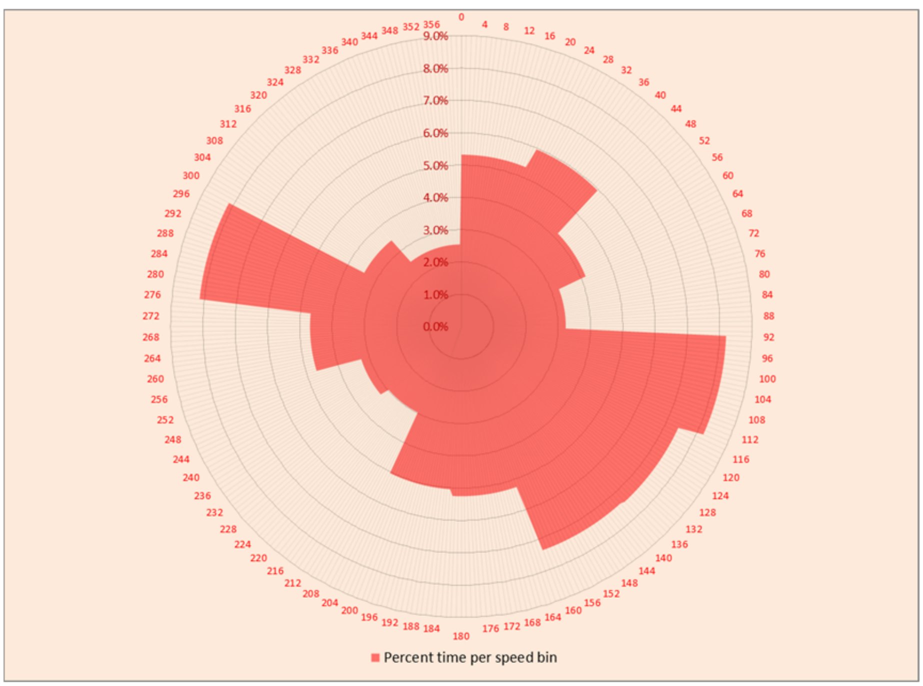

Figure B.10 Wind rose for percentage of time RG1

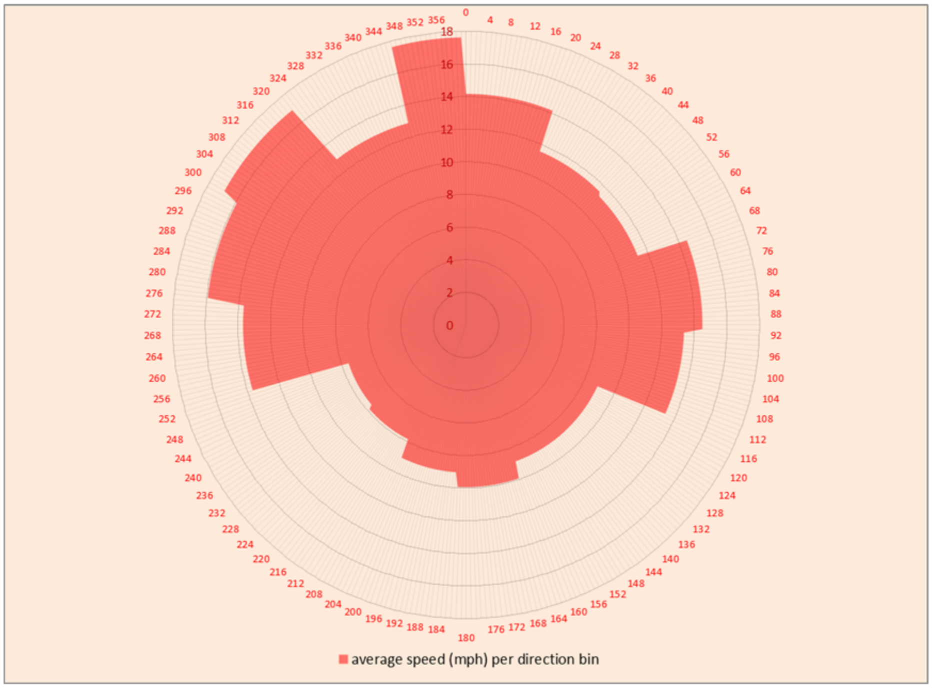

Figure B.11 Wind rose for average speed of RG2

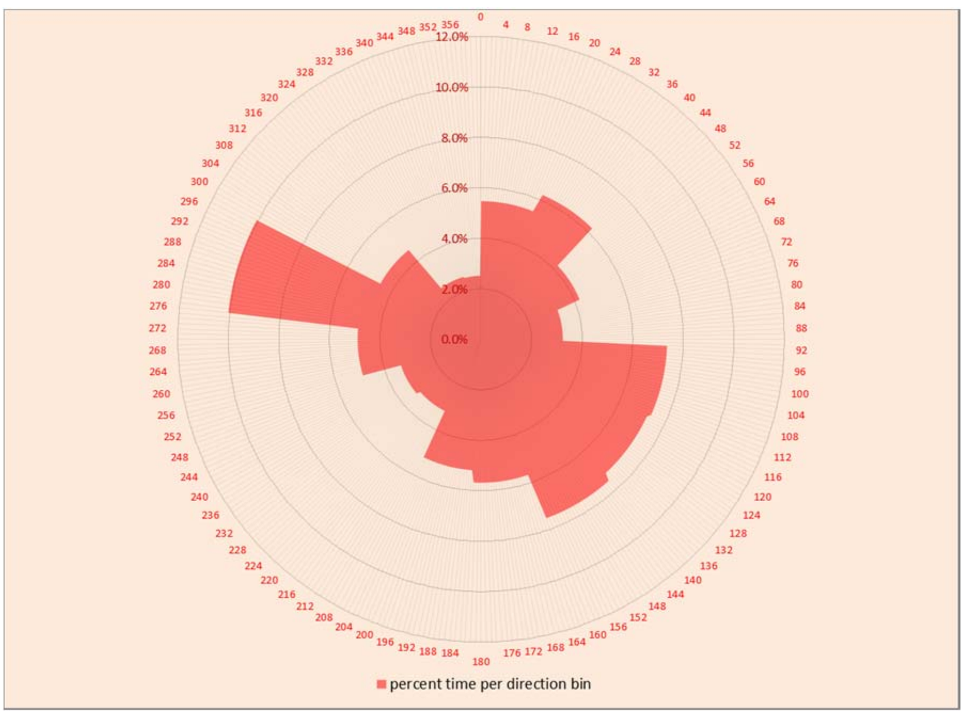

Figure B.12 Wind rose for percentage of time RG2

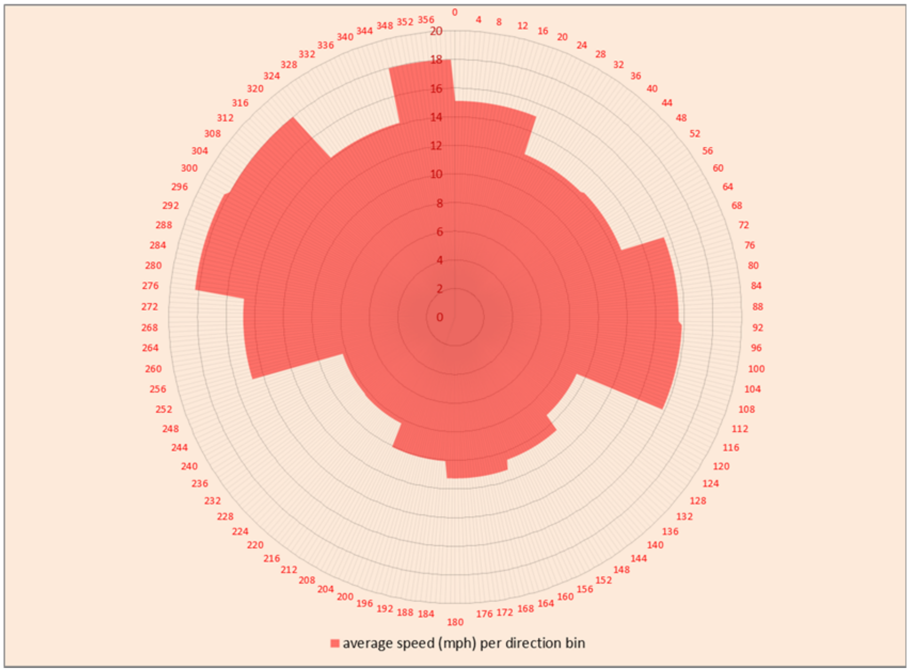

Figure B.13 Wind rose for average speed of RG3

