NAWEA
NORTH AMERICAN WIND ENERGY ACADEMY

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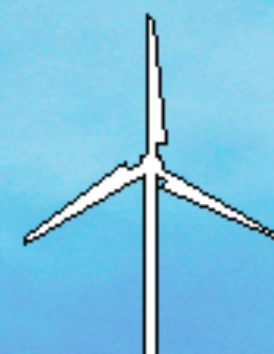
Model and Procedures for Reliable Near Term Wind Energy Production Forecast



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Outline

Research Motivation

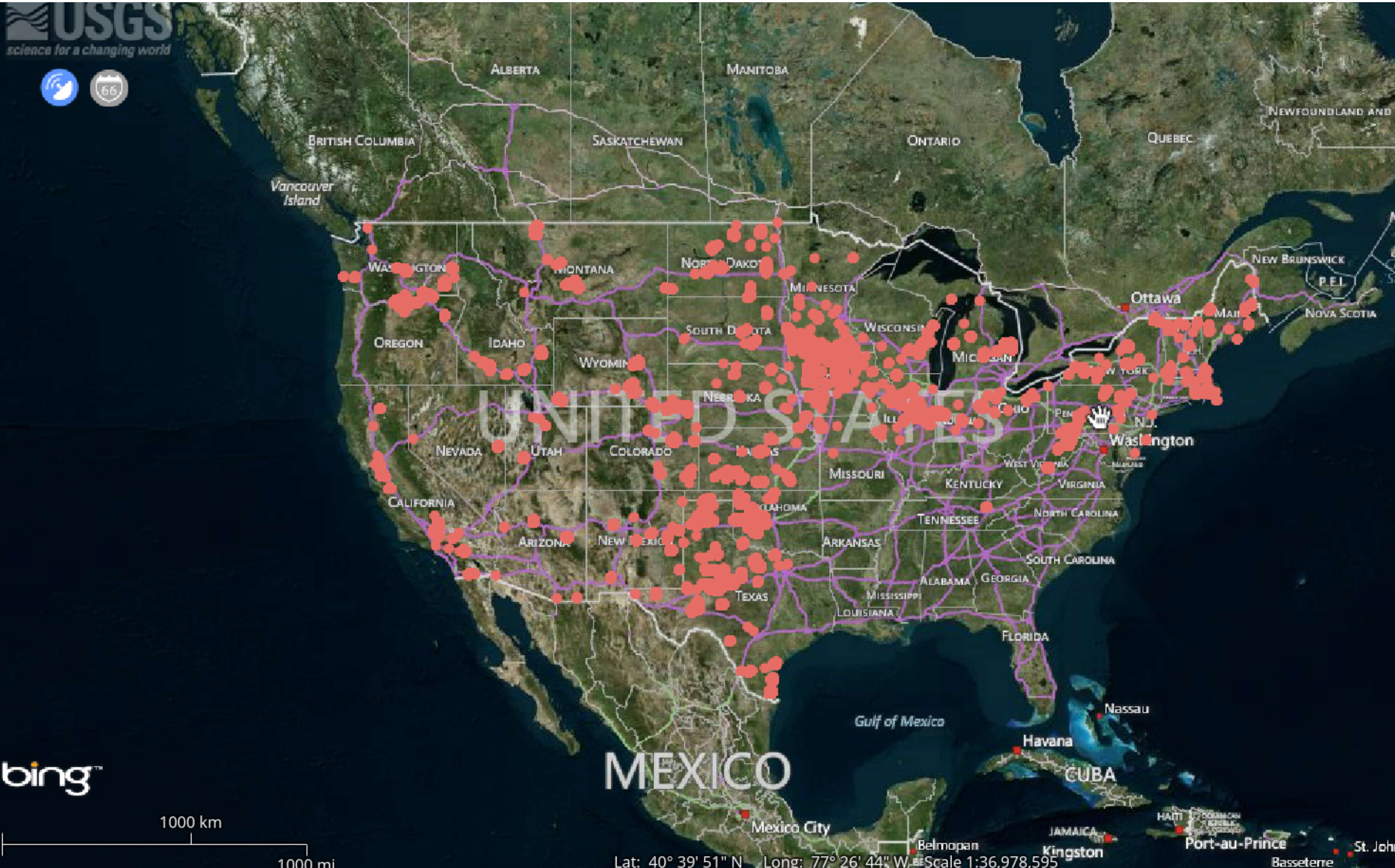
- **What is Distributed generation (DG)?**

Distributed generation (DG), also known as on-site generation, distributed resources (DR), distributed energy resources (DER) or dispersed power (DP) is the use of small-scale power generation technologies located close to the load being served.

- **What is advantages of Distributed generation (DG)?**

For some facilities, DG can lower costs, improve reliability and reduce emissions. DG may also add redundancy that increases grid security.

Research Motivation



Research Motivation

- **What is current situation of Distributed wind turbines?**

In 2013, 30.4 megawatts (MW) of new distributed wind capacity was added, representing nearly 2,700 units across 36 states, Puerto Rico, and the U.S. Virgin Islands (USVI).---*2013 Distributed Wind Market Report by DOE*

U.S. Distributed Wind Market Highlights

2013 distributed wind: **30.4 MW, 2,700 units, $90 million value**

2013 turbines greater than 100 kW: **24.8 MW, 18 units, $54 million value**

2013 small wind: **5.6 MW, 2,700 units, $36 million value**

2013 top states for distributed wind: **CO, KS, OH, MA, AK, IN, ND**

2013 top states for small wind: **NV, IA, MN, OK, NY, TX, HI**

2013 small wind turbine exports: **13.6 MW, 2,900 units, $103 million**

2003-2013 cumulative distributed wind: **842 MW**

2003-2013 cumulative small wind domestic sales: **137 MW**

2003-2013 cumulative small wind exports: **73 MW**

Research Motivation

- **Why is it important to predict wind power output?**

In the electricity grid at any moment balance must be maintained between electricity consumption and generation - otherwise disturbances in power quality or supply may occur.

- Unexpected wind fluctuations increase requirements for spinning reserves and raise electricity system production costs
- Unexpected large ramp events can affect electricity system reliability and may cause safety issue
- It is required by next generation electric grid or smart grid---stability and security

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Research Motivation

- **Wind energy prediction current situation**

Large wind farms: Have observation stations and commercial prediction systems which is quite accurate
Distributed wind turbine : Use directly by the commercial or industrial

- **Research Goal**

Provide more reliable and accurate prediction of distributed wind generation directly using weather forecast.

