Statistical Analysis of Operational and Environmental Factors as they Relate to Small Wind Turbine Survivability in Harsh Environments

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Abstract

The practicality of using small wind turbines for off-grid power production in isolated, harsh environments is the subject of this work. Memorial University researchers, in collaboration with Bell-Aliant engineers have undertaken this study using the communication company's operational experience with small wind installations at hilltop microwave relay stations along the coast of Labrador. Bell-Aliant intends to objectively determine the value of adding wind power generation to traditional diesel generation and photovoltaics. This paper specifically details a multi-variable regression analysis used to determine the significance of various operational and environmental factors in the survivability of small scale wind turbines in this harsh environment.

Introduction

Bell-Aliant operates an extensive network of microwave relay stations, which span up the coast of Labrador and inland to Labrador City, most of which are only accessible by helicopter. Each of the 29 sites was powered solely by diesel generators with battery banks until solar power was introduced in the early 1990's. Introduction of wind power began in 2003 and Bell-Aliant currently operates six sites with complete wind-solar-diesel hybrid systems.

There are 37 turbines in total throughout the six sites, all of which are Southwest Windpower's Whisper 100 model (WH100), presented in Figure 1. The WH100 is rated at 900 Watts, has three blades and a 2.1 meter diameter.

The motives for introducing wind power at these off-grid sites: i) the prospect of improving battery life by reducing deep cycling that occurs at night and ii) the high cost and environmental risk of traditional diesel, which has to be brought in by helicopter. The increase in availability and decrease in costs of micro WECS that occurred over the past decade have enabled this transition.

Whisper 100 Technical Specifications

Rotor Diameter – 2.1 m
Weight - 21 kg
Start-Up Wind Speed - 3.4 m/s
Voltage - 12, 24, 36, 48 VDC
Rated Power - 900 watts at 12.5 m/s
Body - Cast aluminum
Blades - 3-Carbon reinforced fiberglass
Overspeed Protection - Patented side-furling
Survival Wind Speed - (55 m/s)

Technical specifications and picture from:
http://www.windenergy.com/products/whisper_100.htm

Figure 1: Picture and Technical Specifications of the Whisper 100 Wind Turbine

Site Characteristics

Broadly speaking, the prevailing conditions at these six sites are severe. Temperatures often fall well below -30 degrees Celsius and there are frequent strong and turbulent winds, in excess of 130 km/hour. Atmospheric icing, such as rime or glaze icing, is prevalent during the year, except for a few short summer months. At some of Bell-Aliant operated sites over two meters of rime icing can accumulate on the communication tower. These meteorological conditions create challenges for the effective operation of micro WECS. More site specific information can be found in Table 1.

Objective, Methods and Hypothesis

There have been mechanical failures at existing WECS sites leading to an increase in costly maintenance trips. The main objective of this study is to develop a quantitative tool for evaluating site suitability for WH100 installations. The study is confined to Labrador and evaluation based upon remotely measured turbine output which is assumed to reflect equipment integrity or uptime.

For future sites, Bell-Aliant would like to improve power production, increase the longevity of the turbines and reduce maintenance requirements. Researchers at Memorial University would like to give Bell-Aliant a rational basis for continuing or discontinuing their WECS program as well as give direction for new, industry relevant, research.

The authors collected and reduced data for a wide range of meteorological and geographic conditions for six sites with 14 month operation records available, then undertook a multi-variable regression analysis to isolate and quantify the influence or importance of any or all variables on the dependent variable. The primary dependent variable is the daily cumulative power output for each unit which is assumed, though visual confirmation was not possible, to reflect turbine status.

The hypothesis is that the regression will show that for specific ranges of prevailing meteorological conditions in combination with specific site characteristics, turbines will fail, often catastrophically, and therefore these conditions should be avoided or mitigated. Present practice is ad hoc and assessments for site suitability for WECS are highly subjective. Thus the intended result of this work is to improve reliability and confidence in decision making.

Data Assembly

From the existing records it was necessary to define a machine failure as production stoppage over several days that could not be explained by low winds, maintenance visits or diesel generator starts, which override the wind turbine power production. Daily production data was analyzed in conjunction with recorded maintenance history and anecdotal operation data from Bell-Aliant engineers. Some failures can be attributed to severe icing, causing a temporary stoppage of the rotor, while others were of a catastrophic nature, requiring the replacement of the entire unit. A common catastrophic failure occurs while furling during excessive wind speeds and gusts. The impact of the furling mechanism causes flexural failure of the nacelle, which leads to the rotor and generator falling ten meters to the ground.