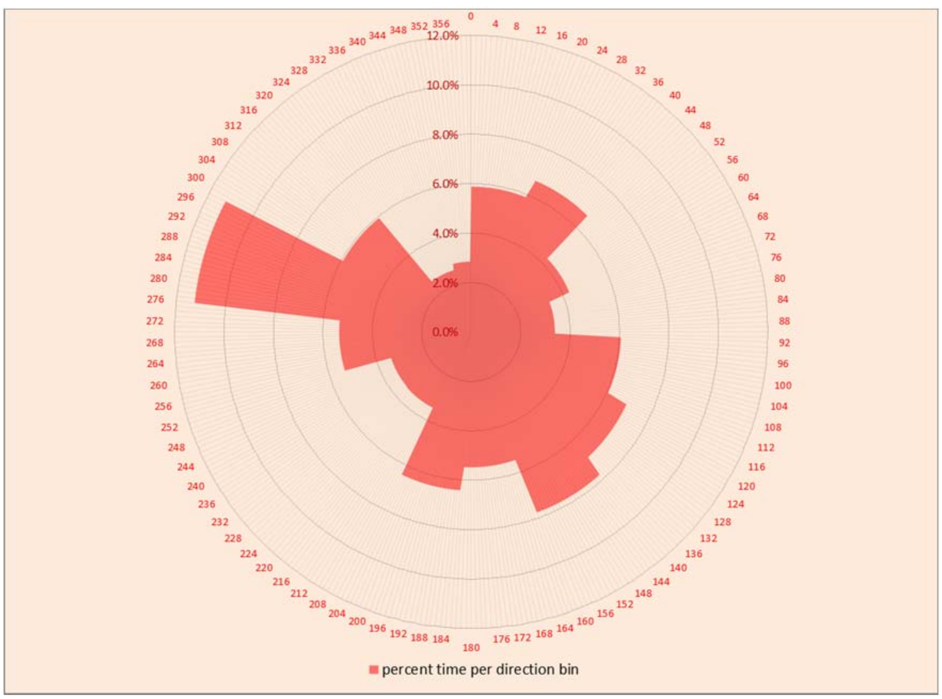

Figure B.14 Wind rose for percentage of time RG3

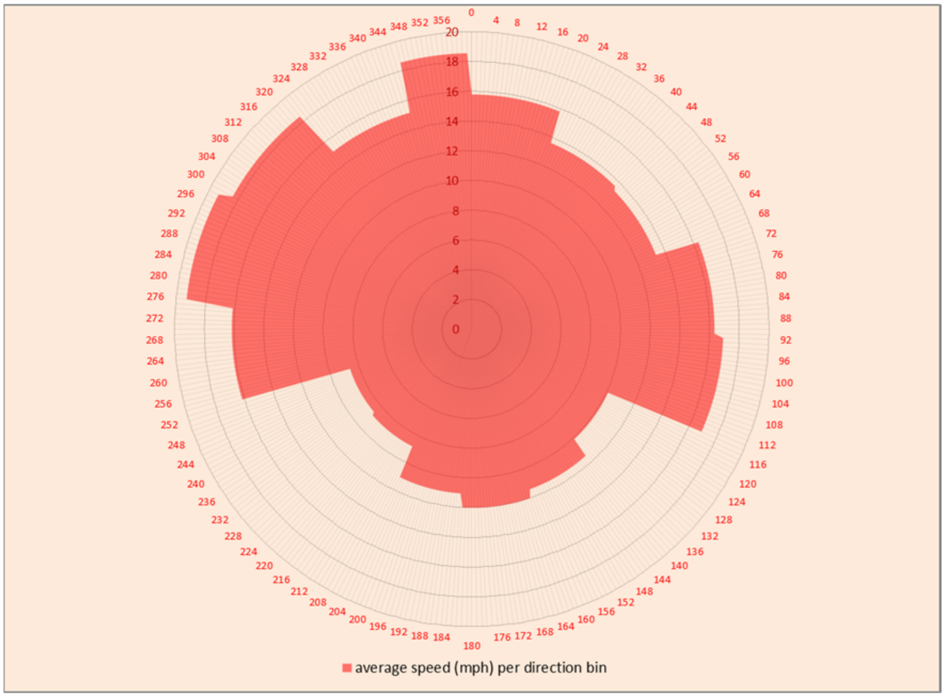

Figure B.15 Wind rose for average speed of RG4

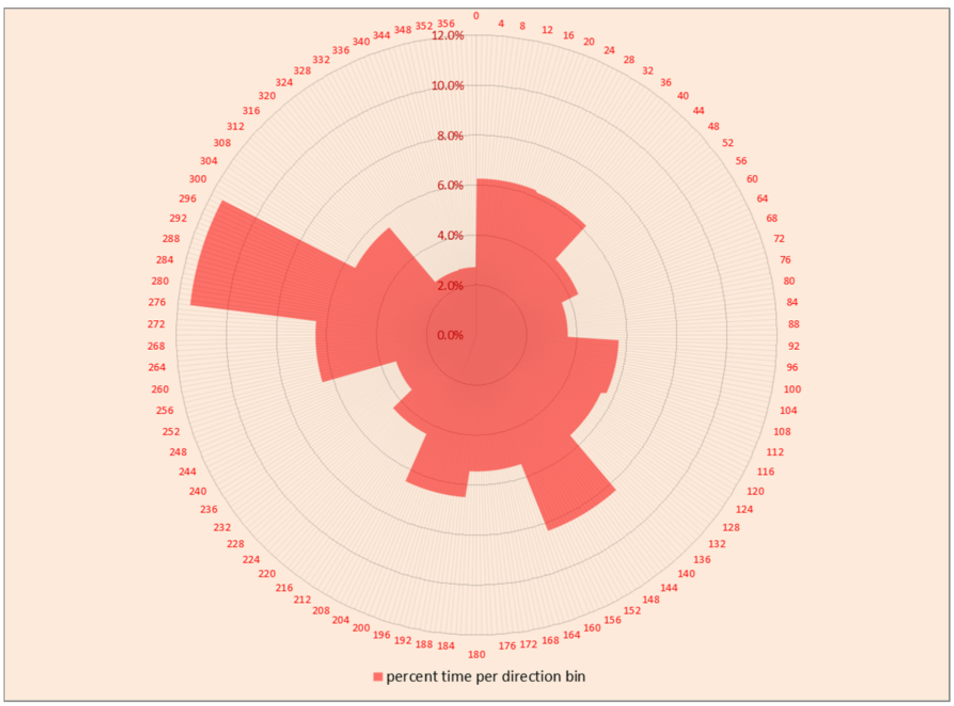

Figure B.16 Wind rose for percentage of time RG4

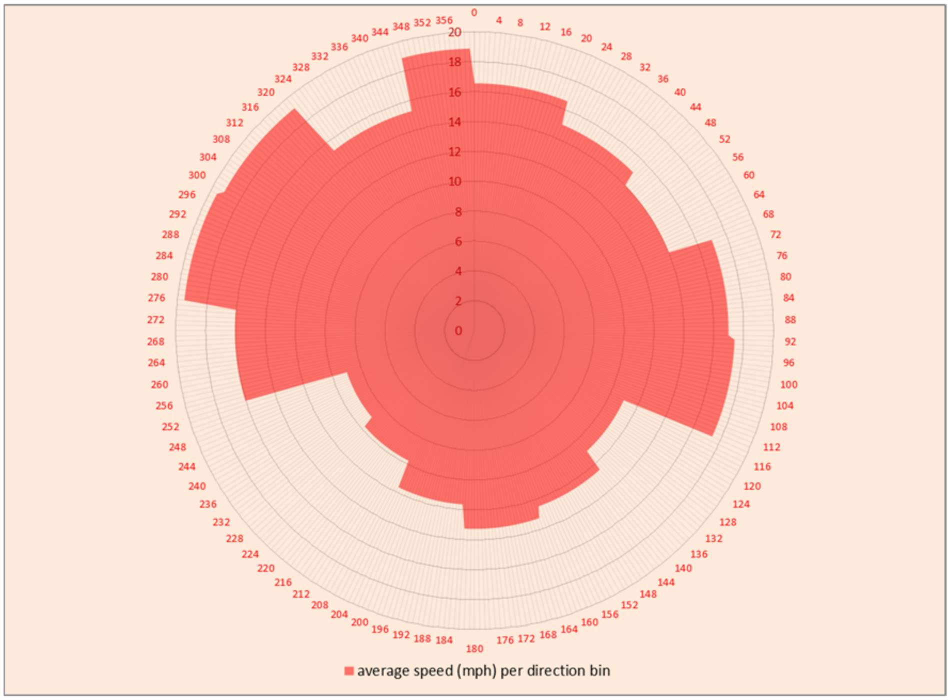

Figure B.17 Wind rose for average speed of RG5

