# APTC's Tok 0051 Met Tower Wind Resource Report

APTC photo

May 7, 2012

Douglas Vaught, P.E.
V3 Energy, LLC
Eagle River, Alaska

V3 Energy LLC
Eagle River, Alaska 907.350.5047

## Summary

The wind resource measured at the Tok 0051 met tower site is good with measured wind power class 4 by measurement of wind power density and wind speed. The site experiences very low wind shear which is ideal for constructability as lower hub heights are possible. On the other hand, Venturi effect speed up of wind occurs at lower elevations at the met tower site, which yielded higher calculated extreme wind probability at 20 meter level than the 40 meter level. Site turbulence is moderately low and less than one might be expect in a mountain environment. Site temperatures are typical for inland Alaska with cool summers and cold winters, although lowest recorded temperatures are not as cold as experienced in the nearby community of Tok.

## Met tower data synopsis

| | |
|---|---|
| Data dates | September 15, 2009 to April 3, 2012 (31 months); status: operational |
| Wind power class | Class 4 (good) |
| Wind power density mean, 50 m | 410 $W/m^2$ |
| Wind speed mean, 50 m | 6.88 m/s (15.3 mph) |
| Max. 10-min wind speed | 31.5 m/s |
| Maximum 2-sec. wind gust | 42.4 m/s (94.5mph), February 2011 |
| Weibull distribution parameters | k = 1.54, c = 7.18 m/s |
| Wind shear power law exponent | 0.049 (very low) |
| Roughness class | 0.00 (description: smooth) |
| IEC 61400-1, 3rd ed. classification | Class II-C at 40 meters; Class I-C at 20 meters |
| Turbulence intensity, mean (at 40 m) | 0.100 (at 15 m/s) |
| Calm wind frequency (at 50 m) | 32% (< 4 m/s) (31 mo. measurement period) |

## Test Site Location

A 50 meter NRG Systems, Inc. tubular-type meteorological (met) tower was installed at the Tok 0051 met tower site in September 2009. The location is on a mountain ridge approximately 19 km (12 miles) straight-line distance southwest of Tok, Alaska and 9.7 km (6.0 miles) northwest of Alaska Highway 1 that connects Tok to Anchorage and the Kenai Peninsula. Alaska Energy Authority's high resolution wind map predicts Class 5 (of 7 named wind classes) at this location (refer to wind map below).

### Site information

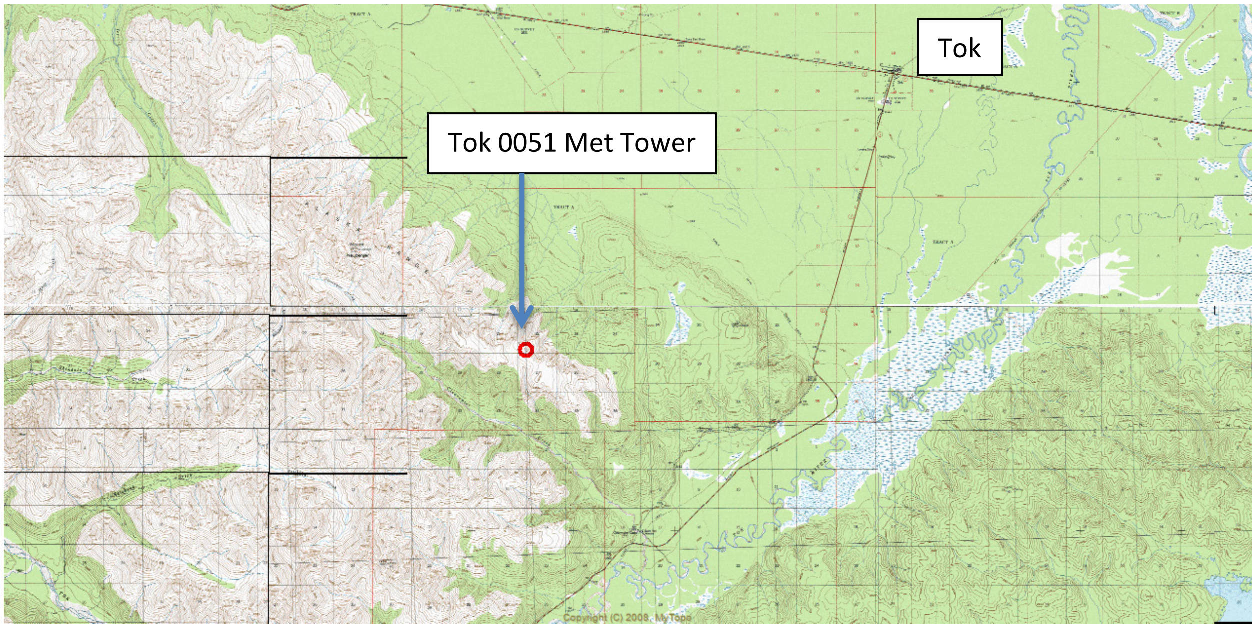
| | |
|---|---|
| Site number | 0051 |
| Latitude/longitude | N 63° 14.008" W 143° 17.485" |
| Time offset | -9 hours from GMT (Yukon/Alaska time zone) |
| Site elevation | 1,503 meters (4,930 ft.) |
| Datalogger type | NRG SymphoniePlus, 10 minute time step |
| Tower type | Tubular XHD tall tower, 50 meter height |