Meteorological conditions with potential to influence turbine performance and integrity were identified as: temperature extremes, wind and gust intensity and precipitation. Not uncorrelated to this were site characteristics such as elevation, latitude, and proximity to large bodies of water.

Table 1: Site Specific Parameter and Average Failure Information

Parameter	Double Mer	Flower Bay	Mulligan
Average Failures	*16.6*	*10.7*	*8.6*
Elevation	717	415	357
Latitude	54.2167	55.8194	53.8617
Distance to Water	6	0	4
Distance to Ocean	135	15	160
Average Humidity	0.00342	0.00326	0.00352
Minimum Temperature	242.19	243.36	240.21
Average Wind Speed	17.13	15.93	13.54
Total Precipitation	3252.13	5374.24	7492.7
Average Low-Level Cloud	53.84	51.3	57.68
Atmospheric Pressure	97056	97946	994400
Turbulent Kinetic Energy	10.57	9.36	7
Regional Max Gust	134.5	152	117
Regional Min Temp	242.85	245.65	240.05
Regional Max Precip	30.45	22.1	38.8
Parameter	**Zoar**	**Sand Hill**	**Ossok**
Average Failures	*10.3*	*12.1*	*9*
Elevation	322	631	620
Latitude	56.1931	53.2392	53.4961
Distance to Water	0	6	4
Distance to Ocean	5	50	420
Average Humidity	0.00326	0.00374	0.00343
Minimum Temperature	242.81	244.5	239.04
Average Wind Speed	14.82	17.03	14.88
Total Precipitation	8043.74	6597.11	3697.06
Average Low-Level Cloud	53.24	52.84	57.16
Atmospheric Pressure	100013	97930	94114
Turbulent Kinetic Energy	8.6	10.76	7.73
Regional Max Gust	95	120	69.5
Regional Min Temp	242.55	245.45	235
Regional Max Precip	43.2	59.4	33.1

The control parameter values, presented in Table 1, were taken from geographical information, measured meteorological data and North American Regional Reanalysis (NARR) data [1]. Specific geographical parameters included elevation (m), latitude (degrees), proximity to the ocean (km) and degree of surrounding area covered by water (assigned a factor between one and ten based on the percentage of surrounding surface area covered by water). Measured meteorological data included minimum regional temperatures (K), maximum wind gust speeds (m/s) and maximum daily precipitation levels (mm). From the NARR data, selected parameters (*NARR acronym*, units) include specific humidity (*spfh10m*, kg/kg), temperature (*tmp10m*, K), wind (*ugrd10m* and *vgrd10m*, m/s), precipitation (*apcpsfc*, kg/m^2), low level cloud cover (*lcdclcl*, %), surface pressure (*pressfc*, Pa) and turbulent kinetic energy (*tkehlev1*, J/kg).

Data Simplification and Restrictions

The data spanned a 14 month period stretching from October 28th, 2006 to December 28th, 2007, which was selected for the consistency of both dependent and independent variables. Statistical summaries of the meteorological and NARR data were included in order to simplify the analysis and to compensate for various gaps in data. The regression analysis had to be performed using average failures per turbine per site, due to the innately high cross-correlation between dependent variables (i.e. for each individual site all of the independent parameters were the same, even though the frequency of each turbine's failure was not).

Not all of the client's turbines are included in the study due to assumed data collection errors and unattended long term failures.

Statistical Analysis

In this section the results of the statistical analysis, which was performed using Minitab 14, is presented. The correlations between average turbine failure rate and individual independent variables are given in Table 2 below. The Pearson Coefficient, r, is a common measure of correlation between two variables, with a value of 0 indicating no correlation and values of +1 and -1 indicating perfect positive and negative correlations respectively. The p-value displays the probability that the correlation value was due to chance and needs to be below 0.05 (5%) to be considered statistically significant.

Table 2 and Figure 2 below show the resulting individual correlations with average failure rate. As can be seen there are two strong and statistically significant correlations, wind speed and turbulent kinetic energy. These correlations are represented graphically in Figures 3 and 4.