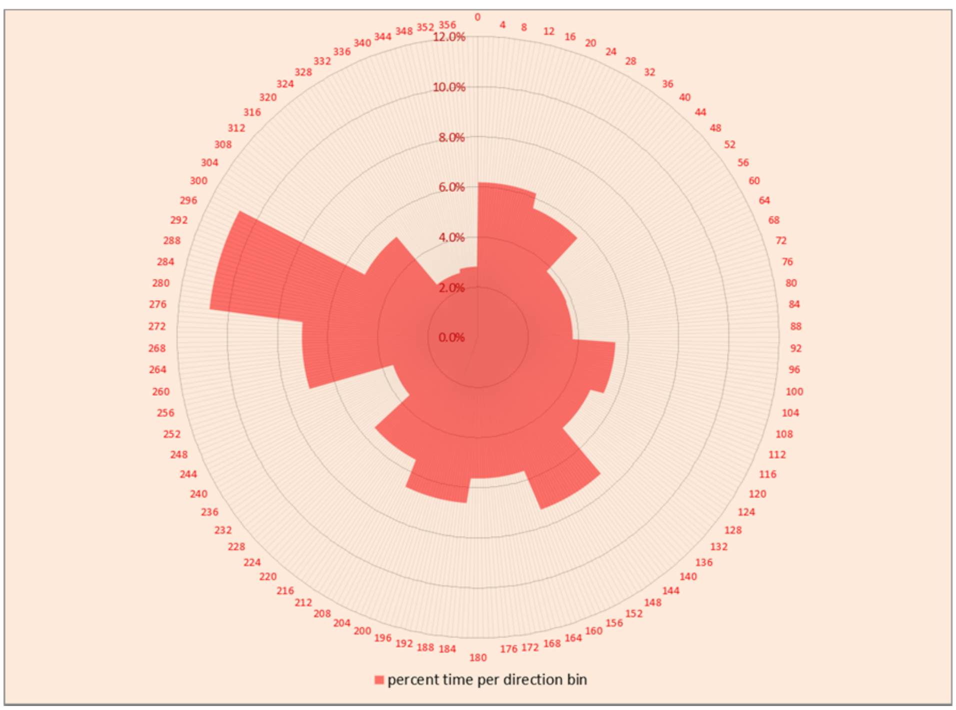

Figure B.18 Wind rose for percentage of time RG5

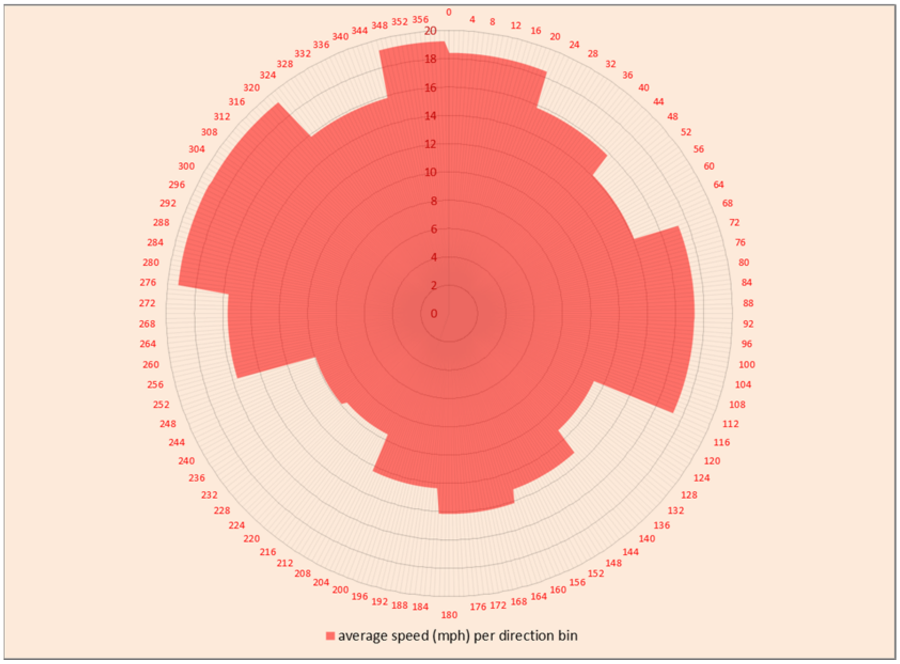

Figure B.19 Wind rose for average speed of RG6

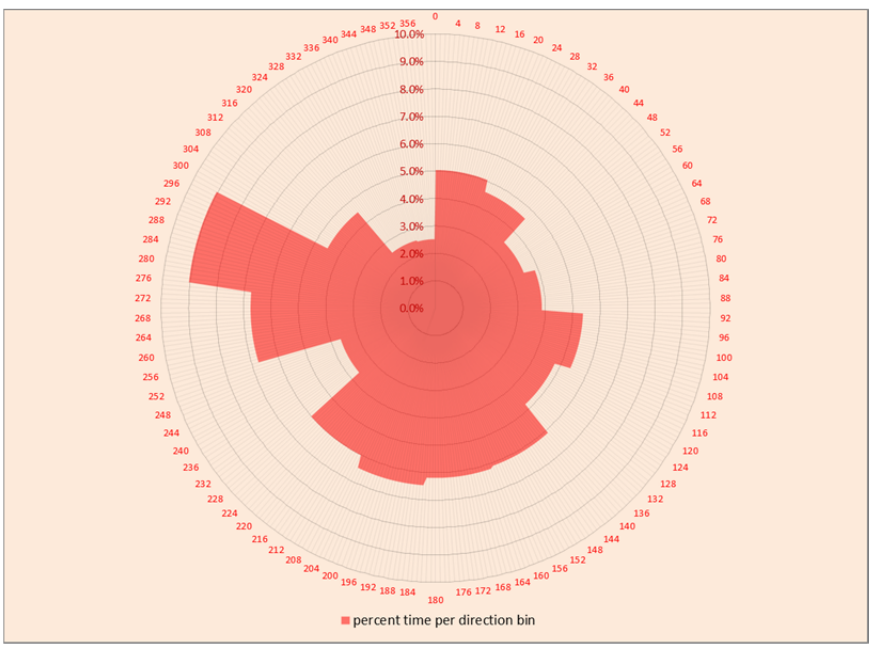

Figure B.20 Wind rose for percentage of time RG6

B.2 Lake Michigan (near shore) results

Table B.32 Summary of results of different range gates