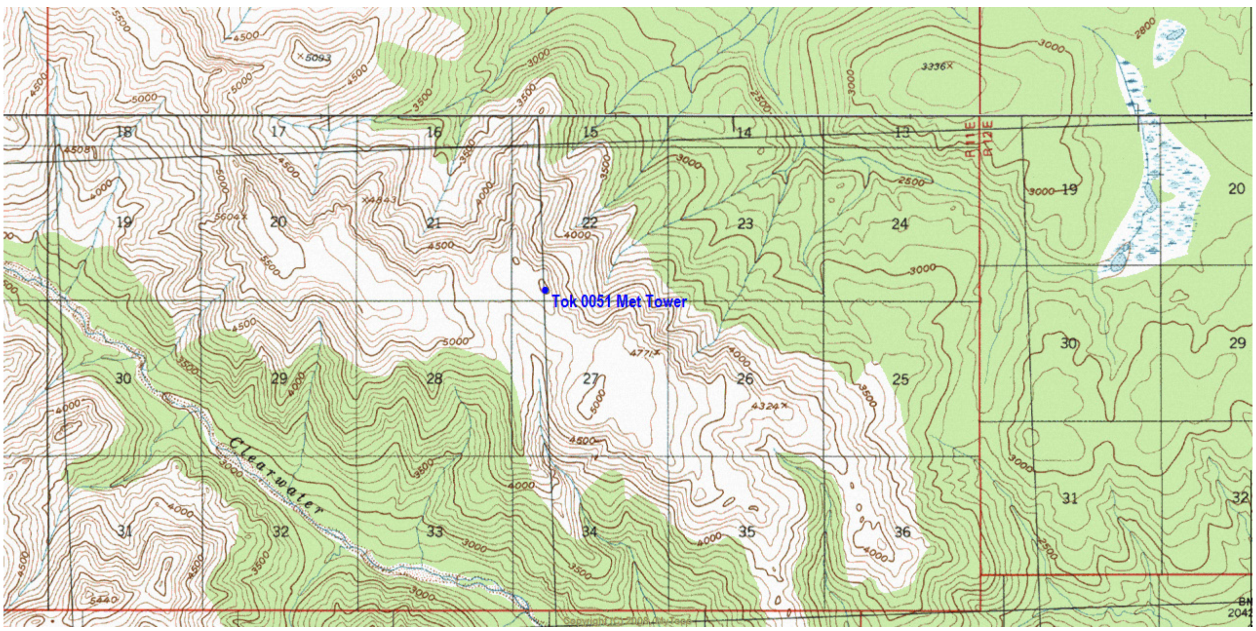
## Tower sensor information

| Channel | Sensor type | Serial Number | Height (m) | Multiplier | Offset | Orientation |
|---|---|---|---|---|---|---|
| 1 | NRG #40C anemometer | 111409sw | 50.3 | 0.760 | 0.34 | SW |
| 2 | NRG #40C anemometer | 112119se | 49.7 | 0.759 | 0.35 | NE |
| 3 | NRG #40C anemometer | 112187sw | 39.6 | 0.757 | 0.36 | SW |
| 7 | NRG #200P wind vane | n/a | 50.7 | 0.351 | 146 | NW |
| 8 | NRG #200P wind vane | n/a | 43.6 | 0.351 | 146 | NW |
| 9 | NRG #110S Temp C | n/a | 2 | 0.136 | -86.3 | |
| 10 | iPack Voltmeter | n/a | 2 | 0.021 | 0 | |
| 13 | NRG #40C anemometer | 112198se | 40.1 | 0.761 | 0.35 | NE |
| 14 | NRG #40C anemometer | 112183sw | 32 | 0.760 | 0.34 | SW |
| 15 | NRG #40C anemometer | 111424sw | 24.3 | 0.757 | 0.37 | N |