Research Motivation

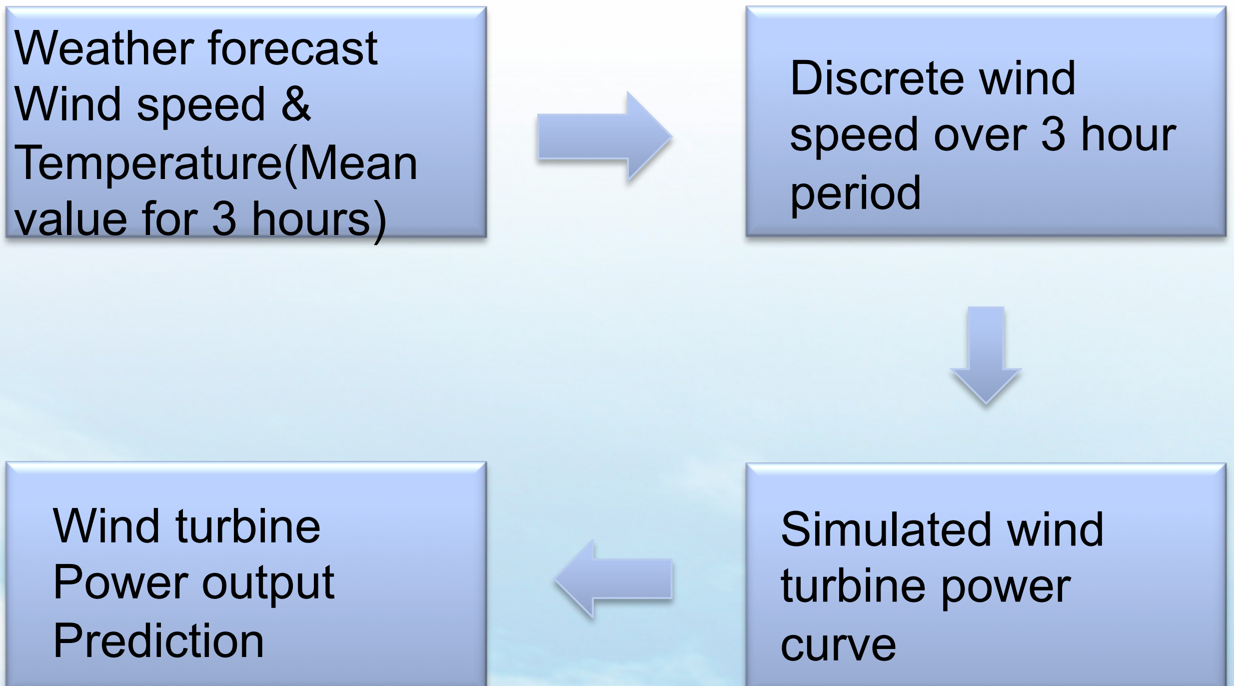
- **Advantages:**

1. Weather forecast is easy to get and cost less. No need to pay extra for those distributed wind turbines.

2. The weather forecast will be more and more accurate as meteorology develops.

Introduction

Forecast system Overview



Introduction

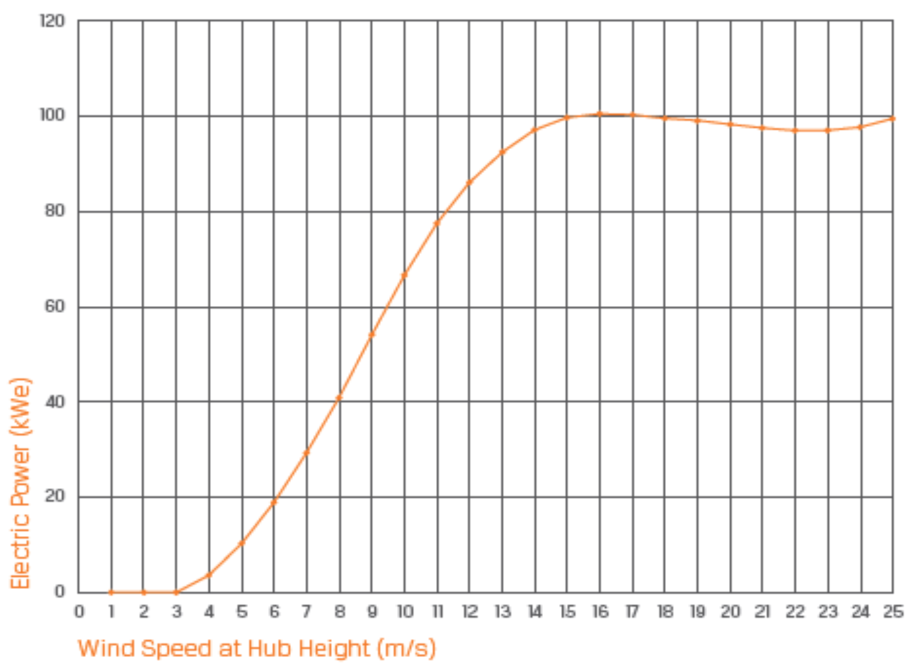
Prototype wind turbine:

Installed in November 2010 financial support from the Ohio Third Frontier Program.

Introduction

Prototype wind turbine:

Power Curve: 21-Meter Rotor Standard Air Density (1.225 kg/m³)

