WIND ENERGY MODELING FOR RESIDENTIAL-SCALE WIND POWER AND SENSITIVITY OF ECONOMIC VALUATION TO ERRORS IN WIND SPEED ESTIMATES

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ABSTRACT

A residential-scale wind turbine has the potential to provide annual savings in electricity cost for a homeowner. The estimated annual saving is calculated based upon the estimated annual energy output (AEO) of a turbine. The annual energy saving is a key input in determining the net present value (NPV) and simple payback period (SPP), which are major factors in the economic evaluation. Since the power output of a turbine, and thus the AEO, are dependent upon the cube of the velocity, an accurate estimate of wind speed is crucial for turbine's economic valuation. The first part of this study used wind speed data from meteorological towers and flow modeling software to predict the output of a residential-scale turbine and compare the predictions to the actual energy production. Then, it is demonstrated that the uncertainty in estimated wind speed leads to the uncertainty in economic valuation of a residential-scale wind turbine.

1. INTRODUCTION

Distributed power generation has recently become more popular because of its flexibility, security, improved efficiency and lower energy costs (1). Generally, distributed generation is defined as residential or non-utility owned installations that generate electricity on-site often using wind or solar energy (2). Although there is no national standard for distributed energy, state incentives for individual homeowners and requirements for utilities are increasing its use (3).

Solar and wind are both good candidates for distributed power generation. Between the two, errors in solar irradiance estimates have a lesser impact on AEO than errors in wind speed estimates (4). This is because solar irradiance and solar power output increase or decrease proportionally to each other. For wind, there is a cubic relationship between wind speed and power in the wind, as shown in Equation 1, where P is power, ρ is air density, A is rotor swept area, and V is wind speed.

$$P = \frac{1}{2}\,\rho\, A\, V^3 \qquad (1)$$

When wind speed doubles, power increases 8-fold. An increase in the available power increases the annual energy production of a wind turbine since energy is directly related to power, as shown in Equation 2.

$$Energy = Power\ x\ Time \qquad (2)$$

The strong dependence of wind power on wind speed creates a challenge for annual energy predictions, because small errors in wind speed predictions can have a significant impact on predictions of wind energy. Accurate wind speed and energy production predictions allow utilities and others interested in installing wind turbines to make informed decisions in how to meet their electricity needs. In general, if an individual were to install a small-scale wind turbine, they would need to rely on the installer or the turbine company to help them calculate the annual energy output for their location. Wind-modeling software is one powerful tool used in predicting wind speed and energy production for utility scale projects, and may be applicable for residential-scale projects.

A residential-scale wind turbine has the potential to provide annual savings in electricity cost. The estimated annual cost savings is calculated based upon the estimated annual energy output (AEO). The calculation of the AEO requires information about the wind speed at the location being considered. These relations show how the accuracy of the AEO, and thus the annual savings, are affected by the accuracy of the wind speed estimate.

This paper will also demonstrate how economic valuation of a residential-scale wind turbine is greatly affected by errors in wind speed estimates.

Another study looking at the net present value for a single wind turbine at Principia College in Illinois found a positive net present value. In their sensitivity study, they found that even for a 20-year life-expectancy, the net present value would still be positive for a 10% decrease in predicted energy production. For the 30-year life-expectancy, the net present value remained positive for up to a 30 % decrease in predicted energy production (5).

2. METHODS

2.1 Wind Energy Modeling

WindPRO (6) is wind-industry standard software used to plan and design wind projects of all sizes. The Wind Atlas Analysis and Application Program (WAsP) (7) is a module within WindPRO used to calculate wind speed and direction throughout the modeling domain. The WindPRO/WAsP software combination operates as a microscale model that is commonly used by the wind industry to predict wind speed and energy production, as well as evaluate noise, visual impacts and grid integration impacts.

WindPRO/WAsP calculated the predicted annual energy output using wind speed and direction data from two met tower sites, referred to as the reference sites. The prediction was made for one site, referred to as the prediction site, where a residential wind turbine was already installed. The predictions were compared to the actual annual energy output to assess the model's accuracy.

Wind energy production was predicted at the same site as a residential-scale wind turbine in Northern Arizona. The study area (Doney Park) is also 10 km north east of the City of Flagstaff. The wind turbine at the study site will be referred to as the Scharf turbine. It is a 2.4 kW Skystream 3.7 turbine with a hub height of 9 m. The Scharf turbine was installed in late 2008 and on average, produces about 3 megawatt-hours (MWh) per year.

WindPRO/WAsP requires information about mean wind speed, wind speed standard deviation, and direction in order to compile wind characteristics at a particular site. For the purposes of this study, one year of data was chosen from April 2011 to March 2012.