Range Gate	Altitude (m)	Average wind speed (mph)	Energy output (MWh)	Capacity factor
RG1	55	18.42	496.257983	45.90%
RG2	60	18.41	570.131649	52.73%
RG3	75	19.00	636.239385	58.85%
RG4	90	19.45	673.605597	62.30%
RG5	110	19.49	680.455134	62.94%
RG6	120	19.68	662.845907	61.31%

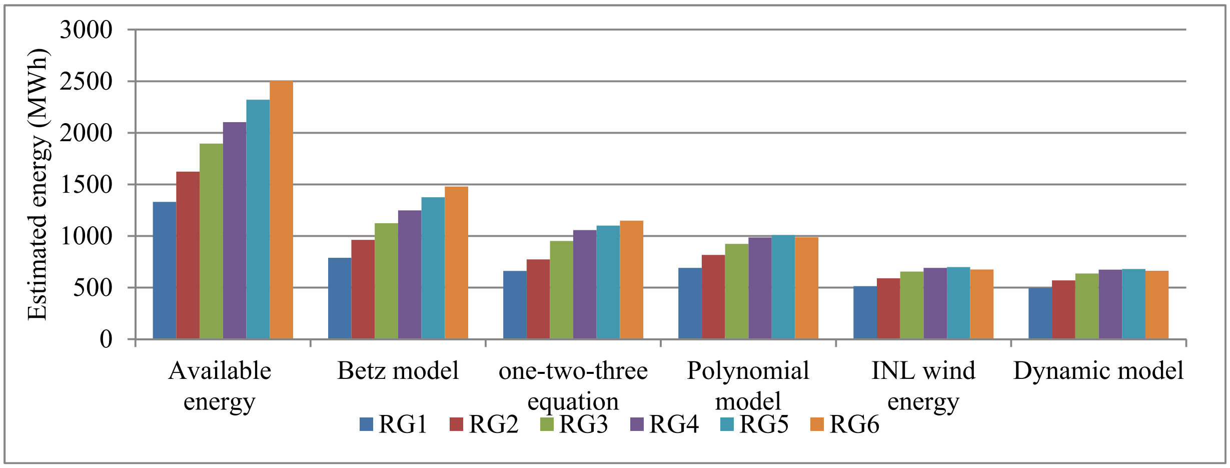

Figure B.21 Comparison of energy estimated by different models (1 min data set)