### *Google Earth image, Tok and Tok 0051 met tower site*

### *Topographic maps*




## Data Quality Control

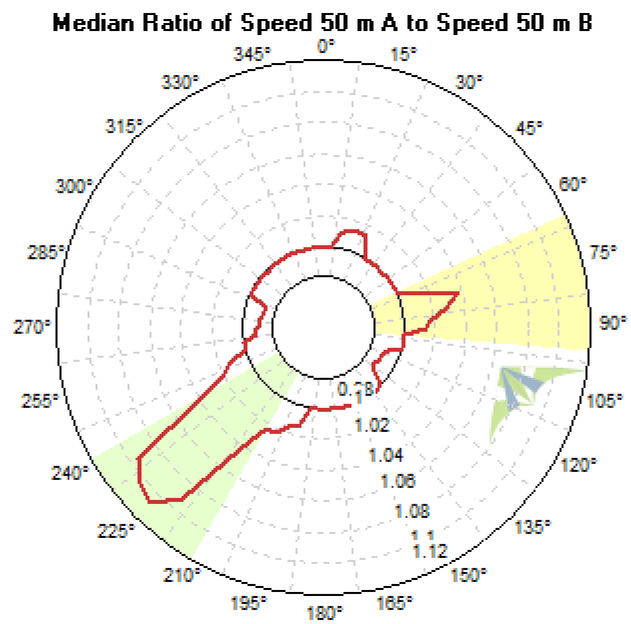
Data was filtered to remove presumed icing events that yield false zero wind speed data and non-variant wind direction data. Data that met criteria listed below were automatically filtered. In addition, data was manually filtered for obvious icing that the automatic filter didn't flag, invalid or low quality data for situations such as logger initialization and other situations, and tower shadowing effects (this latter filtering is only possible with paired anemometers, in other words, two anemometers at or near the same height on the met tower).

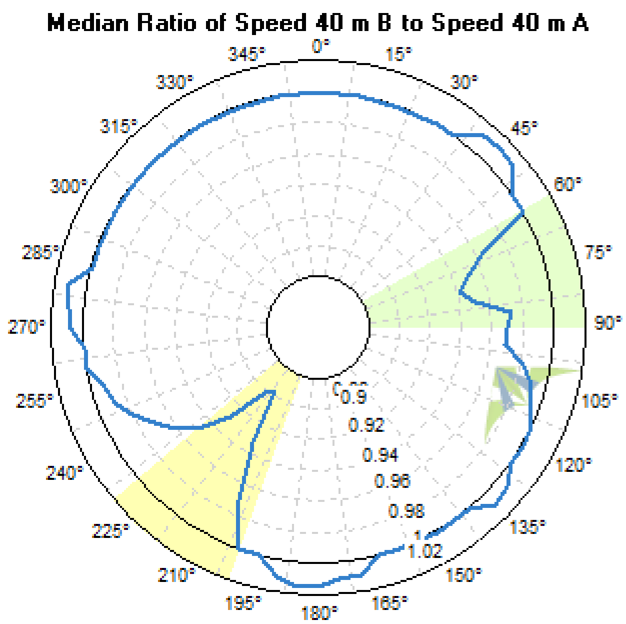
- Anemometer icing – data filtered if temperature < 1°C, speed SD = 0, and speed changes < 0.25 m/s for minimum 2 hours
- Vane icing – data filtered if temperature < 1°C and vane SD = 0 for minimum of 2 hours
- Tower shading of paired anemometers – refer to graphic below

In addition and for unknown reasons, both 50 meter anemometers have exhibited odd behavior, especially the 50 meter A anemometer on channel 1, with periods of zero or substantially reduced output, but then followed by apparent recovery and normal operation. Because the 50 m A anemometer was more problematic, a filtering algorithm was run to remove 50 m A data when the absolute difference between it and 50 m B data was greater than 1 m/s for one or more time steps.