Table 2: Independent Variable Correlations

Parameter	r	p
Latitude	-0.054	0.919
Elevation	0.661	0.153
Distance to Water	0.458	0.361
Distance to Ocean	-0.261	0.617
Humidity	0.087	0.870
Temperature	0.438	0.385
Wind Speed	**0.831**	**0.040**
Precipitation	-0.506	0.306
Low Level Cloud Cover	-0.444	0.377
Atmospheric Pressure	-0.438	0.385
Turbulent Kinetic Energy	**0.825**	**0.043**
Regional Max Gust Speed	0.480	0.335
Regional Max Precipitation	0.445	0.376
Regional Min Temperature	-0.051	0.924

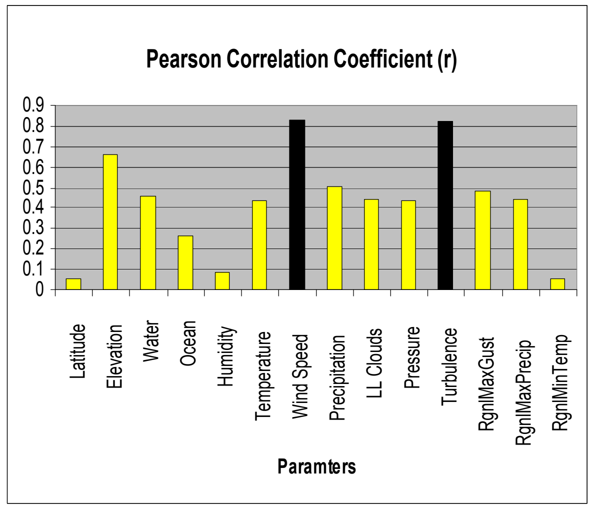

Figure 2: Correlation Strength of Independent Variables (black denotes statistically significant variables)

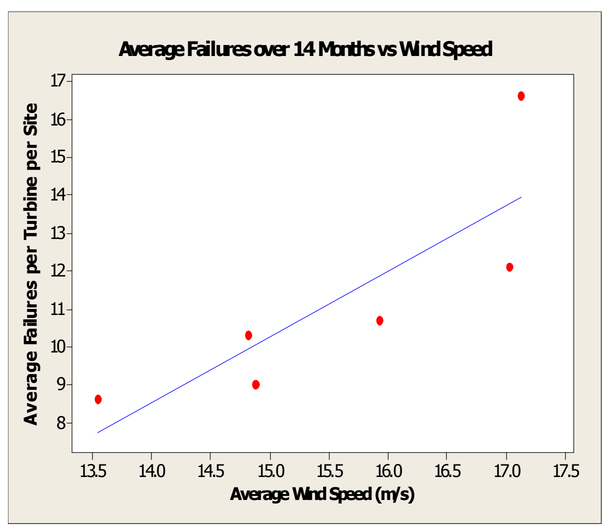

Figure 3: Scatterplot of average turbine failure versus average wind speed

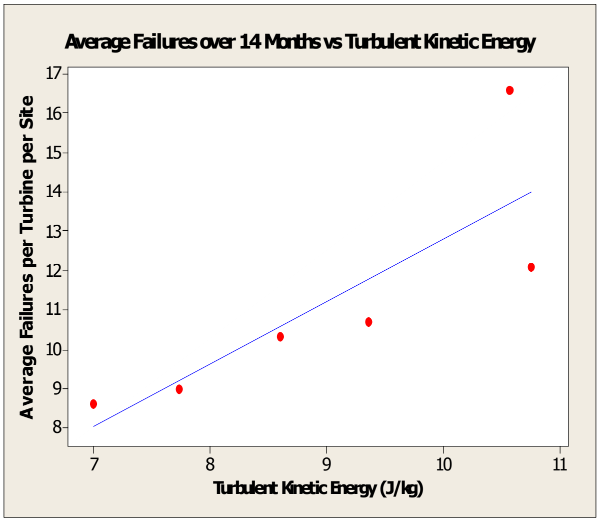

Figure 4: Scatterplot of average turbine failure versus turbulent kinetic energy

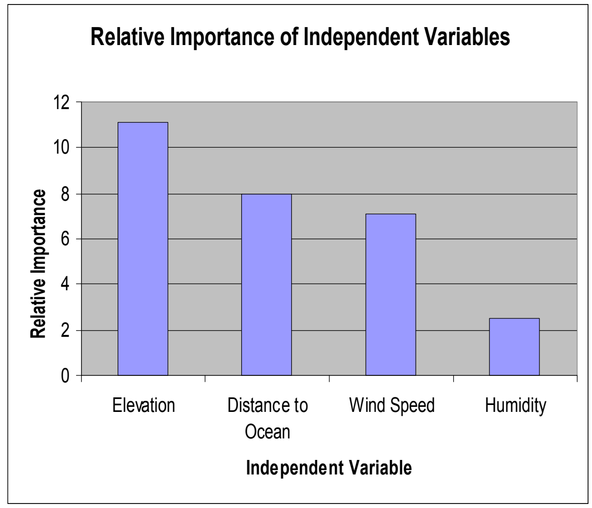

Figure 4 – Relative Importance of Independent Variables

As there are only six data points, corresponding to each of the six sites, the regression model is statistically restrained to four independent variables, similar to an analysis conducted previously by the authors [2]. However, due to the large array of dependent variables to work with, many models needed to be explored in order to determine which was the most suitable. Of all the regression models found only three were statistically significant, yet only one met the other main statistical criteria for validity, which are a high predictive R-squared value and relatively low cross-correlation between independent variables. The regression equation (a), with units previously listed, and standardized regression equation (b), with dimensionless units, are as follows. Standardized means the magnitude of each coefficient is proportional to the level of influence the parameter has on the dependent variable.

