

Understanding and Quantifying the Uncertainty in Tower Extrapolation and AEP estimations using SODAR

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Summary

Some traditional approaches in wind resource assessment have not evolved to take into account the growing trend of larger wind turbines and higher hub heights. For example, it is common to measure the wind resource with a 60 m tower, extrapolate to hub height, and then use this extrapolated wind speed distribution to estimate the AEP (Annual Energy Production). The purpose of this study is to quantify the uncertainty of this approach to AEP estimation with the use of SODAR data.

Second Wind Triton® data from 111 sites were used. For each site, the 40 and 60 m data were first used as if they were anemometers. For every ten-minute interval, the 40 and 60 m wind speeds were extrapolated to 80 m using both the power and log law shear profiles. The extrapolated 80 m wind speed distributions were combined with a 1.5 MW power curve to estimate the AEP. Subsequently, the Triton data measured across the rotor was used to determine an equivalent hub height wind speed distribution and an AEP was calculated.

Using the power law profile to extrapolate led to an overestimation of energy production while the log law method did not yield a significant error. The uncertainty, when using either extrapolation method, was high at 4.2% and 3.0%.

When the measured 80 m wind speeds were used to determine the AEP and the wind shear across the rotor was not considered, the estimate was overpredicted. The mean error was 1.3% with an uncertainty of 1.4%.

Introduction and Background

When planning the construction of a wind farm, the first and, arguably, the most important determining factor of its feasibility is the wind resource at the site. In the early days of the wind industry, a standard approach was formed where meteorological (met) towers were installed, the wind speed at two or more heights were measured and extrapolation techniques were applied to determine the hub height wind speed. While this methodology may be sufficient for wind turbines with relatively small rotor diameters installed on short towers, it is becoming more and more apparent that, in the current state of the industry, this technique is inadequate.

Presently, the typical hub height of a wind turbine is 80 m or greater however, due to the high cost and complexity of tall tower installations, the standard height of a met tower is only 60 m. Additionally, the rotor radius of commercial wind turbines is at least 40 m, which means that the swept area of the rotor typically extends from 40 to 120 m (assuming an 80 m hub height). It is therefore not surprising that relying solely on 60 m met towers to conduct a wind resource assessment can lead to significant error and uncertainty. The main objective of this study is to assess the magnitude of this error and uncertainty at a range of sites with varying topographic and atmospheric conditions.

There are various techniques for extrapolating tower data up to hub height in order to estimate the annual energy production (AEP). For example, a constant wind shear exponent may be used to extrapolate or it may be assumed that the wind speed distribution fits a Rayleigh distribution [4]. In

this paper, the “traditional approach” used to estimate the AEP is thought to be the most robust of the various techniques and is defined as follows. Wind speed measurements are acquired at two heights (40 and 60 m) and, at every ten-minute interval, the wind speed is extrapolated up to 80 m. These extrapolated wind speeds are used to determine the 80 m probability density function (PDF) and the AEP is then estimated by multiplying the PDF and the power curve of a wind turbine.

In the “traditional approach”, there are two main sources of uncertainty. The first one is in the extrapolation of the 40 – 60 m data to a hub height of 80 m. There exist two standard methods for wind shear estimation and these include the power law and the log law shear profiles. The log law, shown in Equation 1, originated from boundary layer flow in fluid mechanics and atmospheric research [2]. Equation 2 shows the power law profile, which is based on empirical data and is used by many in the wind industry. The first objective of this study was to quantify the error and uncertainty in using either the power law or log law to extrapolate the wind speed from 40 – 60 m up to a hub height of 80 m.

Equation 1: Log Law Shear Profile

$$\text{Log Law: } U(z) = \frac{U^*}{k} \ln\left(\frac{z}{z_0}\right)$$

where : $U(z)$ = Wind speed at height, z
 U^* = Friction Velocity
 $k = 0.4$ (von Karmen's constant)
 z_0 = Surface Roughness Length

Equation 2: Power Law Shear Profile

$$\text{Power Law: } \frac{U(z)}{U(z_r)} = \left(\frac{z}{z_r}\right)^\alpha$$

where : $U(z)$ = Wind speed at height, z
 $U(z_r)$ = Wind speed at reference height, z_r
 α = Power Law exponent

The second source of uncertainty in the “traditional approach” is associated with the assumption that the hub height wind speed is representative of the wind speeds over the entire swept area of the rotor [1]. When the rotor diameters are relatively small, this assumption may be valid however as the rotor size of modern wind turbines continues to increase, it is becoming necessary to account for wind speed variations across the span of the rotor. Antoniou et al [1] have defined an equivalent hub height wind speed, which is the weighted average of the wind speed across the swept area of a wind turbine as shown in Equation 3. The second objective of this study was to quantify the error and uncertainty in the AEP estimation when wind speed variation across the rotor is not accounted for.