Note also that the icing filter flagged much more data from the 50 m A anemometer than the others. This is not indicative of enhanced icing conditions at that sensor; rather its performance issues in general.

### *Tower shading filter plots*



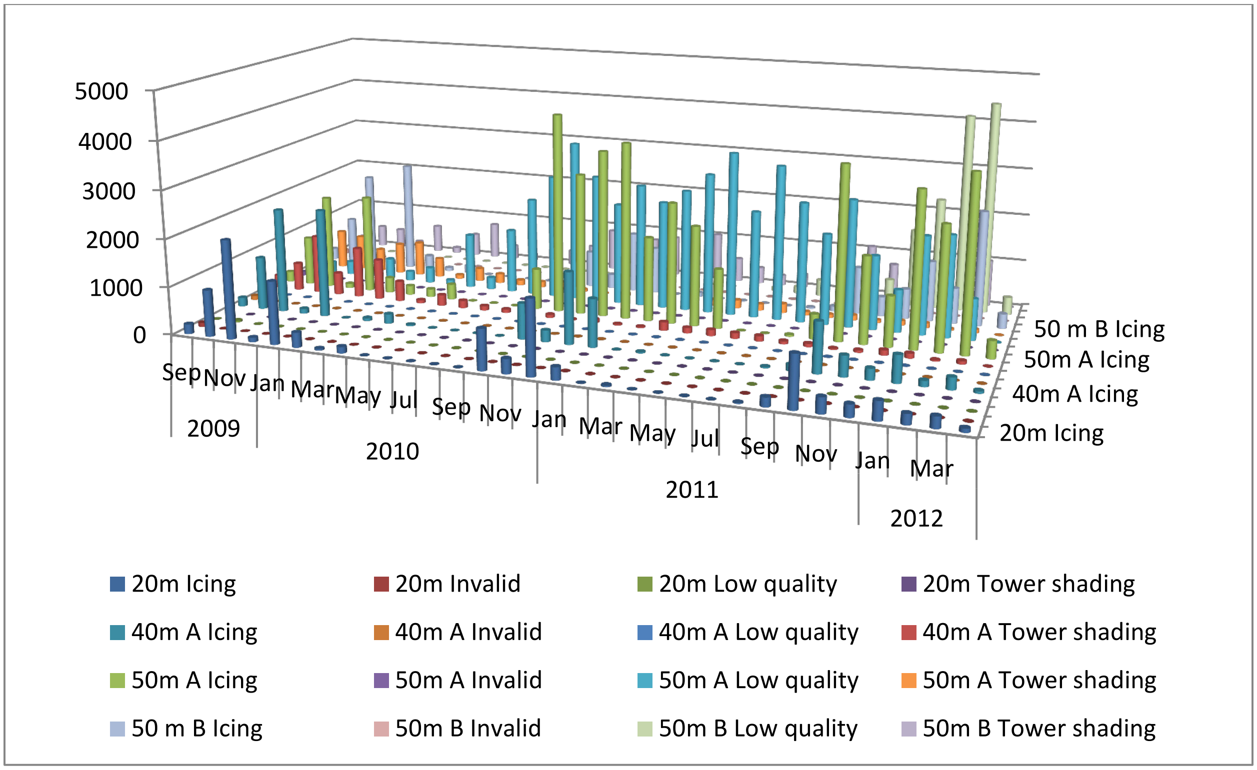




### *Sensor data recovery table*

| Label | Possible Records | Valid Records | Recovery Rate (%) | Unflagged data | Icing | Invalid | Low quality | Tower shading |
|---|---|---|---|---|---|---|---|---|
| Speed 50 m A | 134,148 | 59,437 | 44.3 | 59,437 | 46,528 | 82 | 51,906 | 6,754 |
| Speed 50 m B | 134,148 | 92,762 | 69.2 | 92,762 | 16,679 | 82 | 14,551 | 18,011 |
| Speed 40 m A | 134,148 | 116,196 | 86.6 | 116,196 | 12,546 | 82 | 0 | 7,024 |
| Speed 40 m B | 134,148 | 105,934 | 79.0 | 105,934 | 9,534 | 82 | 0 | 19,843 |
| Speed 30 m | 134,148 | 121,401 | 90.5 | 121,401 | 12,566 | 82 | 33 | 0 |
| Speed 20 m | 134,148 | 123,115 | 91.8 | 123,115 | 10,854 | 82 | 33 | 0 |
| Direction 50 m | 134,148 | 127,799 | 95.3 | 127,799 | 6,193 | 81 | 0 | 0 |
| Direction 40 m | 134,148 | 126,098 | 94.0 | 126,098 | 7,894 | 81 | 0 | 0 |