(a) $\#F = + 0.0560\ E_L - 0.0384\ D_0 - 3.95\ V_W - 10479\ H + 85.1$

(b) $\#F = + 11.1\ E_L - 7.98\ D_0 - 7.09\ V_W - 2.51\ H + 8.81$

Legend
$\#F$ = Number of Average Failures over 14 month period
E_L = Elevation (meters)
D_O = Distance to Ocean (kilometers)
V_W = Average Wind Speed (meters / second)
H = Specific Humidity (kilograms / kilograms)

The predictive R-squared and p-value for these equations are respectively 99.26% and 0.007.

Results and Discussion

Although this model fits each of the statistical requirements for validity it does not necessarily represent the real world. One can see from (a) and (b) that wind speed appears to have a negative effect on failure rate, in the sense that as wind speed increases, failure rate decreases. This result is counter-intuitive and contradicts the correlation of wind speed to turbine failure, which is strongly and significantly positive. To illustrate the point consider two extreme, although unlikely, situations. First of all, if there was a mean wind speed of zero there would be no turbine failures as defined above. However, if there was an extreme arbitrary mean wind speed of 500 km/hr almost nothing would be able to survive. As such, the authors deduce that the above model is not an accurate representation of factors contributing to turbine failure.

The authors believe that in order to produce a model that is valid both statistically and in reality, improved data collection processes need to be undertaken.

Data Collection Recommendations

In an ideal situation, a continuous record of site specific meteorological conditions, continuous visual records, and turbine specific data loggers would produce the most useful and relevant information for regression. More feasible data collection recommendations are outlined below.

The collection of site specific wind speed and direction throughout the year would be an asset. Current wind speed data is only an approximation of the actual conditions at the hill top sites. The wind speed independent variable (NARR data) is an approximate average covering a 32 kilometer square [2], based on meteorological model output. The maximum wind gust speed is taken directly from airports, typically within 50 kilometers of respective sites. As each of these sites sits on a hill top, one can assume that local topography plays an important role in mean wind speed and gust strength. A similar argument can be made for local temperature measurements.

A record of the location of each turbine within each site would also be useful. As turbines at any single site fail on different occasions, applying the same control parameters to each will always result in error within a statistical model. Locations relative to the edge of a steep incline and to prevailing wind direction as well as its position within the array are all potentially important considerations.

Similar meteorological stations and local situational data should also be collected and examined for sites under consideration for turbine implementation.

Detailed records of field modifications performed on specific turbines should be kept. Other maintenance records of each turbine repaired or replaced, including date, thorough photographic evidence and a note of possible weather conditions at the time of failure would provide further insight.

As alluded to earlier in the paper, consistent and reliable daily power production and diesel start data would help eliminate uncertainty in analysis. Clear and reliable daily power production data is critical to developing a useful model as it is used to determine the only dependent variable in the study: turbine failure.

Conclusions

While there are strong correlations indicating that higher wind speed and turbulent kinetic energy in the atmosphere have a detrimental effect to the operation of micro WECS at Bell-Aliant's Labrador sites, it does not adequately explain all of the turbine failures. A multi-variable regression analysis produced a model that, while statistically acceptable, was not reflective of reality.

Memorial University researchers have developed a list of parameters required for an effective and useful regression analysis. These include site specific meteorological data, individual turbine locations relative to the array and surrounding topography, detailed maintenance records and reliable, consistent power production data. The authors believe that the stated objective of developing a quantitative tool for evaluating site suitability will be achieved once relevant data has been captured.

References

[1] Mesinger, F. *et al* (2006) North American Regional Reanalysis. Bulletin of the American Meteorological Society, v 87, n 3, March, 2006, p 343-360.

[2] Roberts, J., Bruneau, S., White, G., Card, J. (2007) Performance Analysis of Off-Grid Micro WECS in Harsh Environments. Canadian Wind Energy Association 2007 National Conference proceedings, Quebec City, QC.