To achieve the objectives of this study, wind data at a wide variety of sites and with wind speeds measured across the rotor diameter (i.e. 40 to 120 m) was required and it was found that Second Wind's database of Triton Sonic Profiler data could provide this information.

Equation 3: Equivalent Hub Height Wind Speed

$$U_{eq} = \frac{\sum_{i=1}^N U_i A_i}{A}$$

where : U_{eq} = Equivalent Hub Height wind speed
 U_i = Wind Speed at midpoint of rotor section, i
 A_i = Area of rotor section, i
 A = Total rotor area

Description of Second Wind's Triton Sonic Profiler

Second Wind's Triton is a phased-array monostatic SODAR and was commercialized in 2008. Since then, more than 100 Tritons have been installed at many different types of locations around the world. To date, over 800,000 hours of Triton data have been collected. With this vast dataset, problem statements, such as the one posed in this study, can be addressed and meaningful results can be obtained.

Tritons measure wind speed and direction by emitting high frequency acoustic pulses into the atmosphere. The Triton beeps in three consecutive directions: A, B and C (Figure 1). All three beam directions are tilted 11.4° from vertical and are spaced 120° from one another. After each beep, a portion of the acoustic energy is backscattered due to turbulence and temperature gradients in the atmosphere. The Triton measures the return signal and the frequency content is analyzed at each station height. The change in frequency from the transmit frequency is directly proportional to the radial wind speed along the beam. At every ten-minute interval, the average radial wind speeds are combined to form the horizontal wind speed, vertical wind speed and wind direction.

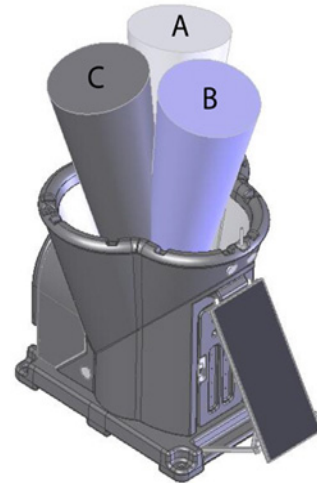


Figure 1: Triton Sonic Profiler

Since the commercialization of the Triton, several validation studies have been conducted to verify to reliability and accuracy of the Triton wind measurements. Second Wind and many its customers have carried out correlation studies and have achieved very good results. Additionally, two third-party groups have conducted validation studies of the Triton. The results of these independent studies showed excellent agreement between the Triton and tower measurements. Furthermore, it was found that the uncertainty in the Triton measurements were comparable to those found from conventional anemometry [3,5]. Triton data sets can therefore be used as "pseudo towers" to quantify the error and uncertainty of tower-based wind resource assessment techniques. In this paper, 111 Triton data sets are used to determine the uncertainty in tower extrapolation and AEP estimations.

Site and Data Set Descriptions

Since the commercial release of the Triton, more than 100 units have been installed worldwide. These sites include those with simple, flat terrain as well as numerous sites in hilly terrain and some on ridgelines. Additionally, many Tritons have been deployed in forested areas and others on coastlines. To better understand how tower extrapolation and AEP estimation uncertainty can vary in different conditions, sites with various types of topographic and atmospheric conditions were selected for this study.

A total of 111 Triton data sets were used. North American sites accounted for 81 of the locations, there were 16 European sites and 14 sites from Australia and New Zealand. All the locations were categorized based on their topography and were labeled as either one of the following four terrain types: 1) flat, 2) hilly/ridgeline, 3) forested or 4) coastal. The total number of flat sites was 44 while the hilly or ridgeline sites made up 48 of the locations. There were 17 sites located in forested areas and 2 of the sites were in coastal areas. The length of each Triton data set varied from as short as one month to as long as fifteen months. Table 1 and Figure 2 summarize the length of the 111 Triton data sets that were incorporated in this study.