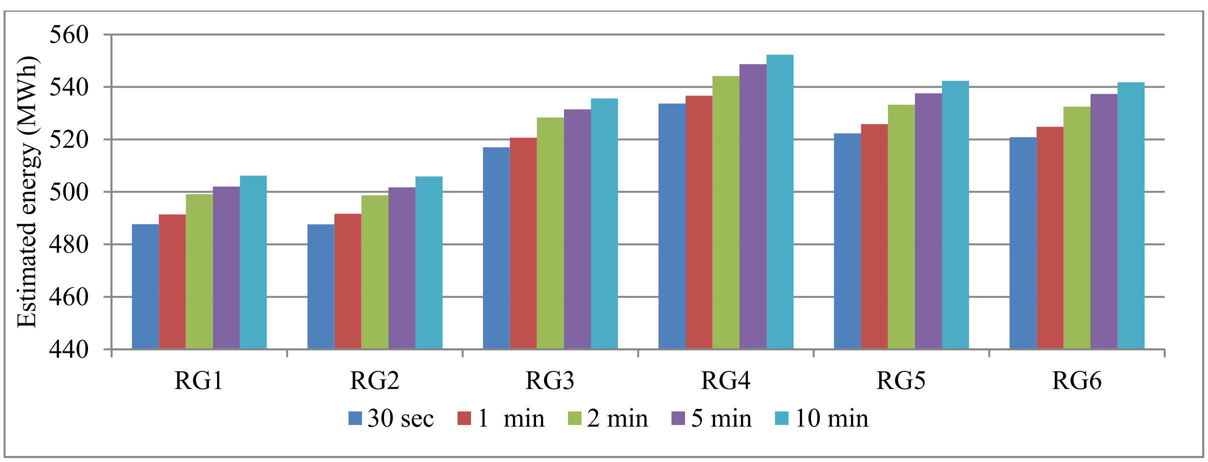

Figure B.22 Comparison of energy estimated by different frequency data sets (yaw rate 1 deg/sec)

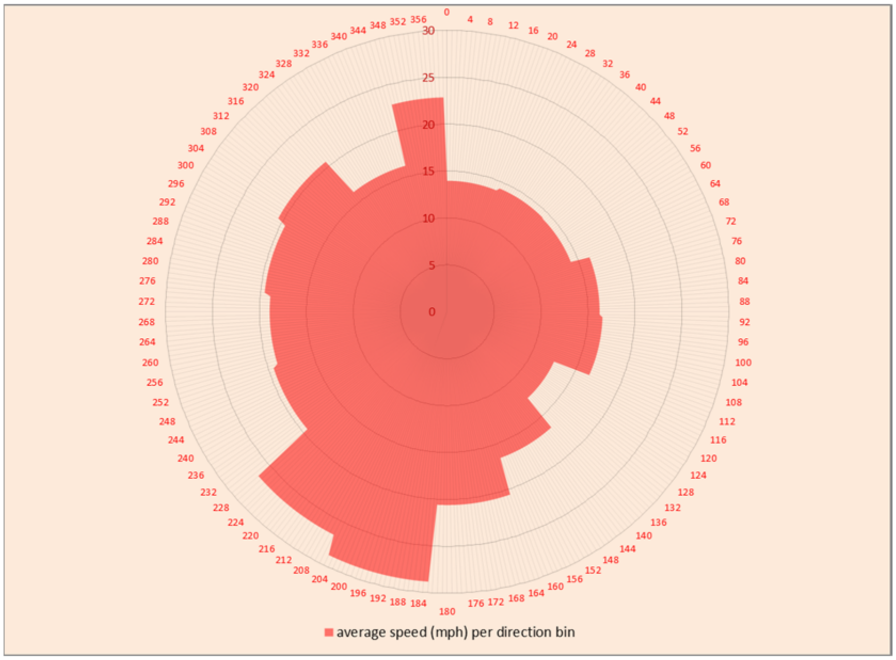

Figure B.23 Wind rose for average speed of RG4 (90 m)

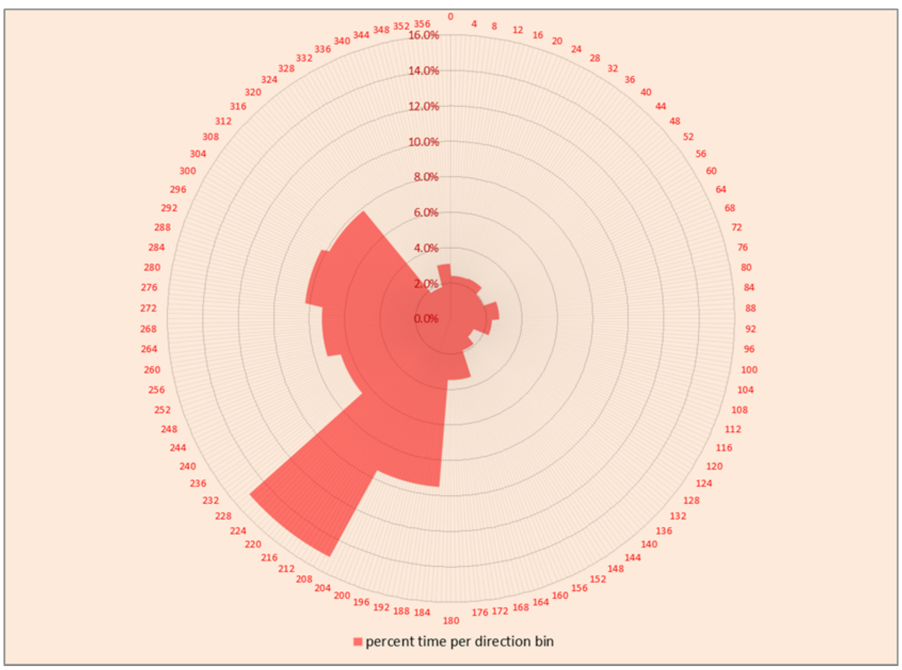

Figure B.24 Wind rose for percentage of time RG4 (90 m)