The first met tower, at Nova Terra, was located 6 km north of the Scharf turbine while the second tower, at Star School, was located 23 km east of the study site. Measurements were taken at two different heights at Nova Terra, 20 m and 33 m, and three heights at Star School, 20 m, 32 m and 33 m. The mean wind speed varies from 4.1 m/s to 4.7 m/s depending on the met tower and the height with higher wind speeds being seen at the Star School met tower and 33 m. The prevailing wind direction in this area is west south-west.

For this study, predictions were made using the 33 m and 20 m data from Nova Terra and the 20 m data from Star School.

In addition to the wind speed and direction data collected at the met towers, height contour lines and roughness information are used as inputs to the model. Height contour lines were created in the software Global Mapper using a Digital Elevation Model. In WindPRO, the modeler identifies the roughness type of an area and marks that area within the software, creating a roughness map. WAsP then uses this roughness map when determining the shape of the vertical wind shear profile (8).

2.2 Economic Valuation Process

The economic valuation process of a residential-scale wind turbine in this paper considers only two parameters: the net present value (NPV) and simple payback period (SPP). The calculation of the net present value (NPV) requires the present value (PV).

The annual saving or the avoided electricity cost is a key input in determining the PV, NPV, and SPP. Equation 3 shows how variable cost (in cents/kWh) from a utility company is normally applied to convert the AEO to the annual saving (A).

$$A = \text{AEO (in kWh) x variable cost (in cents/kWh)} \quad (3)$$

Equation 4 relates PV and A, where i is the interest rate (%) and n is the estimated lifetime (years).

$$PV = A\,\frac{(1+i)^n - 1}{(i)(1+i)^n} \quad (4)$$

Calculation of the net present value (NPV) also requires several factors: possible rebate from a utility company (UR), possible Federal tax credit (FTC) and State tax credit (STC), possible tax on rebate (TR), and out of pocket cost (OPC). The OPC is calculated by using Equation 5, where TIC is the total installation cost (9).

$$OPC = TIC - STR - FTC - UR + TR \quad (5)$$

After the PV and OPC have been defined, the NPV can be determined by using Equation 6. NPV will determine financial decision and any investment will look for positive value of NPV.

$$NPV = PV - OPC \quad (6)$$

SPP is the number of years required for the actual OPC to be paid off before the system provides any profit from the savings. Equation 7 is used to calculate SPP.

$$SPP = \frac{OPC}{A} \quad (7)$$

To simulate how errors in wind speed estimates and AEO affect the economic valuation of a residential-scale wind turbine, the results from a recent study using WindPRO/WAsP were presented in two parts. The first simulation used wind data from 33-m Nova Terra met tower and it was assumed that a residential-scale wind turbine were to be installed at this location. The simulation was conducted in order to see how NPV and SPP changed if the mean wind speeds were assumed to be under- and over-predicted by 10%. The Rayleigh distribution was applied to the Skystream 3.7 power curve to get the AEO, which was then used to calculate the annual savings, NPV and SPP. The second simulation will focus on Scharf wind turbine and will use WindPRO/WAsP results from the study. The actual AEO from the Scharf turbine and the predicted AEO using wind data from three met towers (33-m Nova Terra, 20-m Nova Terra, and 20-m Star School) were used. The change in NPV and SPP were calculated based on the change in AEO. The following assumptions were applied to both first and second simulations (9):

- Avoided cost of electricity = 12 cents/kWh
- Interest rate (i) = 5%
- Estimated lifetime period (n) = 25 years
- Total installation cost (TIC) = $17,760
- State tax credit (25% of TIC – max $1,000) = $1,000
- Federal tax credit (30% of remaining TIC – after State tax credit taken into account) = $5,028
- Utility rebate ($2.5/Watt – max 50% TIC) = $6,000
- Tax on rebate (28%) = $1,680

The economic valuation of a residential-scale wind turbine may include another parameters other than NPV and SPP. The above state assumptions might not always be applicable and the assumed values might also be different for another region. For simplicity, they will be applied to the calculation presented in the next section.

3. RESULTS AND DISCUSSION

3.1 Wind Energy Modeling Results

Between April 2011 and March 2012, the Scharf turbine's actual energy production was 2.90 megawatt-hours (MWh). This annual energy production was compared to the predicted energy production for the different met towers and heights during this period. In Fig. 1, the top line is the actual energy production. Below that is the first prediction using 33-m Nova Terra met tower to predict the energy output, which is 3.1 MWh in this case. That prediction has an error of 7.1%, shown as the red bar above the prediction value. The other predictions follow below.