| Label | Possible Records | Valid Records | Recovery Rate (%) | Unflagged data | Icing | Invalid | Low quality | Tower shading |
|---|---|---|---|---|---|---|---|---|
| Temperature | 134,148 | 133,904 | 99.8 | 133,904 | 0 | 88 | 0 | 0 |
| Voltmeter | 134,148 | 133,904 | 99.8 | 133,904 | 0 | 88 | 0 | 0 |

### *Data recovery graph, problems with 50 meter anemometers*

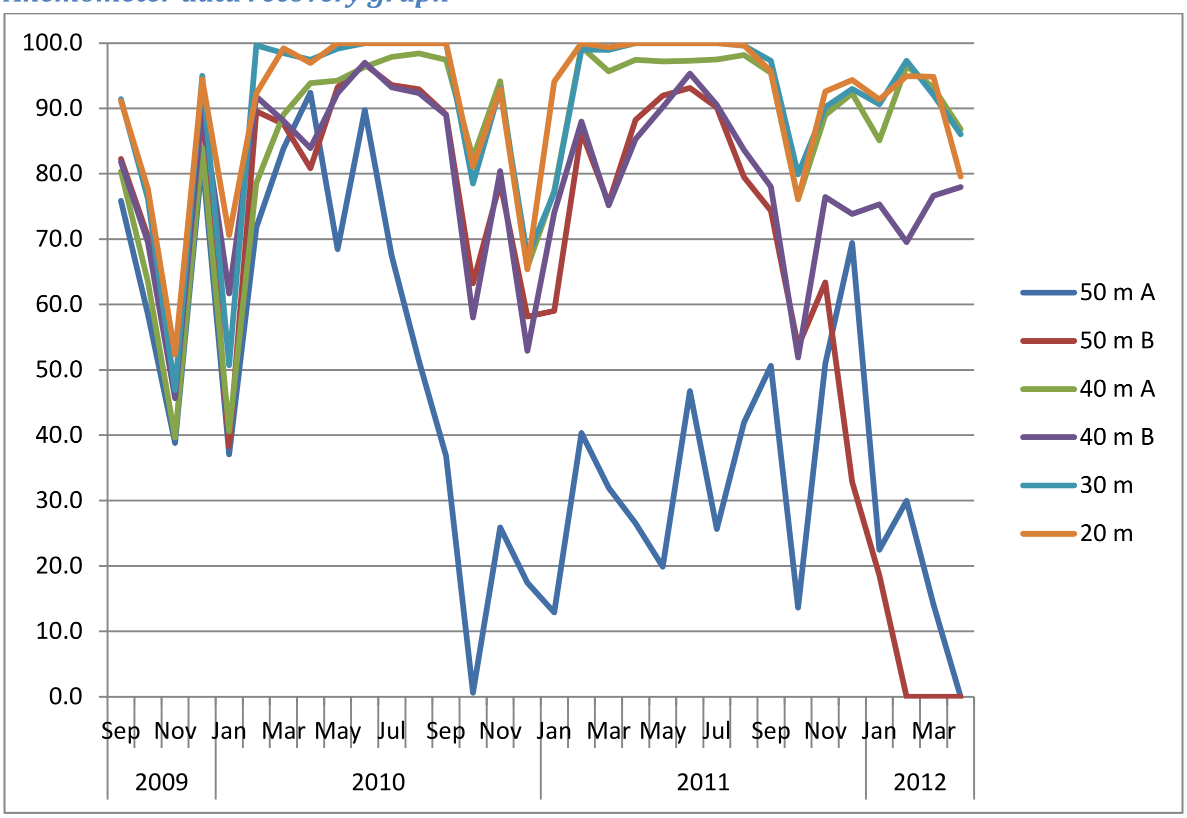



### *Sensor data recovery percentage by month*

| | | Anemometers | | | | | | Vanes | |
|---|---|---|---|---|---|---|---|---|---|
| Year | Month | 50 m A | 50 m B | 40 m A | 40 m B | 30 m | 20 m | 50 m | 40 m |
| | Sep | 75.9 | 82.3 | 80.3 | 81.8 | 91.4 | 91.1 | 90.8 | 89.8 |
| | Oct | 58.5 | 70.4 | 63.6 | 69.6 | 76.2 | 77.7 | 73.2 | 80.9 |
| | Nov | 38.8 | 46.2 | 39.7 | 45.7 | 46.9 | 52.3 | 89.1 | 76.0 |
| 2009 | Dec | 82.3 | 90.4 | 84.0 | 89.9 | 95.0 | 94.5 | 93.9 | 92.8 |
| | Jan | 37.1 | 38.3 | 40.6 | 61.7 | 50.7 | 70.6 | 89.5 | 87.6 |
| | Feb | 71.8 | 89.6 | 78.6 | 91.8 | 99.6 | 92.3 | 95.8 | 95.2 |
| | Mar | 83.9 | 87.6 | 89.1 | 88.1 | 98.5 | 99.2 | 100.0 | 99.7 |
| | Apr | 92.4 | 80.8 | 93.8 | 83.9 | 97.4 | 96.9 | 96.6 | 97.8 |
| | May | 68.5 | 93.2 | 94.2 | 92.4 | 99.2 | 100.0 | 96.3 | 93.0 |
| | Jun | 89.8 | 96.8 | 96.3 | 97.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| | Jul | 67.4 | 93.6 | 97.9 | 93.2 | 100.0 | 100.0 | 100.0 | 100.0 |
| | Aug | 51.4 | 92.9 | 98.4 | 92.3 | 100.0 | 100.0 | 100.0 | 100.0 |