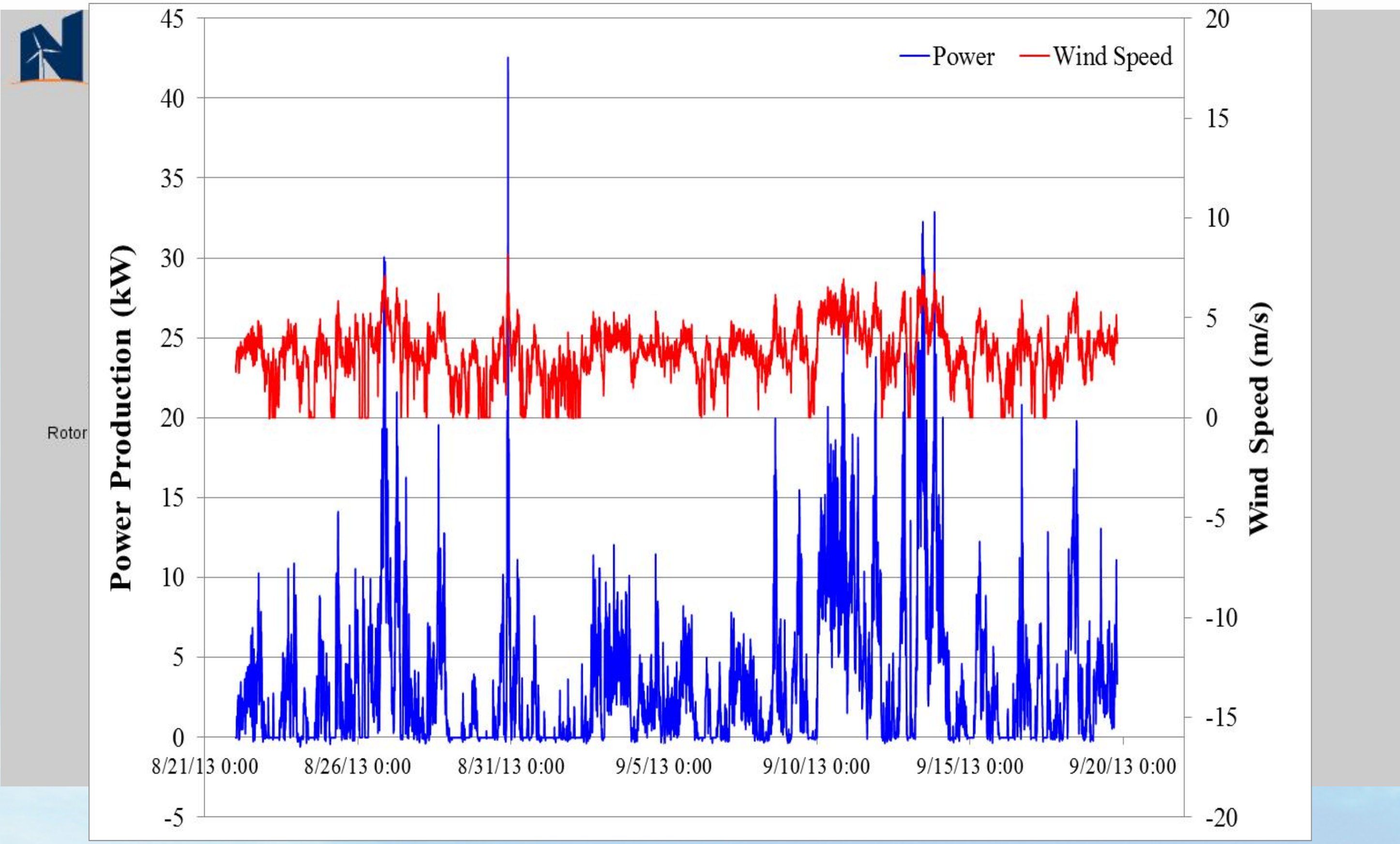


Wind Speed (m/s)	Power (kWe)	Wind Speed (m/s)	Power (kWe)
1	0	14	97.3
2	0	15	100.0
3	0	16	100.8
4	3.7	17	100.6
5	10.5	18	99.8
6	19.0	19	99.4
7	29.4	20	98.6
8	41.0	21	97.8
9	54.3	22	97.3
10	66.8	23	97.3
11	77.7	24	98.0
12	86.4	25	99.7
13	92.8		

1 m/s = 2.24 mph

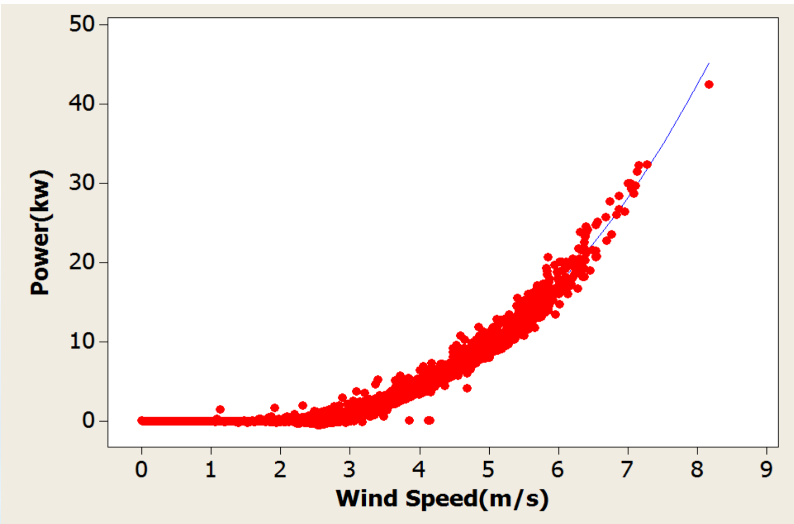
Introduction

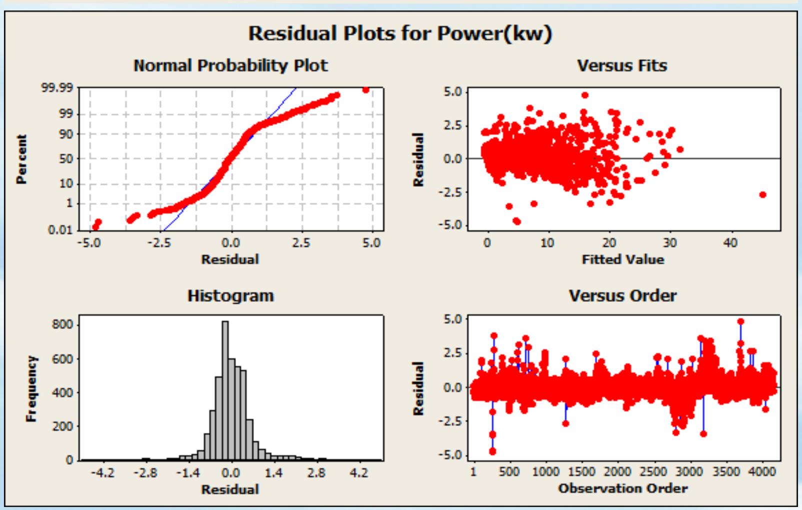
Campbell-Scientific Data acquisition system(DAQ):



Power prediction Procedures

Measure wind turbine power curve based on one month data





Statistic analysis of simulate curve:

S = 0.629797 R-Sq = 98.1%
R-Sq(adj) = 98.1%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	84447.1	28149.0	70967	0.0
Error	4143	1643.3	0.4		
Total	4146	86090.4			

Power prediction

Measure wind turbine power curve

$$P_w = 0.215 - 0.962v + 0.199v^2 + 0.073v^3$$

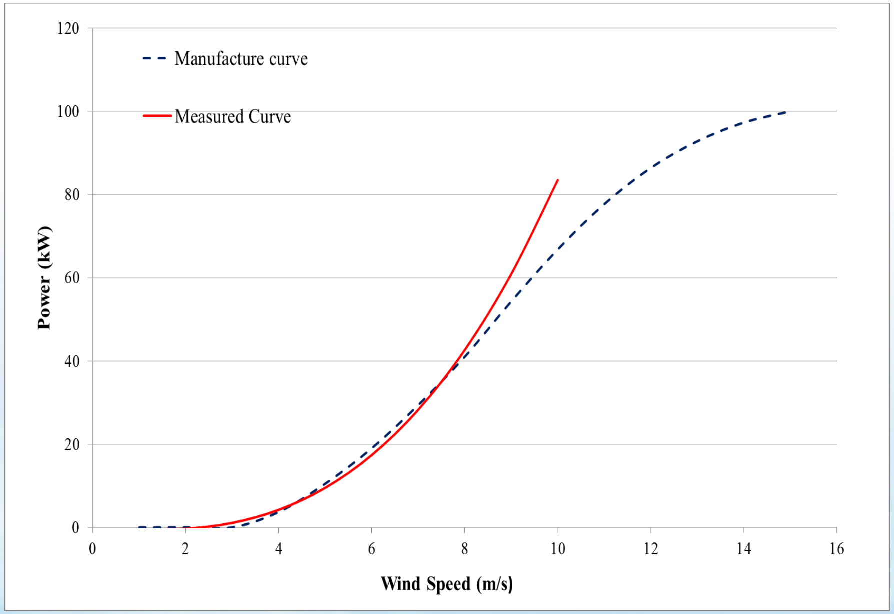
The Pearson product-moment correlation coefficient (PPMCC or PCC) is used to measure the degree of linear dependence between two variables