B.3 NOAA field station deployment results

Table B.33 Summary of results of different range gates

Range Gate	Altitude (m)	Average wind speed (mph)	Energy output (MWh)	Capacity factor
RG1	55	14.02	496.257983	19.62%
RG2	60	14.77	570.131649	22.54%
RG3	75	15.83	636.239385	25.15%
RG4	90	16.40	673.605597	26.63%
RG5	110	16.61	680.455134	26.90%
RG6	120	16.85	662.845907	26.20%

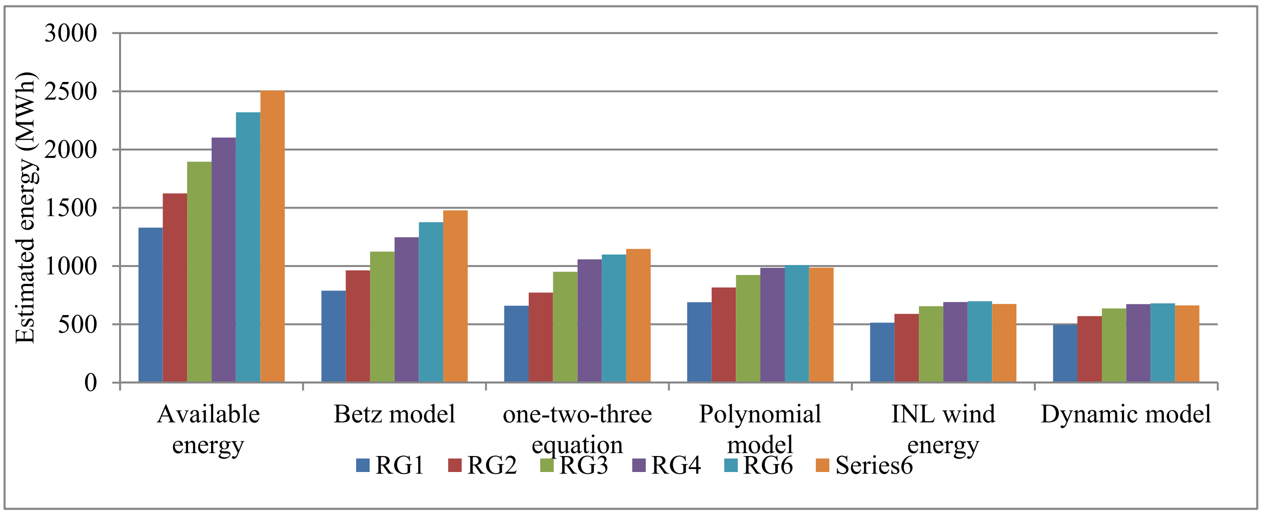

Figure B.25 Comparison of energy estimated by different models (1 min data set)

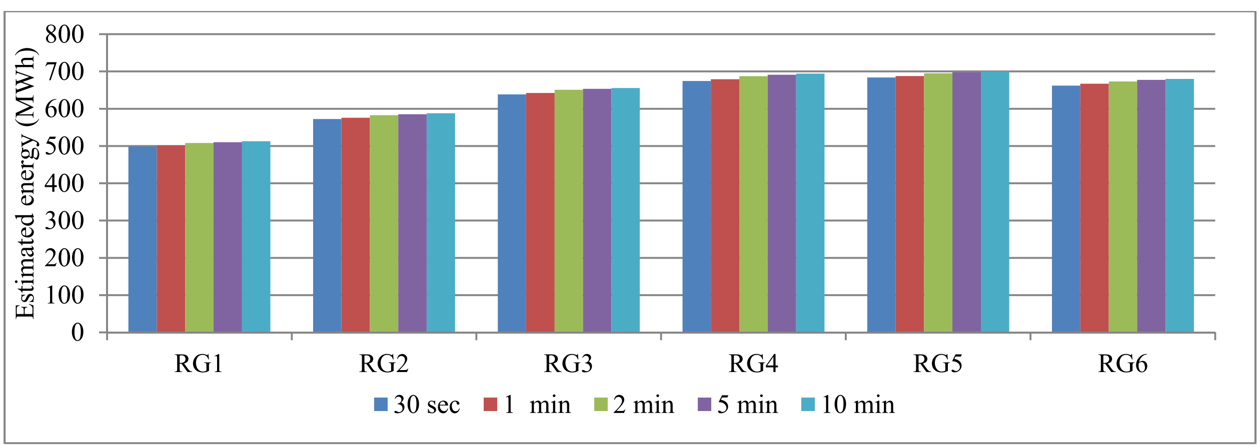

Figure B.26 Comparison of energy estimated by different frequency data sets (yaw rate 1 deg/sec)

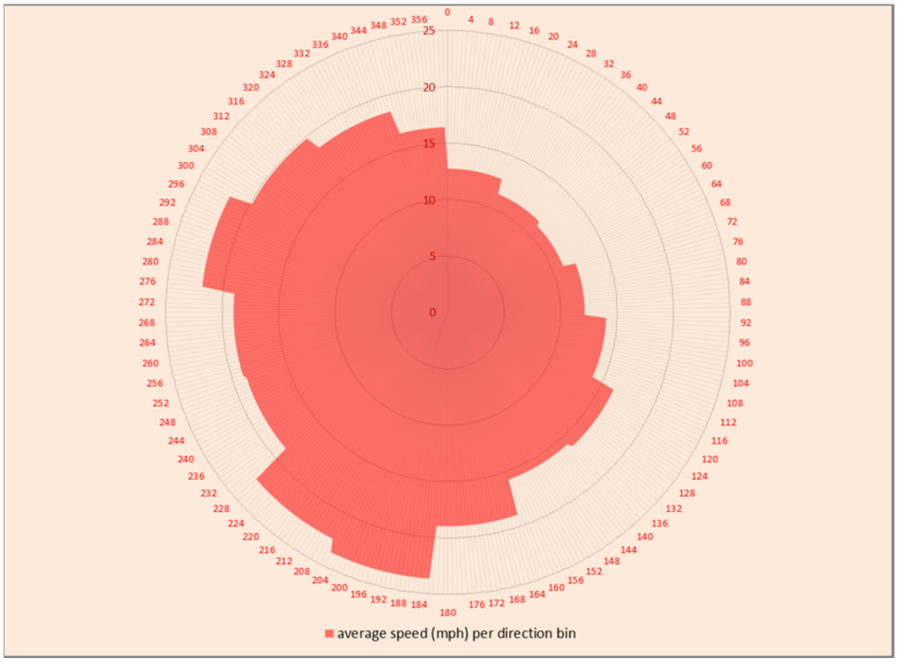

Figure B.27 Wind rose for average speed of RG4 (90 m)