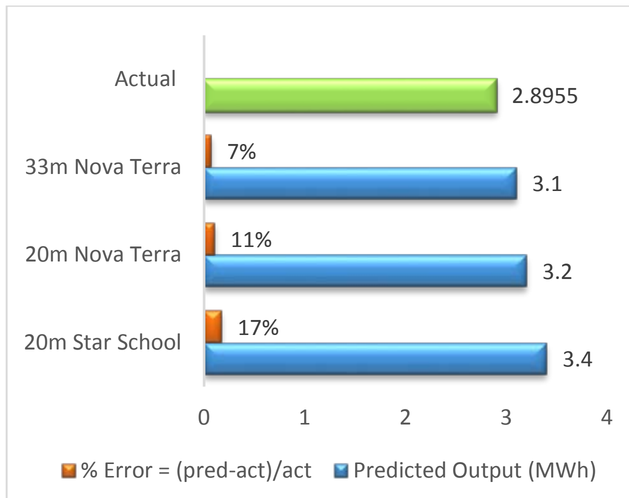

Fig. 1: Predicted annual energy output for Scharf turbine compared to actual annual energy output for April 2011 to March 2012

Predicted energy output for the Scharf turbine ranged from 3.1 to 3.4 MWh depending on the met towers and heights used for the prediction. The results were consistently in the same range with an error of 7% to 17% as seen in Fig. 1.The model over-predicts wind production at the site. The model assumes the turbine is operating 100% of the time with no losses. However, in reality, the turbine is shutdown periodically for maintenance. There are also periods of time where the blades are iced over and are not moving efficiently. Since the model does not account for this loss of productivity, it is expected that it would be slightly over-predicting the energy output.

3.2 Economic Valuation Results

The first part of the economic valuation used 12-direction wind data from 33-m Nova Terra met tower, as shown in Table 1.

TABEL 1: ANNUAL MEAN WIND SPEED FOR 33-M NOVA TERRA MET TOWER

Wind Direction	Annual Mean Wind Speed (m/s)	Frequency (%)
N	4.03	10.6
NNE	2.92	5.1
ENE	2.55	2.8
E	2.17	2.4
ESE	2.66	4.8
SSE	2.63	5.8
S	4.32	7.8
SSW	6.94	17.1
WSW	7.66	18.6
W	2.54	6.5
WNW	1.74	6.2
NNW	3.56	12.2

The wind speeds from Table 1 were assumed to be off by ± 10% for all directions. The Rayleigh distribution was applied to calculate AEO based on the actual mean wind speed data, the assumption of 10% under-predicted wind speed, and the assumption of 10% over-predicted wind speed.

Fig. 2 shows that under-predicting the wind speed by 10% produced a -17.6% error in AEO and a -248.6% error in NPV. On the other hand, over-predicting the wind speed by 10% produced a 16.4% error in AEO and a 231.5% error in NPV. This condition can be explained by the cubic relationship between the power, thus the AEO, and the wind speed, as shown in Equation 1 and Equation 2. Over-prediction in wind speed results in higher AEO estimate, which subsequently produces higher saving. The higher saving results in higher PV, and thus higher NPV for the same out of pocket cost. In Fig. 2, the negative error in SPP shows that over-predicted wind speed shortens the SPP.

The second part of the economic valuation was related to the results shown in Fig.1. Fig. 3 shows the error between the actual AEO and the predicted AEO from each tower, as well as the corresponding error in NPV and SPP. Each met tower produced over-predicted AEO. As a consequence, the corresponding NPV was also over-predicted. In Fig. 3, each of negative errors in SPP shows that over-predicted AEO also shortens the SPP.

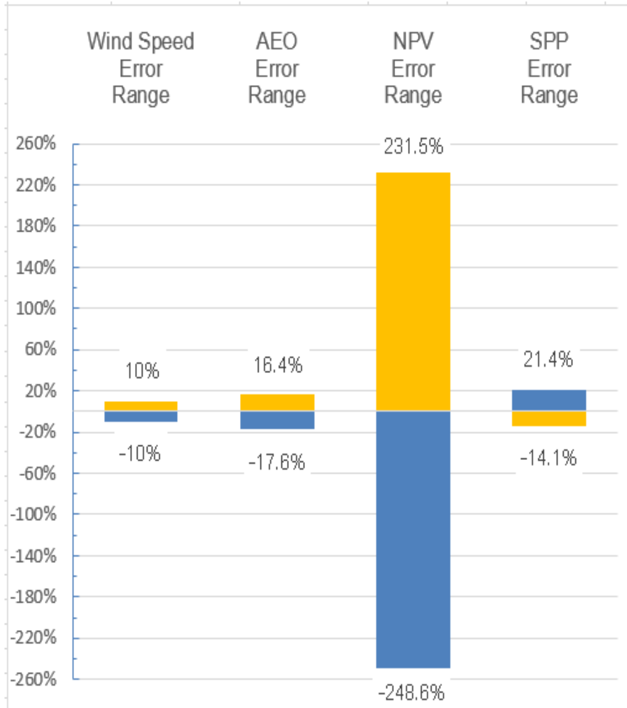

Fig. 2: Error ranges in AEO, NPV and SPP due to under- and over-predicted wind speed.