$$r = \frac{1}{n-1}\sum_{i=1}^{n}\left(\frac{X_i - \overline{X}}{s_X}\right)\left(\frac{Y_i - \overline{Y}}{s_Y}\right) \qquad S_X = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - \overline{X})^2} \qquad \overline{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$$

where *r* is Pearson product-moment correlation coefficient, Pearson correlation of power and wind speed is 0.816 means there is a high correlation between wind speed and power output.

Power prediction

Measure wind turbine power curve



Manufacture curve and measured curve

The measured curve exceeds 8m/s may not reliable because there is no real measured wind speed as shown as above.

where ρ (kg/m³) is air density, p is absolute pressure, R_{Sp} is specific gas constant for dry air, 287.058 J/(kg·K) and T (°C) is temperature

Power prediction

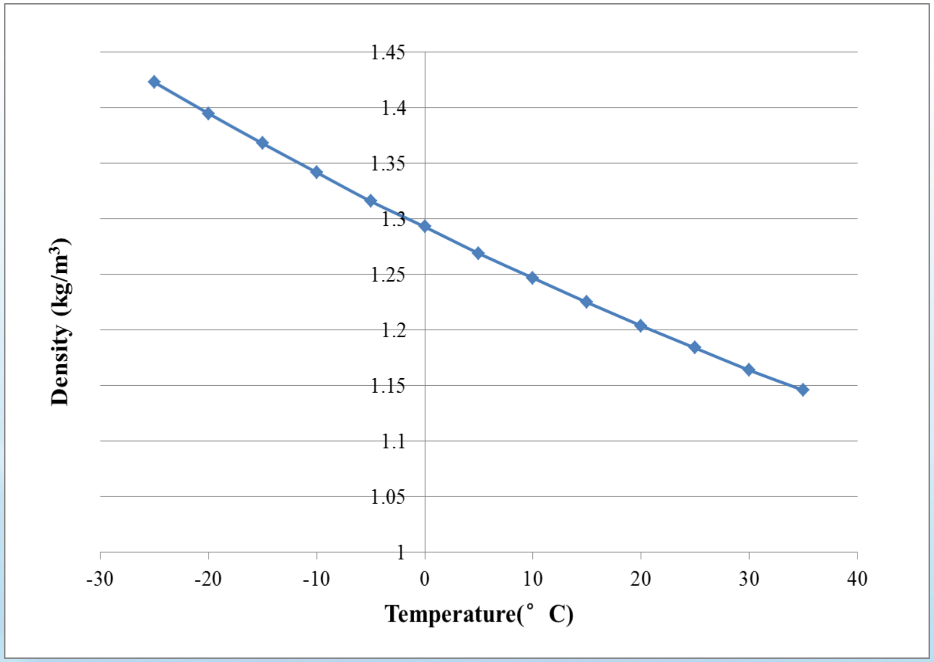
Take temperature into consideration

$$P_w = \frac{1}{2}\rho A v^3 C_p$$

The density of air changes with temperature, as shown in the figure for pressure at 1 atm:

$$\rho = \frac{p}{R_{Sp} \times T}$$

where ρ (kg/m³) is air density, Rsp is specific gas constant for dry air and T (°C) is temperature



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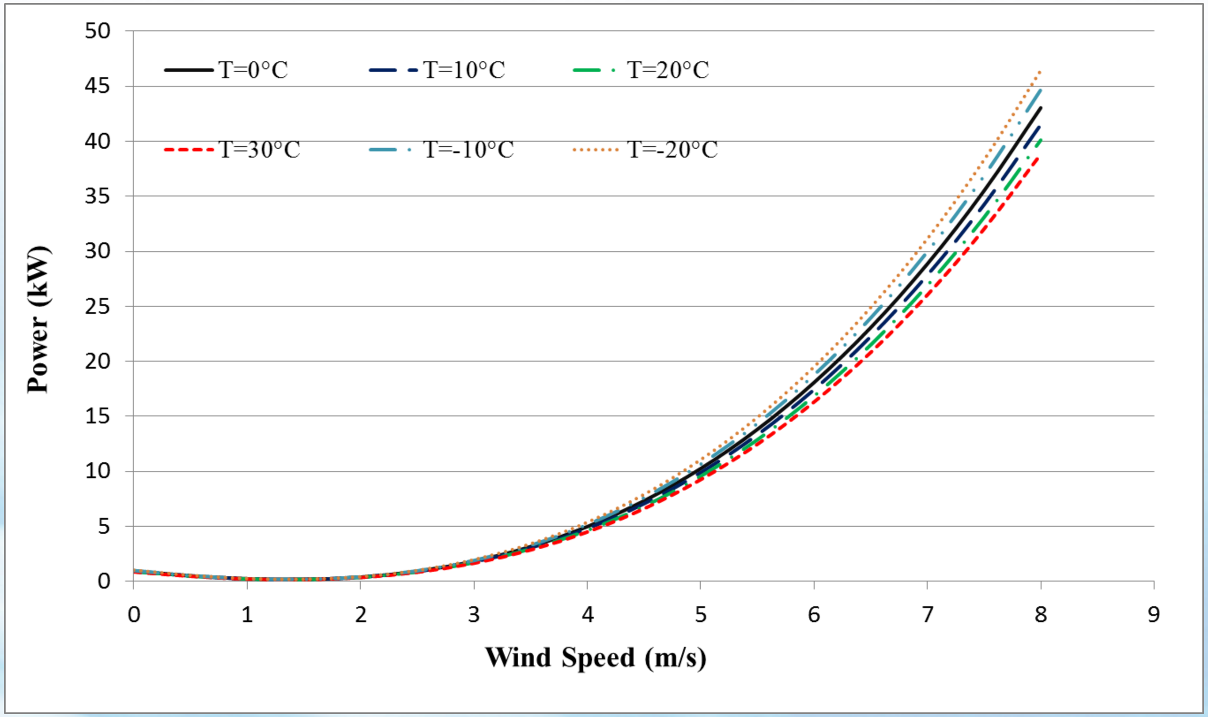
Power prediction

New power equation:

$$P_{w1} = \frac{P_w}{\rho(T)} \Rightarrow P_{w1} = 0.1732 - 0.7799v + 0.1726v^2 + 0.0542v^3$$



Power curve under different temperature

Power prediction

Wind Simulation

The transient wind velocities include two components:

(1) mean wind speed and

(2) turbulent wind speed,

$$U_{tot}(t,z) = U_z(z) + u_z(t,z)$$

where $U_{tot}(t,z)$ is the total wind speed; $U_z(z)$ is mean wind speed component which varies with height z above ground and $u_z(t)$ is the fluctuating turbulent wind speed that varies with time t at a height of z above ground.