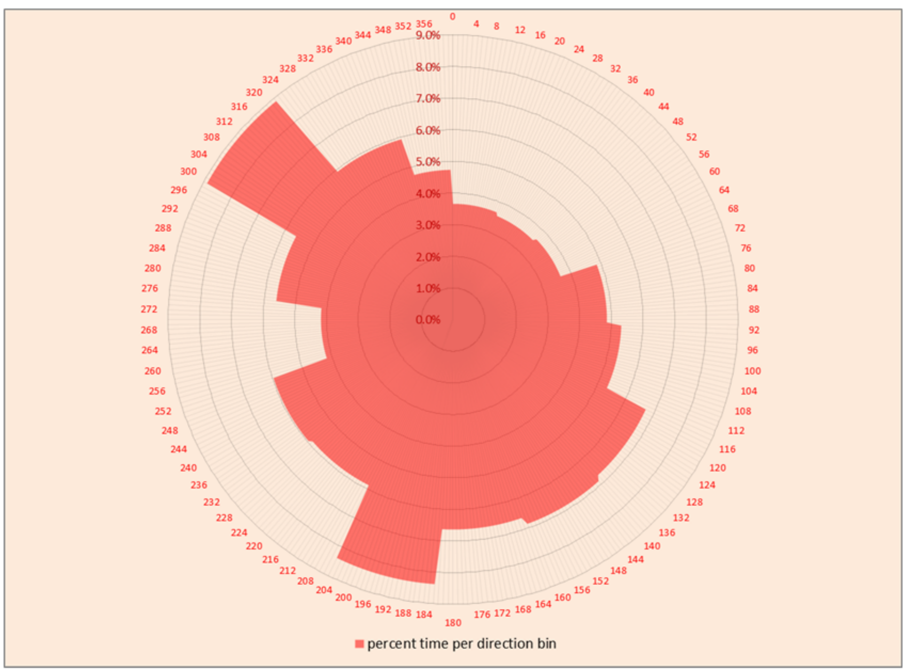

Figure B.28 Wind rose for percentage of time RG4 (90 m)

B.4 Mid-lake Plateau deployment results

Table B.34 Summary of results of different range gates

Range Gate	Altitude (m)	Average wind speed (mph)	Energy output (MWh)	Capacity factor
RG1	75	19.07	1707.732224	37.9%
RG2	90	19.64	1786.540252	39.3%
RG3	105	19.83	1805.26632	39.7%
RG4	125	19.55	1754.083151	38.5%

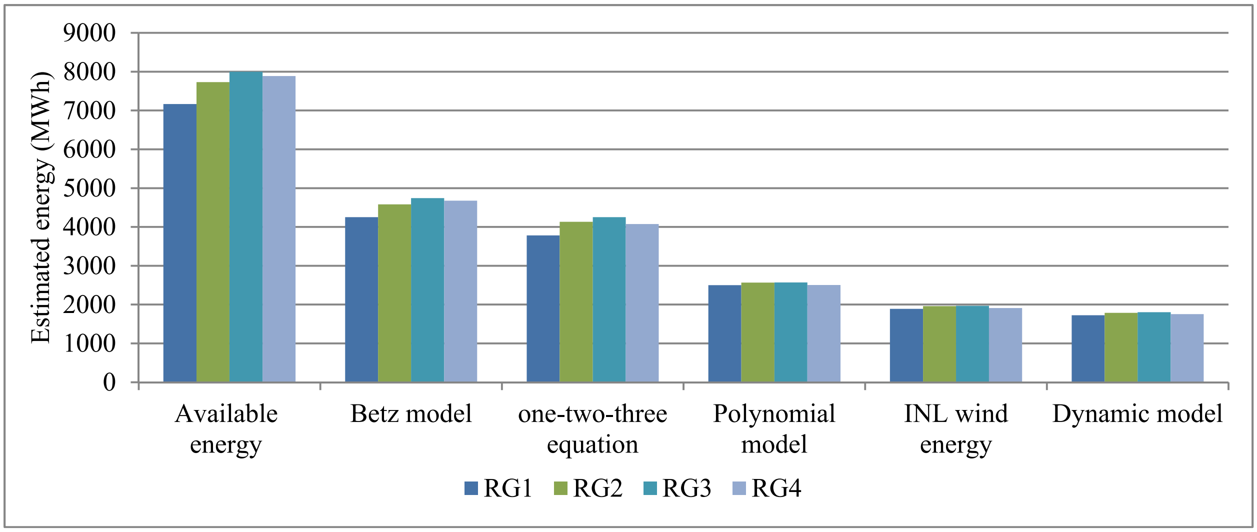

Figure B.29 Comparison of energy estimated by different models at mid-lake deployment (1 min data set)

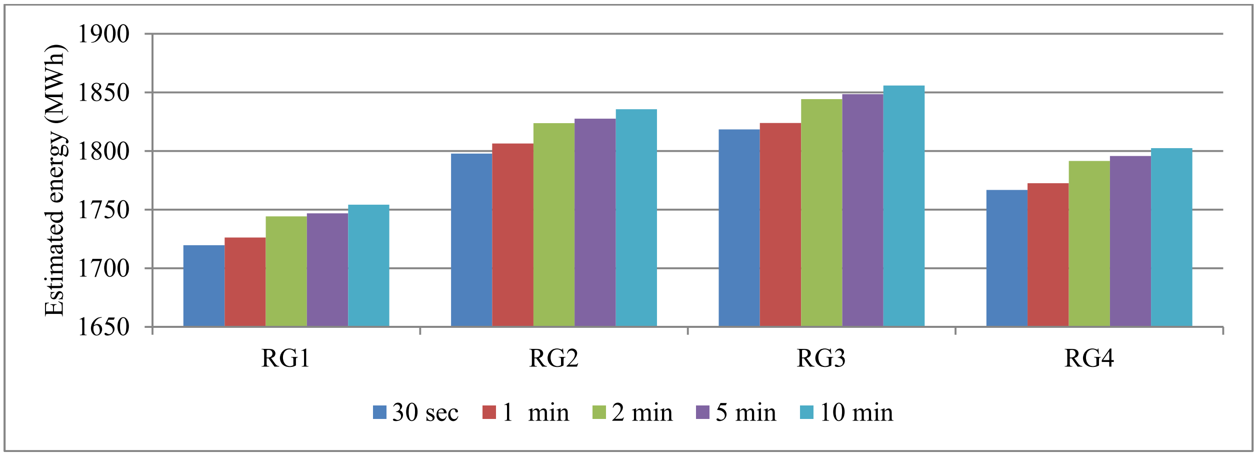

Figure B.30 Comparison of energy estimated by different frequency data sets (yaw rate 1 deg/sec)