Table 1: Length of Triton Data Sets

Length of Data Set (days)	Flat	Forested	Hilly / Ridgeline	Coastal
20	0	0	0	0
40	2	2	4	0
60	4	3	2	0
80	1	2	0	0
100	7	0	1	0
120	5	1	9	0
140	5	4	4	0
160	0	0	6	0
180	1	0	4	0
200	0	0	4	0
220	3	0	2	0
240	4	0	3	0
260	1	1	1	0
280	2	1	2	0
300	1	1	2	0
320	2	0	0	1
340	0	0	1	0
360	1	0	0	1
380	1	0	0	0
400	0	0	3	0
420	1	1	0	0
440	0	0	0	0
460	3	1	0	0
480	0	0	0	0
500	0	0	0	0
More	0	0	0	0

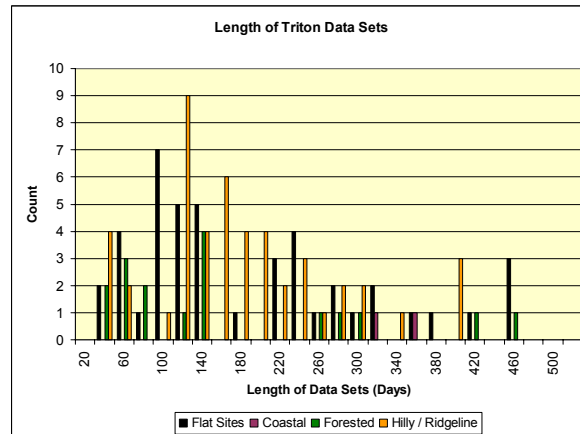


Figure 2: Length of Triton Data Sets Used in Study

Methodology of AEP Calculations

This section describes the methodology that was followed in calculating the AEP for every Triton data set. It should be noted that since, the majority of the data sets are less than one year in length, the AEP estimations are not reflective of the actual AEP at the various sites however they can be used, in a relative sense, to compare the results of the various techniques.

The methodology used in this study can be described in five steps, all of which are explained in more detail in this section:

- 1) Download and filter Triton data sets.
- 2) Determine extrapolated and equivalent 80 m wind speeds.
- 3) Compile wind speed data and determine the 80 m PDFs.
- 4) With the PDFs, calculate the AEP using a GE 1.5 xle power curve.
- 5) Compare the differences in AEP estimates.

1 - Triton Data Download and Filtering

Triton data from 111 sites were downloaded from Second Wind's SkyServe™ and were then filtered based on a minimum quality factor of 90% and a vertical wind speed range of +/- 1.5 m/s.

At every ten-minute interval, the Triton measures wind data at 10 heights from 40 to 200 m. Calculated along with each wind measurement is a wind quality factor. This factor varies from 0 – 100% and is a function of the signal-to-noise ratio (SNR) and the number of valid samples collected over the ten-minute interval. Implementing a minimum 90% quality factor effectively removes any invalid Triton measurements from the data set. The vertical wind speed filter eliminates any data that may have been affected by precipitation or other extraneous noise sources.

Additionally, the data sets were filtered to only include ten-minute averages when concurrent valid data was captured at all heights between 40 and 120 m. Since the equivalent hub height wind speed requires data across the span of the rotor, it was necessary to filter the data in such a way that the AEP estimates could be compared to one another.

2 - Hub-height Extrapolation and Equivalent Wind Speed Calculation

For each filtered data set, at every ten-minute average, three calculations were performed.

First, using the 40 and 60 m data, a power shear exponent was found (Figure 3) and an extrapolated 80 m wind speed was determined using the power law (Eq. 1). Secondly, also using the 40 and 60 m data, a surface roughness was calculated (Figure 4) and an extrapolated 80 m wind speed was found using the log law (Eq. 2). Third, using data across the rotor (i.e. 40 to 120 m), as shown in Figure 5, the equivalent 80 m wind speed was calculated (Eq. 3).