Power prediction

1. Mean wind Speed Adjust:

$$U_z(z)$$

The NOAA (*National Oceanic and Atmospheric Administration*) provides mean hourly wind speed in Cleveland area which must be adjust over time period and height in order to use in the simulation.

The *Durst curve* is used here to convert wind speed data measured and averaged over one time interval to another time interval.

Power prediction

Mean wind Speed Adjust over height and terrain

Using *the Power Law*, the wind speed at any height above the ground can be determined using the following expression

$$U_z(z) = U_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha_0}$$

Terrain type	Surface drag coefficient
Very flat terrain(dessert)	0.002-0.003
Open terrain(grassland)	0.003-0.006
Suburban terrain(buildings 3-5m)	0.0075-0.02
Dense urban (buildings 10-30m)	0.03-0.3

where α is the power-law surface drag coefficient changing with terrain;
z_{ref} is reference height above the ground equals to 10m
U_{ref} is the reference wind velocity measured at reference height.

Power prediction

2. Turbulent wind speed component

The model used here to simulate turbulent wind speed was developed by Davenport, A. G.(1961) and utilizes the wind turbulence spectral density $S_k(k,z)$ proposed by Kaimal, J. (1972):

$$u_z(t,z) = \sum_{k=1}^{n}\left\{\sqrt{(2\times S_k(f_k)\times\Delta f} \times\cos[(2\times\pi\times f_k(k)\times t+\phi_k]\right\}$$

where ϕ_k is Gaussian random number distributed uniformly between 0 and 2π which is chosen for each central frequency; t is time value in the simulation, and n is the number of frequencies for which the given spectrum $S_k(k,z)$ has been evaluated for specific frequencies f_k.

Power prediction

In which:

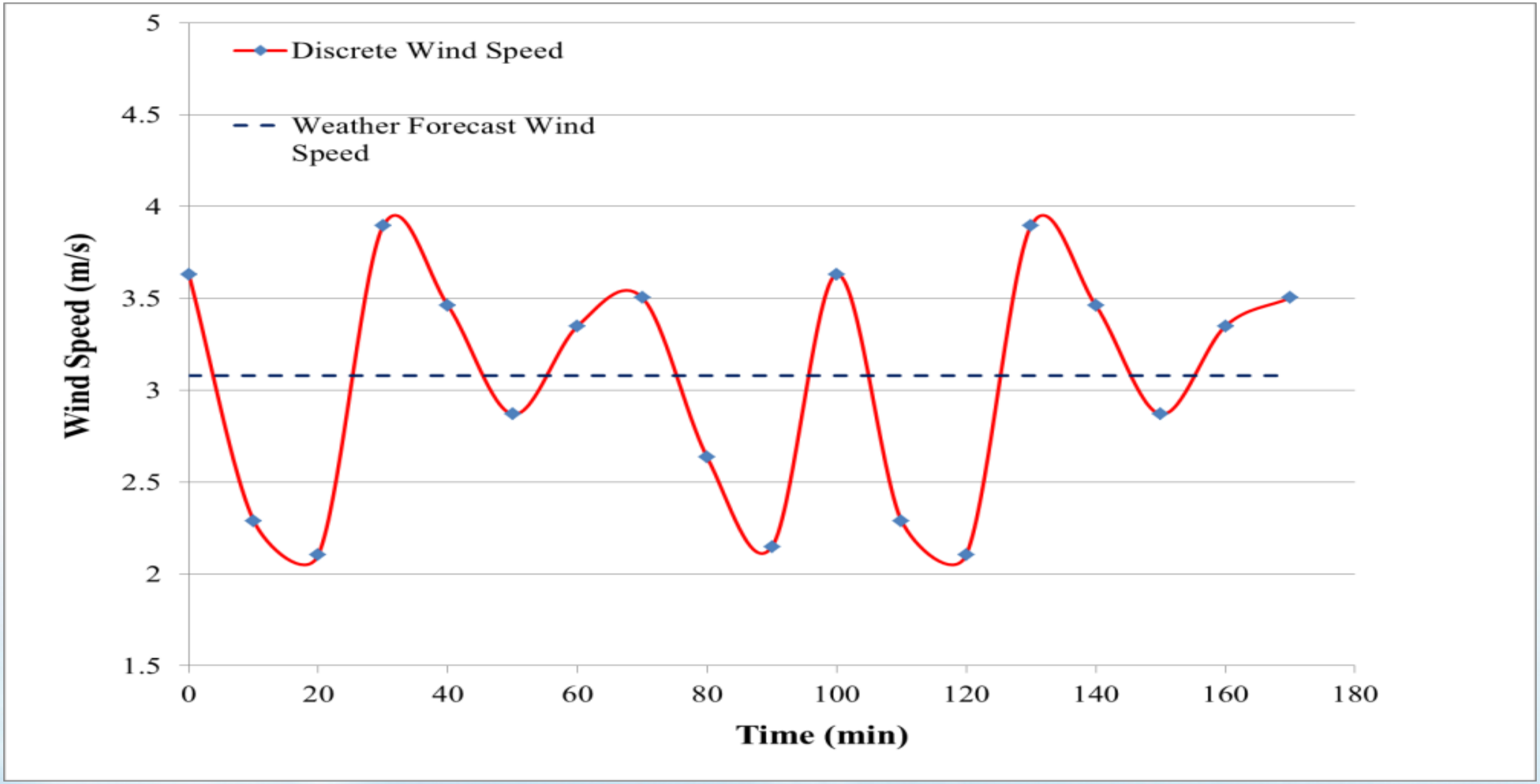
$$S_k(k,z) = \frac{\left(200 \times U_1^{\,2} \times z\right)}{U_z(z) \times \left[1 + 50 \times f_k(k) \times \frac{z}{U_z(z)}\right]^{\frac{5}{3}}}$$

$$f_k(k) = k \times \Delta f$$

$$U_1^{\,2} = K \times U_{ref}^{\,2}$$

$$K = \left(\frac{0.4}{\log(10/z_0)}\right)^2$$

where Δf is frequency increment; k is the number of frequency increment; K is the surface drag coefficient. 0.4 here is an experimentally value known as von Karman's constant.