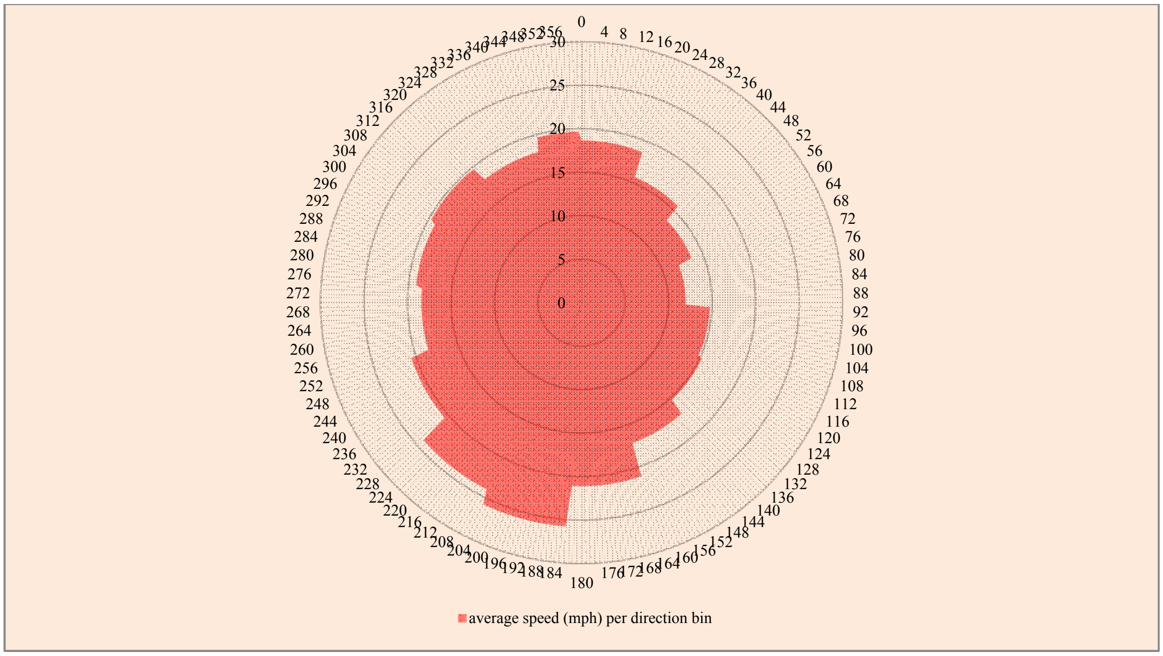

Figure B.31 Wind rose for average speed of RG2 (90 m)

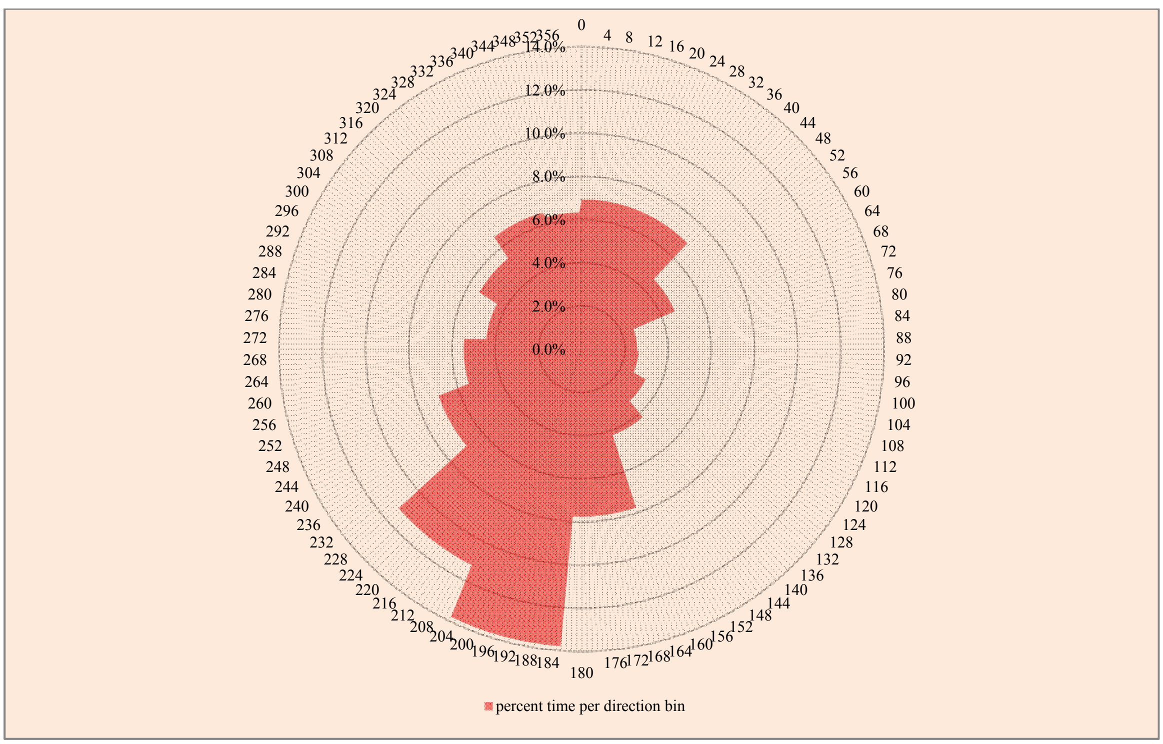

Figure B.32 Wind rose for percentage of time RG2 (90 m)