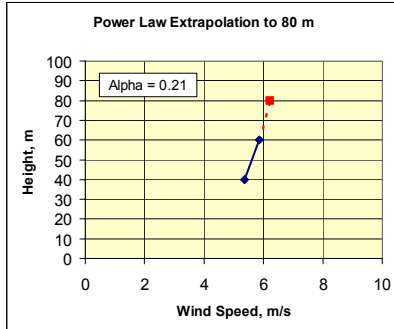


Figure 3: Power Law Extrapolation to 80 m

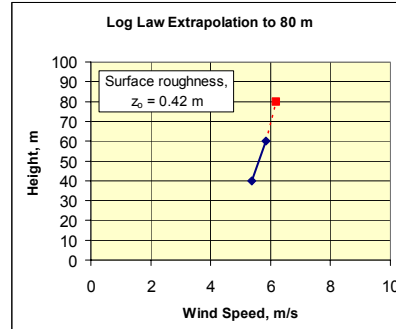


Figure 4: Log Law Extrapolation to 80 m

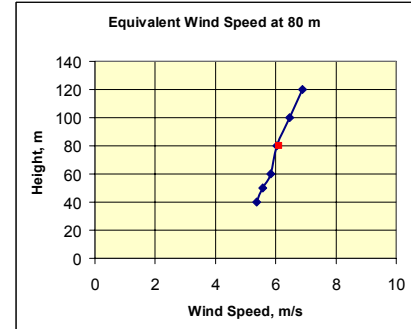


Figure 5: Equivalent Wind Speed at 80 m

3 - Determination of four 80 m Probability Density Functions (PDFs)

Next, for every Triton data set, a probability density function (PDF) was determined for each of the four 80 m wind speed distributions. Figure 6 presents an example of a PDF and the corresponding cumulative distribution function (CDF).

The PDF describes the probability that the measured wind speed will fall within a certain range (Equation 4). For example, in Figure 6, the probability that the wind speed will be between 6 - 7 m/s is equal to the area under the curve between 6 - 7 m/s and is approximately equal to 0.115.

The PDF is the slope of the cumulative distribution function (CDF). The CDF describes the probability that the wind speed is less than or equal to a given wind speed. For example, using the distribution shown in Figure 6, the probability that the wind speed is less than or equal to 8.5 m/s is approximately 0.52. The total area under the PDF is equal to 1.0 and the CDF reaches 1.0 at the upper wind speed limit.

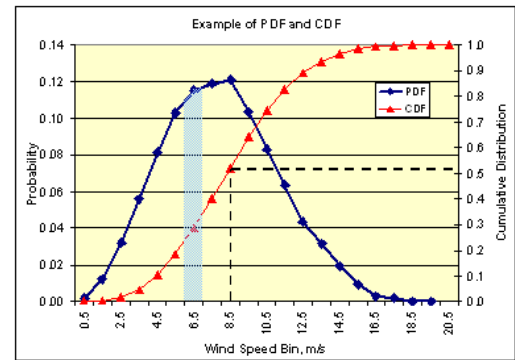


Figure 6: Example of PDF and CDF

Equation 4: Probability Density Function

$$P(U_a \leq U \leq U_b) = \int_{U_a}^{U_b} P(U) dU$$

Figure 7 - 9 show examples of the four PDFs calculated for a flat site, a ridgeline location and a forested area. The three plots show very subtle differences between the various PDFs however, as will be shown, the resulting difference in energy production can be significant.

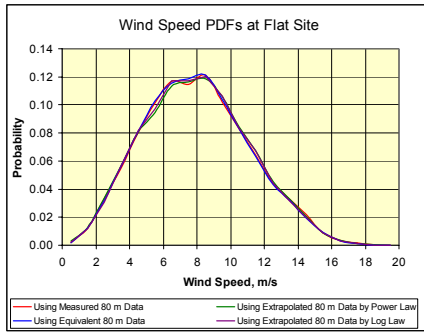


Figure 7: PDFs at Flat Site

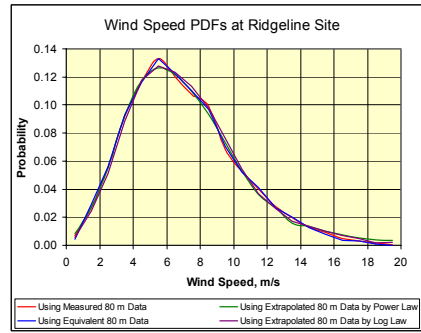


Figure 8: PDFs at Ridgeline Site

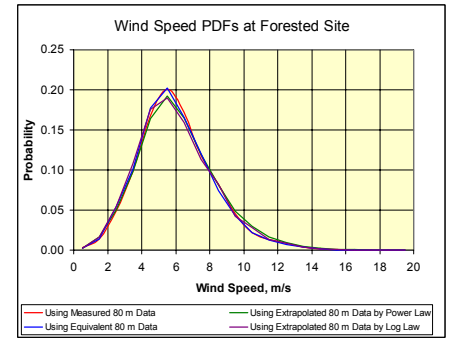


Figure 9: PDFs at Forested Site

4 - AEP Calculations Using a GE 1.5 xle Power Curve

For each Triton data set, using the four 80 m PDFs, the annual energy production (AEP) was calculated based on a GE 1.5 xle power curve (Figure 10). The AEP is estimated by summing, over a range of wind speeds, the product of the wind speed probability and the corresponding power output of the wind turbine and then by multiplying by 8760 hours to give the resulting expected annual energy production in kW-h (Equation 5).