Finally, a 180 minutes wind history was simulated, the resulting simulated wind record, including the adjusted mean wind speed.

In the Figure, for a given mean wind speed of 3.1m/s, the wind velocity is predicted to vary between 2m/s to 4m/s.

Power prediction

Test Data:

- In the research, six sets of data are used to make the power output forecast.
- Three sets of data are from September 2013 and three are of Feb. 2013
- Wind data are of one day ahead and temperature data are from real recorded data because lack of forecast temperature data

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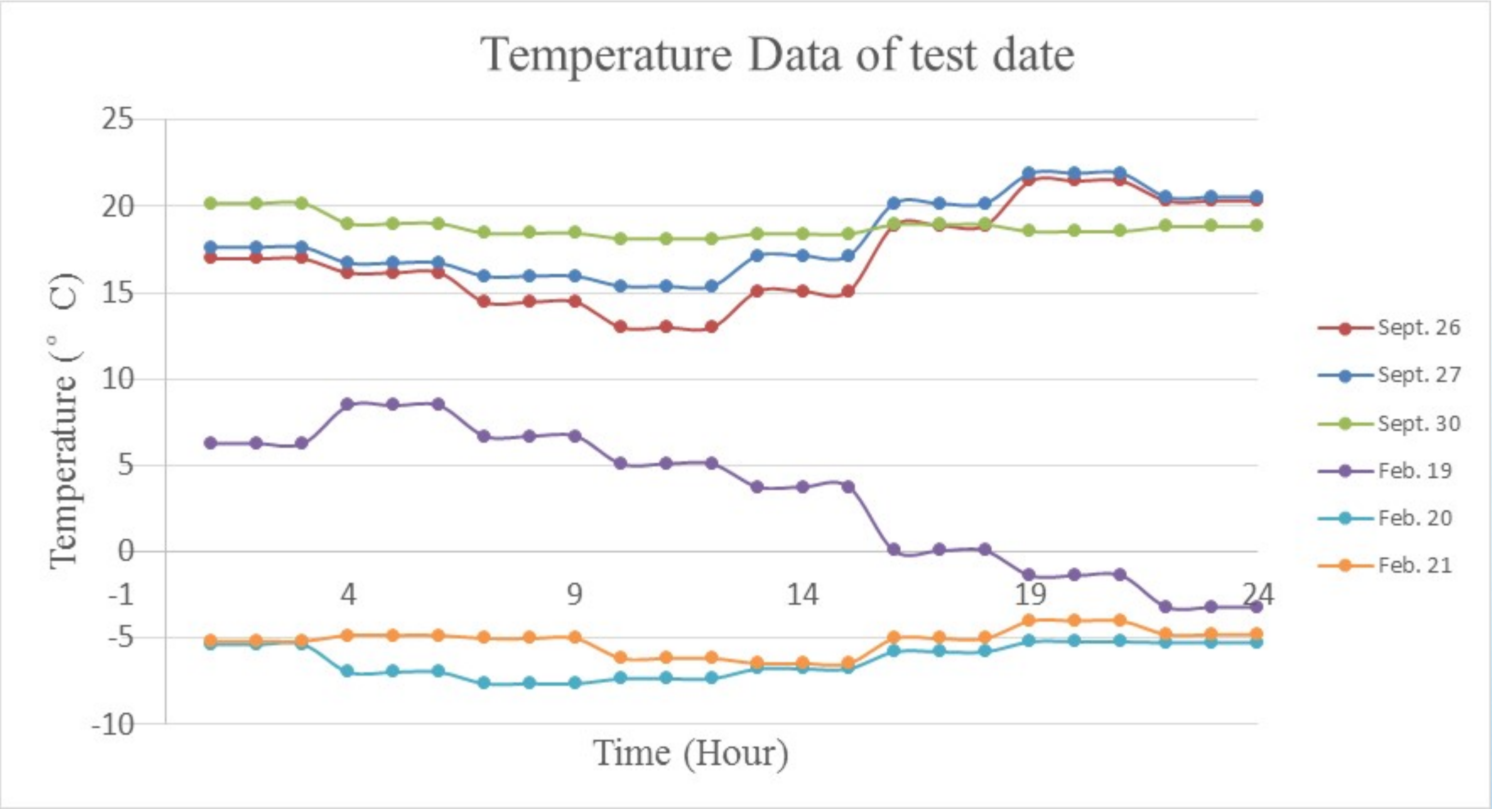
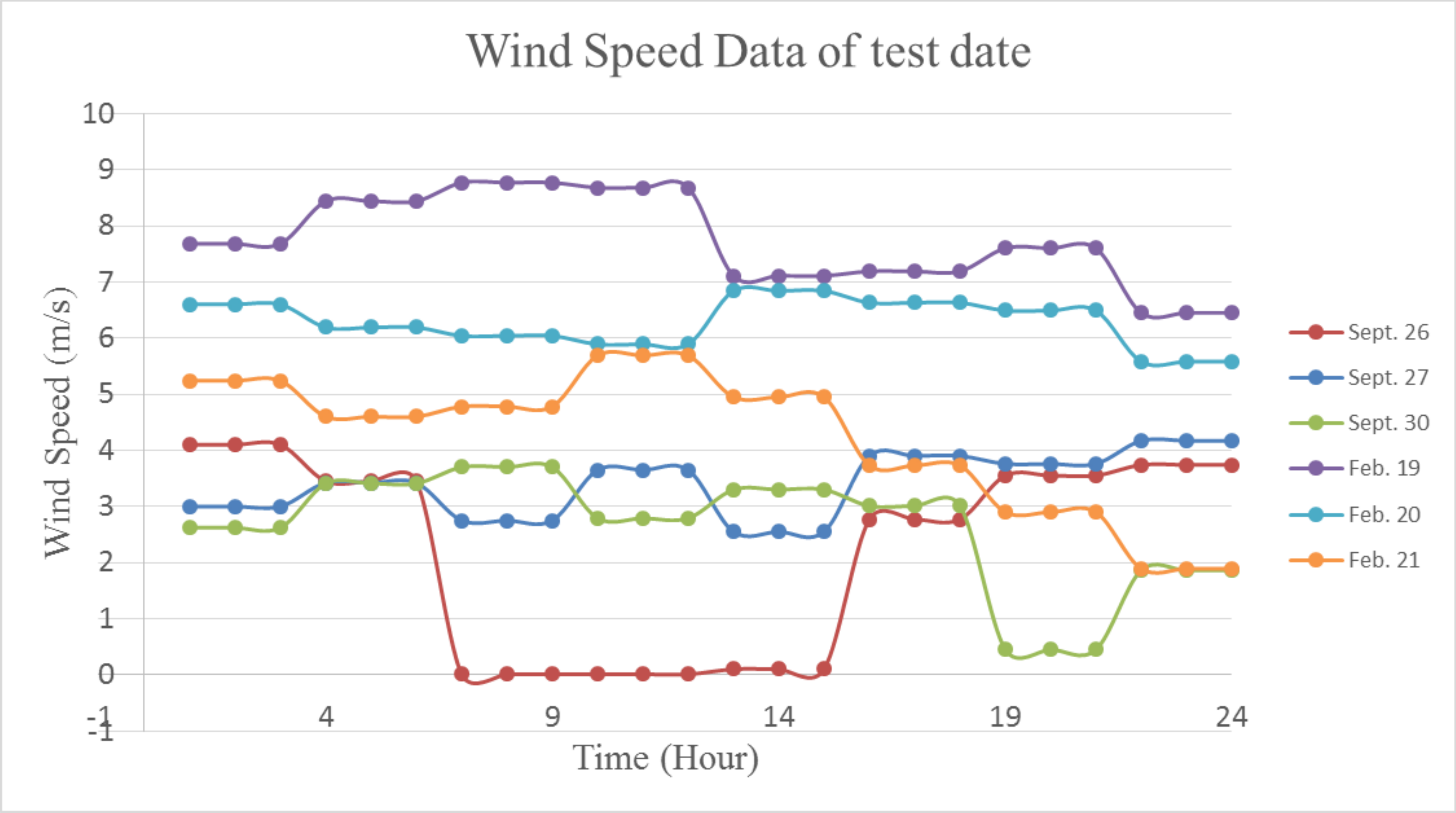
Power prediction