| | Sep | 36.8 | 89.1 | 97.4 | 89.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 2010 | Oct | 0.6 | 63.2 | 82.4 | 58.0 | 78.5 | 81.1 | 85.2 | 80.1 |

| | | Anemometers | | | | | | Vanes | |
|---|---|---|---|---|---|---|---|---|---|
| Year | Month | 50 m A | 50 m B | 40 m A | 40 m B | 30 m | 20 m | 50 m | 40 m |
| | Nov | 25.9 | 78.7 | 94.1 | 80.4 | 93.1 | 92.9 | 93.4 | 90.0 |
| | Dec | 17.5 | 58.1 | 65.7 | 52.9 | 67.3 | 65.4 | 85.3 | 86.7 |
| | Jan | 12.9 | 59.0 | 77.4 | 74.1 | 77.1 | 94.1 | 95.4 | 88.1 |
| | Feb | 40.4 | 86.4 | 99.4 | 88.0 | 99.0 | 100.0 | 100.0 | 100.0 |
| | Mar | 32.0 | 75.5 | 95.7 | 75.2 | 99.0 | 99.3 | 99.7 | 99.4 |
| | Apr | 26.6 | 88.2 | 97.4 | 85.3 | 100.0 | 100.0 | 100.0 | 100.0 |
| | May | 19.9 | 92.0 | 97.2 | 90.2 | 100.0 | 100.0 | 100.0 | 98.3 |
| | Jun | 46.8 | 93.2 | 97.3 | 95.4 | 100.0 | 100.0 | 100.0 | 100.0 |
| | Jul | 25.7 | 90.1 | 97.5 | 90.6 | 100.0 | 100.0 | 100.0 | 100.0 |
| | Aug | 42.0 | 79.5 | 98.2 | 83.7 | 99.6 | 99.6 | 99.6 | 99.5 |
| | Sep | 50.6 | 74.4 | 95.4 | 78.0 | 97.3 | 95.7 | 93.2 | 96.5 |
| | Oct | 13.6 | 53.6 | 76.1 | 51.9 | 79.9 | 76.1 | 89.1 | 83.2 |
| | Nov | 51.0 | 63.4 | 89.0 | 76.4 | 90.2 | 92.6 | 93.8 | 94.2 |
| 2011 | Dec | 69.4 | 32.8 | 92.3 | 73.8 | 93.0 | 94.4 | 94.7 | 91.3 |
| | Jan | 22.5 | 18.6 | 85.1 | 75.3 | 90.6 | 91.4 | 100.0 | 99.5 |
| | Feb | 30.0 | 0.0 | 96.5 | 69.6 | 97.3 | 95.0 | 97.4 | 96.3 |
| | Mar | 14.1 | 0.0 | 93.2 | 76.7 | 92.0 | 94.8 | 99.7 | 98.4 |
| 2012 | Apr | 0.0 | 0.0 | 86.8 | 78.0 | 86.0 | 79.6 | 100.0 | 76.6 |
| All data | | 44.3 | 69.1 | 86.6 | 79.0 | 90.5 | 91.8 | 95.3 | 94.0 |