Equation 5: AEP Estimation

$$AEP = \left[\sum_{j=1}^{N_B} P(U_j) \times Power(U_j) \right] \times 8760 \text{ h}$$

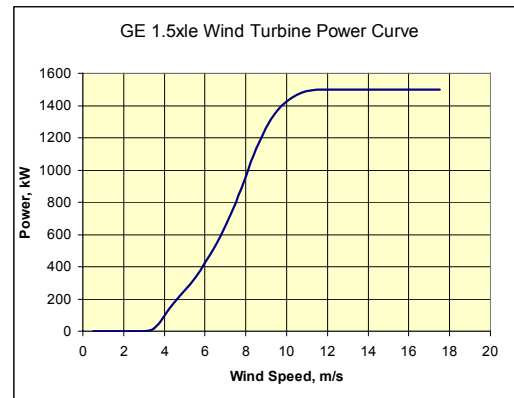


Figure 10: GE 1.5 xle Power Curve

5 - Comparison of AEP Estimates

Finally, the various AEP estimates were compared. First the difference between the AEP found using the measured 80 m data were compared to the AEP found by extrapolating from 40 – 60 m up to 80 m. Recall that two methods were used to extrapolate (power law and log law) and therefore two AEP estimates were generated based on extrapolation techniques. To determine the error and uncertainty associated with extrapolating to hub height, the percent difference in AEP estimates was calculated for each Triton data set as shown in Equation 6.

Equation 6: Percent Difference Between Extrapolated and Measured PDFs

$$\% \text{ Difference in AEP} = \frac{(AEP_{EXTRAPOLATED} - AEP_{MEASURED})}{AEP_{MEASURED}} \times 100$$

The difference was then compared between the energy estimate found using the measured 80 m data and the AEP calculated using the equivalent 80 m wind speed distributions. The difference between these two energy estimates represents the error and uncertainty in the AEP when neglecting to account for wind speed variations across the rotor. Equation 7 shows the percent difference calculated between the two AEP estimates.

Equation 7: Percent Difference Between Measured and Equivalent PDFs

$$\% \text{ Difference in AEP} = \frac{(AEP_{MEASURED} - AEP_{EQUIVALENT})}{AEP_{EQUIVALENT}} \times 100$$

Results of AEP Comparison

The five steps outlined in the previous section were carried out for each of the 111 Triton data sets and the resulting AEP comparisons are presented in this section.

ALL SITES

Figures 11 – 13 show the resulting AEP comparisons from all 111 sites. First, in Figures 11 and 12, the percent difference between the AEP found using the measured 80 m data is compared to the AEP estimates calculated from the extrapolated data sets. The results show that when using the power law to extrapolate to 80 m, the AEP estimate will, on average, be overestimated by 1.9% whereas the log law extrapolation did not lead to a significant error. The standard deviation, or uncertainty, of the AEP estimate when using the power law profile was 4.2% and the log law extrapolation led to an uncertainty of 3.0%.