Temperature data:



Power prediction

Wind forecast data:



Prediction

Predict methods:

Method 1: prediction using weather forecast directly with manufacturer turbine production curve;

Method 2: prediction using weather forecast directly with measured turbine production curve;

Method 3: prediction using simulated wind speed from weather forecast data and manufacturer turbine production curve;

Method 4: prediction using simulated wind speed from weather forecast and measured turbine production curve;

Method 5: prediction using discrete weather forecast data and measured turbine production curve considering temperature effects.

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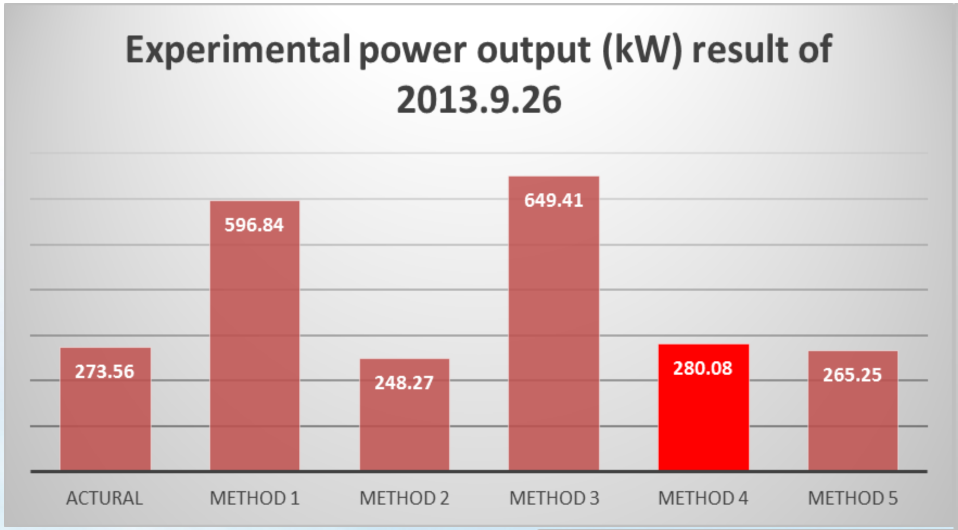
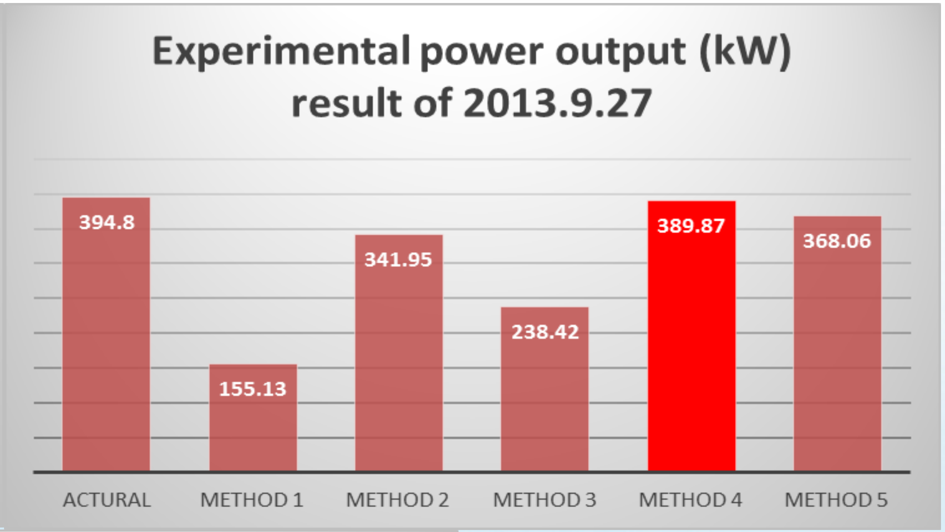
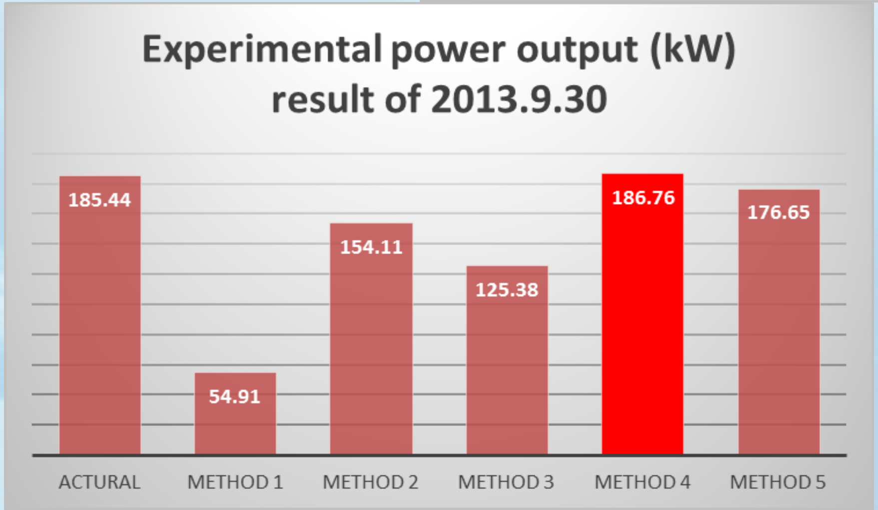
Results

Experiment result of summer time:

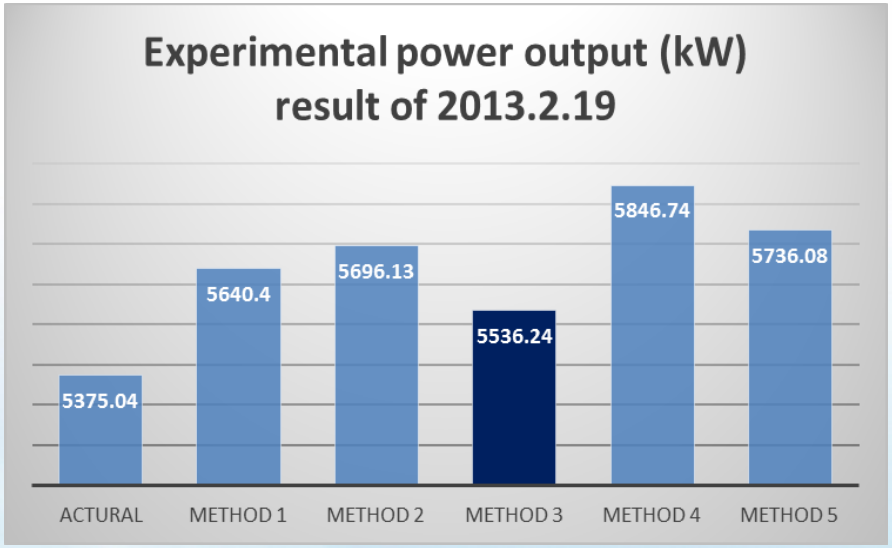


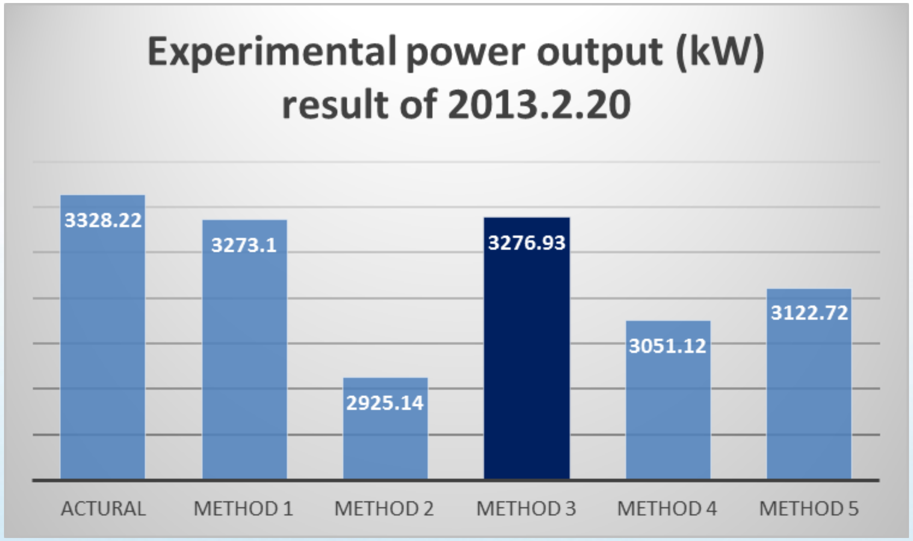


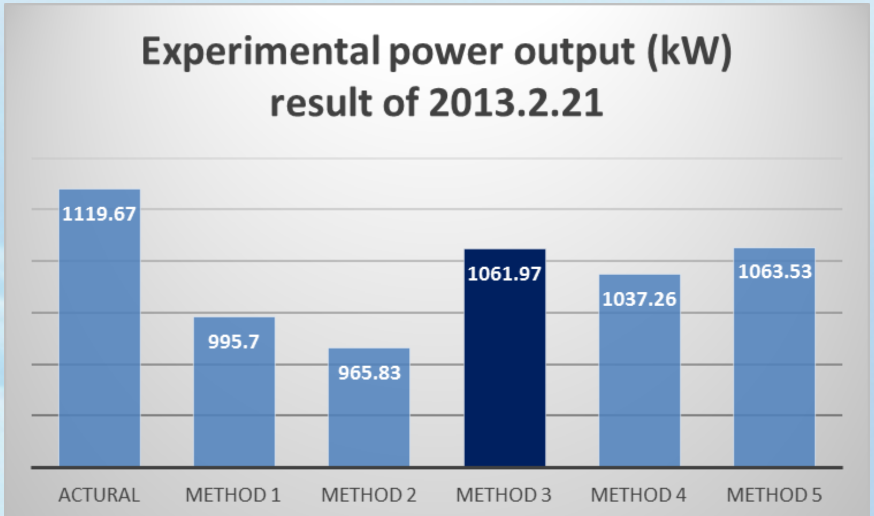


Results

Experiment result of winter time:







Results

Experiment result of summer time:

- It is observed that predict use Method 4, i.e., prediction using simulated wind speed from weather forecast and measured turbine production curve, gives best result with an overall less than 3% from real power production. This method is about 10% more accurate than Method 2, i.e., prediction by directly using weather forecast.
- This method is also more accurate than Method (5), which considers both wind speed and temperature.
- Energy production prediction directly using manufacturer production curve and weather forecast data (Method 1) is unsatisfactory, which resulted in over 60% difference from actual energy production. Using simulated weather data from weather forecast data improved the accuracy, but still more than 30% difference.

Results

Experiment result of winter time:

- Winter data illustrates that the most accurate method is the use of simulated wind speed and manufacture curve which is overall 3% more accurate than predict directly using manufacture curve and weather forecast.
- Prediction using discrete weather forecast data and simulation curve in this case shows overall 8% difference than real number. The reason for the inaccuracy of method (4) in cold weather is that the measured curve is based on lower wind speed. In such case, the manufacture curve is more accurate.
- Method (5), which considers both wind speed and temperature in this case is more accurate than method (4) but less accurate than method (3).

Results

Experiment result:

- Method (5) in both Table 8 and Table 9 takes wind speed and temperature into consideration. It is the second accurate way in both warm and cold weather however not the most accurate way. This might be due to the reason that the ambient temperature also affects the efficiency of the wind turbine. Another reason is because the curve was simulated mainly based on lower wind speed level while the average wind speed is relatively high in the three chosen days.

Conclusion

Conclusion:

- The power output curve of a single wind turbine is different under different temperature. In a certain range, the power output and temperature has a inverse relationship at same wind speed, i.e. the power output is higher under lower temperature at same wind speed.
- In order to increase the accuracy of wind power predicts, different power curve should be used around the year. In this study, the manufacture power curve is more accurate to use in winter and simulation curve is more accurate to use in summer time.
- By comparing Method (1) and Method (3); Method (2) and Method (4), the discrete wind speed method developed in this research can increase the accuracy of energy forecast effectively. Using the simulation wind speed method shows great advantage than predict directly using weather forecast.

Thank You !