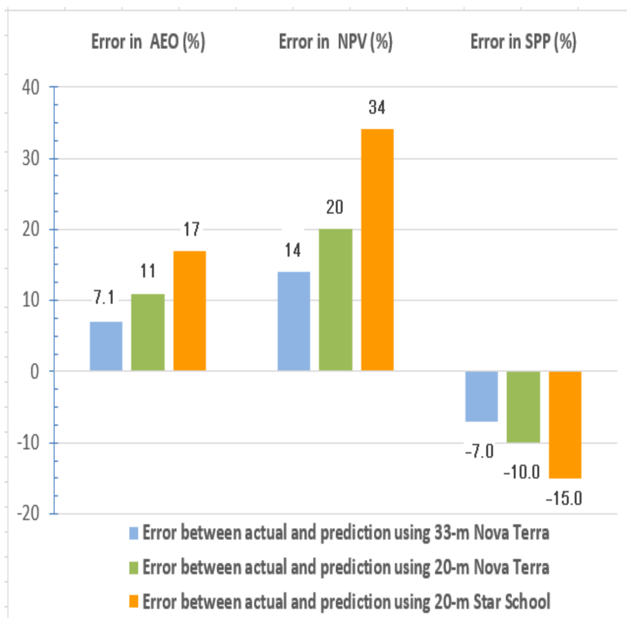

Fig. 3: Effect of errors in AEO to NPV and SPP

The results from the first and the second simulation of the economic valuation process show that errors in wind speed and AEO estimates affect the calculation of the potential annual savings, PV, NPV and SPP. These errors will have implications to any economic decision to be made by the turbine's prospective owner. The accuracy of the wind speed estimates is crucial for economic valuation of a residential-scale wind turbine. The uncertainty in wind speed estimates leads to the uncertainty in economic value and the relationship does not seem linear.
The under-predicted wind speed could impact economic decision from the prospective owner for not installing the turbine because of the under-predicted NPV. Unlike the case of the under-predicted wind speed, the over-predicted NPV due to the over-predicted wind speed could cause the prospective owner to install a turbine which might not provide any economic benefit.

Both under-predicted and over-predicted wind speeds could give false indication in determining the number of years when the turbine would actually start to provide any profit to the owner.

4. CONCLUSIONS

The study found that the WindPRO and WAsP software can be used to predict energy production with a 7-17% error for residential-scale wind turbines in the Doney Park area when using data from met towers less than 25 km away. Minimal differences were found when different locations and heights of wind data were used for the predictions.

In the first simulation using ±10% error band, over-predicted wind speed, thus AEO, results in over-predicted NPV and shorter SPP, and vice versa. The second simulation using WindPRO/WAsP results also shows the same trend that over-predicted AEO results in over-predicted NPV. Both conditions could have significant impact to any economic decision made by turbine's prospective owner.

Accurate estimate of wind speeds is crucial in economic valuation of a residential-scale wind turbine. Therefore, the AEO, annual savings, PV, NPV, and SPP can also be accurately calculated for an economic decision.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

(1) National Renewable Energy Laboratory. Distributed Energy Basics. http://www.nrel.gov/learning/eds_distributed_energy.html. Accessed 18 June 2013

(2) Heather Murphy. Commissioners Approve Rules Requiring 15 Percent of Energy from Renewables by 2025. Arizona Corporation Commission Public Information Office, 2006

(3) North Carolina State University. Database of State Incentives for Renewables and Efficiency. http://www.dsireusa.org/. Accessed 11 August 2013.

(4) John Twidell and Tony Weir. Renewable Energy Resources. Taylor and Francis, 2006

(5) Nicholas Johnson and Barry Solomon, A Net-Present Value Analysis for a Wind Turbine Purchase at a Small US College. Energies, 2010

(6) EMD International A/S. WindPRO 2.5 User Guide. 2006

(7) Niels Mortensen, Duncan Heathfield, Lizbeth Myllerup, Lars Landberg and Ole Rathmann. Getting Started with WAsP 9. 2007

(8) AJ Bowen and Niels Mortensen. WAsP Prediction Errors Due to Site Orography. Riso National Laboratory, December 2004

(9) Dean Howard Smith. Residential Wind Potentials in Arizona: A Report for Arizona Public Service. Northern Arizona University. Sustainable Energy Solutions. Initial Report: Arizona Public Service Distributed Wind Study. Findings for Tasks 1 and 2. June, 2010

(10) Blank Tarquin. Engineering Economy. 6Rev Ed. McGraw-Hill. 2005