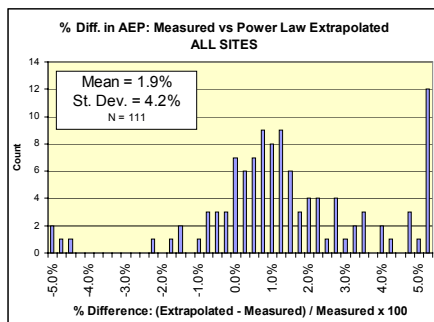


Figure 11: AEP % Diff: Measured vs. Power Law Extrapolated: ALL SITES

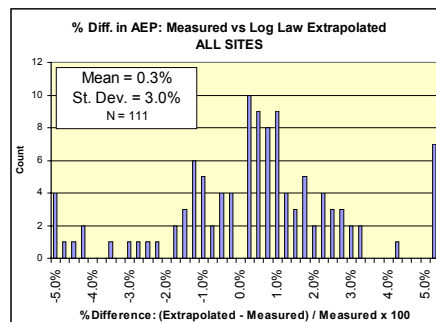


Figure 12: AEP % Diff: Measured vs. Log Law Extrapolated: ALL SITES

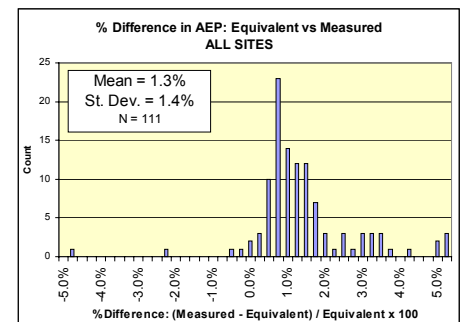


Figure 13: AEP % Diff: Equivalent vs. Measured: ALL SITES

Figure 14 shows the percent difference in AEP estimation when using the measured 80 m wind speed distributions as opposed to the equivalent 80 m wind speeds at all sites.

The mean percent difference was 1.3%, which implies that neglecting to account for wind speed variations across the rotor will lead to a 1.3% overestimation in the AEP. The uncertainty of this distribution was 1.4%.

In the next few sections, the same type of histograms are shown however the sites are divided up according to their terrain classification. First, AEP comparisons are shown for the 44 flat sites used in the study. Then, the results found from the 48 hilly and ridgeline sites are presented. Finally, the AEPs are compared at the 17 forested locations.

FLAT SITES

Figures 14 – 16 show the results of the AEP comparisons made for the 44 flat sites. The mean difference in the AEP estimation when using extrapolated 80 m data was small. When the power law profile was used, the mean error was 0.4% whereas the log law profile extrapolation led to a mean error of -0.6%. The uncertainty for both methods of extrapolation was approximately 2%.

Figure 16 shows the percent difference in AEP estimations using the equivalent wind speed distributions as opposed to the measured hub height wind speeds at the flat sites. It was found that, when the wind speed variation across the rotor was not considered, the mean error in AEP estimation was 1.0% and the uncertainty was 0.7%.

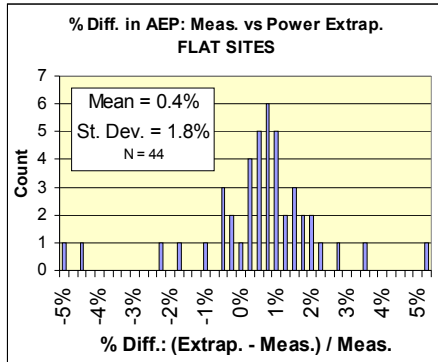


Figure 14: AEP % Diff: Measured vs. Power Law Extrapolated: FLAT SITES

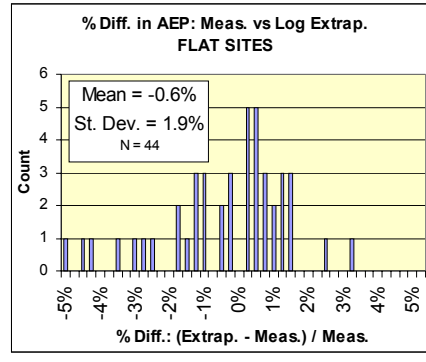


Figure 15: AEP % Diff: Measured vs. Log Law Extrapolated: FLAT SITES

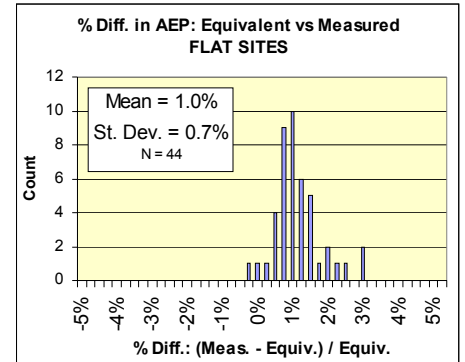


Figure 16: AEP % Diff: Equivalent vs. Measured: FLAT SITES

HILLY / RIDGELINE SITES

The results found from the hilly and ridgeline sites are presented in Figures 17– 19 below. There was much more variation in AEP estimations when extrapolating at these more complex sites. A total of 48 hilly / ridgeline sites were included in this study and it was found that, when using the power law to extrapolate to a hub height of 80 m, the mean error was 1.9% and the uncertainty was 3.6%. When the log law profile was used for extrapolation, the mean error and uncertainty was found to 1.5% and 2.5%, respectively. These results highlight the large range of error one can expect in the AEP estimation when relying on 60 m met tower extrapolations at complex sites.

The percent difference in AEP estimations when using either the measured or equivalent 80 m wind speed distributions are shown in Figure 19. The mean error was 1.0% and then uncertainty was 1.0%. In other words, similar to the results found for the flat sites, if the wind speed variation across the rotor is not considered, the AEP estimation will be, on average, 1% high.

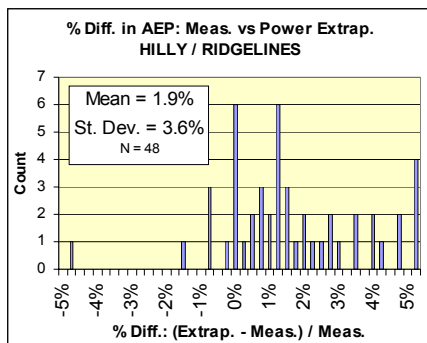


Figure 17: AEP % Diff: Measured vs. Power Law Extrapolated: HILLY / RIDGELINE SITES

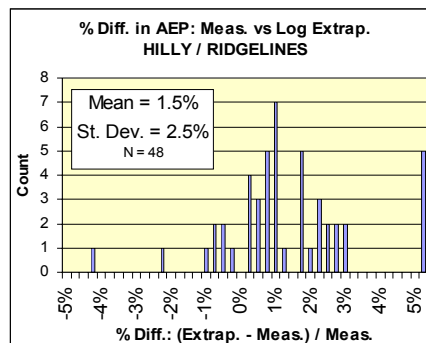


Figure 18: AEP % Diff: Measured vs. Log Law Extrapolated: HILLY / RIDGELINE SITES

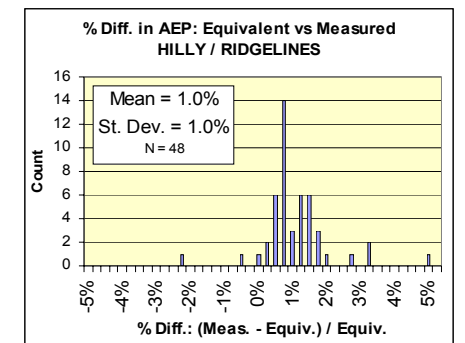


Figure 19: AEP % Diff: Equivalent vs. Measured: HILLY / RIDGELINE SITES

FORESTED SITES

Finally, the AEP estimates found at the forested sites are compared. Figures 20 - 22 show the percent difference in the AEP estimates calculated at the 17 forested locations. For these sites, the power law extrapolation lead to a very significant overestimation in the energy production with a mean error of 5.8% and a large uncertainty of 7.0%. The log law extrapolation did not produce a significant error however the standard deviation was quite high at 5.0%. These results demonstrate the shortcomings of tower extrapolation at forested sites. With the power law, a consistent overestimation was found and, for both the power and log law profiles, the uncertainty in the AEP estimations was large.

The percent difference in the AEP estimates using the measured and equivalent 80 m wind speeds for the 17 forested sites is shown in Figure 22. The mean error was found to be 2.9% and the uncertainty was 2.4%. Similar to the results found at the flat and hilly / ridgeline sites, when the wind speed variability across the rotor is neglected, the AEP will be overestimated. For the forested sites, a higher uncertainty was found than at the flat and hilly / ridgeline sites (2.4% vs. 1.0%).

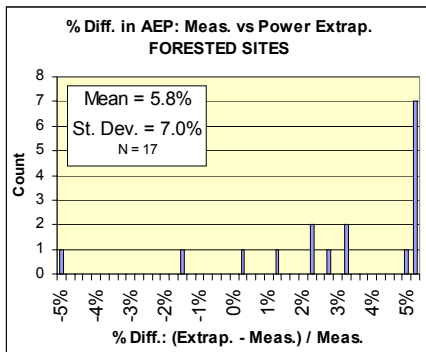


Figure 20: AEP % Diff: Measured vs. Power Law Extrapolated: FORESTED

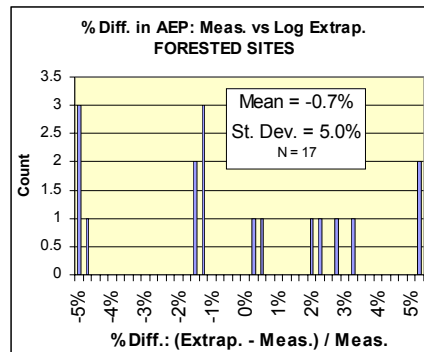


Figure 21: AEP % Diff: Measured vs. Log Law Extrapolated: FORESTED

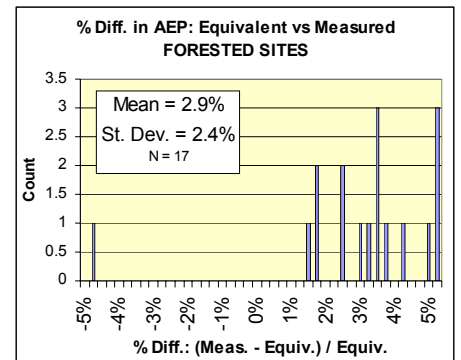


Figure 22: AEP % Diff: Equivalent vs. Measured: FORESTED

Summary of Results

The results of all the energy production comparisons are shown in Table 2. It was found that, when the power law profile was used to extrapolate from 40 – 60 m to a hub height of 80 m, the AEP was overestimated, particularly at forested sites. Overall, the power law profile extrapolation method produced an error of 1.9% with an uncertainty of 4.2%. The log law extrapolation method did not lead to a consistent error however the uncertainty in the AEP estimation was quite high. For all the sites, the mean error found when using the log law profile was 0.3% and the uncertainty was 3.0%.

When comparing the energy production estimates calculated using the measured and equivalent 80 m wind speed distributions, it was found that, if the wind speed variation across the blades of the turbine are not accounted for, the AEP will be overestimated. The mean error was measured at 1.3% with an uncertainty of 1.4%.

Table 2: Summary of all AEP Comparisons

	Measured vs. Power Extrapolated		Measured vs. Log Extrapolated		Equivalent vs. Measured	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
All Sites	1.9%	4.2%	0.3%	3.0%	1.3%	1.4%
Flat Sites	0.4%	1.8%	-0.6%	1.9%	1.0%	0.7%
Forested Sites	5.8%	7.0%	-0.7%	5.0%	2.9%	2.4%
Hilly / Ridgelines	1.9%	3.6%	1.5%	2.5%	1.0%	1.0%

Conclusions

In this study, a total of 111 Triton data sets were used to determine the error and uncertainty in AEP estimations when using a traditional approach of extrapolating 40 – 60 m data up to a hub height of 80 m. In this approach, there are two sources of uncertainty. The first is due to wind speed extrapolation and the second is associated with wind speed variations across the span of the rotor, which can affect the energy production.

Each data set was used to estimate the annual energy production in four different ways. First, using the power law profile, wind speeds were extrapolated from 40 – 60 m to 80 m and the AEP was calculated based on this wind speed distribution. Then, with the log law profile, the 80 m wind speeds were extrapolated from 40 – 60 m and the AEP was estimated. Third, the measured 80 m wind speeds were used to determine the AEP. Finally, the equivalent 80 m wind speeds were found by taking a weighted average over the diameter of the rotor and the AEP was estimated. These four variations of AEP calculations were compared at all 111 sites and the following observations were made.

- 1) Overall, using the power law profile to extrapolate led to an overestimation of energy production. The log law extrapolation method did not demonstrate a bias.
- 2) The uncertainty in the AEP calculation, when using either the power law and log law profiles, was quite high at 4.2% and 3.0%, respectively.
- 3) At flat sites, when extrapolation methods were used, the uncertainty in the energy estimate was found to be ~2%.
- 4) At forested sites, the power law largely overestimated the AEP with a mean error of 5.8%. The log law extrapolation did not yield a bias however the uncertainty in the AEP estimation was large at 5.0%.
- 5) At hilly sites and on ridgelines, both the power and log law yielded energy estimates that were, on average, 1.9% and 1.5% high and with fairly high uncertainties of 3.6% and 2.5%, respectively.
- 6) Overall, when only the 80 m wind speed was used to determine the AEP (i.e. not the equivalent 80 m wind speed), the calculation led to an overprediction. The mean error was found to be 1.3% with an uncertainty of 1.4%.
- 7) At flat and hilly sites, using the measured 80 m wind speed data led to a 1.0% overestimation of the AEP with an uncertainty of 0.7% and 1.0%, respectively.
- 8) At forested sites, if the equivalent 80 m wind speeds were not used in the AEP calculation, the mean error was 2.9% and the uncertainty was found to be 2.4%.

Next Steps

To further understand and quantify the uncertainty in AEP estimations, several variations to this research could be undertaken. For example, it would be interesting to use different wind turbine power curves in the AEP calculations. Also, extrapolating to higher hub heights would yield different results. Using larger rotor diameters would most likely increase the difference in the AEP

between the measured and equivalent hub height wind speed distributions. Finally, including more sites and longer data sets would verify the results of this study.

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