### *Anemometer data recovery graph*

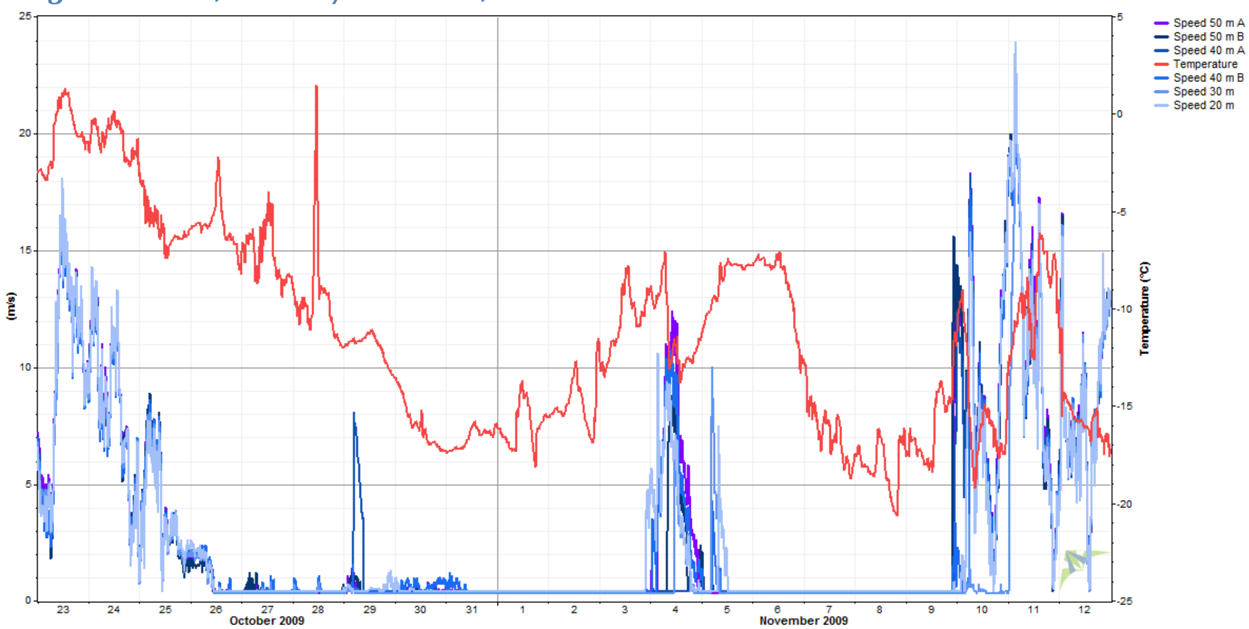


## Documentation of Icing

Rime icing is more problematic for wind turbine operations than freezing rain (clear ice) given its tenacity and longevity in certain climatic conditions. It is not entirely clear from the data whether the icing data loss was from rime ice or other cold climate icing conditions such as freezing rain, sleet, etc. The met tower site is at sufficient elevation for rime icing to occur but may be too far from the coast for consistent exposure to maritime-type conditions. Relative humidity data would have been useful to determine this possibility, but the met tower was no equipped with a relative humidity sensor.

In any event, icing conditions were clearly identifiable in the data, and were concentrated somewhat in the autumn months. An icing event is shown below. Without humidity data, it is not certain that it was snowing at the beginning of data loss on October 26, 2009, but with a temperature at the time of -5° C and subsequent loss of anemometer function for two weeks, this is likely.

### *Icing Event Data, October/November, 2009*




## Wind Speed

Anemometer data obtained from the met tower, from the perspectives of both mean wind speed and mean wind power density, indicate a good wind resource. Note that cold temperatures contributed to a higher wind power density than standard conditions would yield for the measured mean wind speeds. Also note that poor data recovery from the 50 meter level anemometers casts some doubt on data from those sensors, although initial data recover y was good. Data recovery from the 40 meter A anemometer was very good and is used throughout this report to represent speed distribution and other parameters.

### Anemometer data summary

| Variable | Speed 50 m A | Speed 50 m B | Speed 40 m A | Speed 40 m B | Speed 30 m | Speed 20 m |
|---|---|---|---|---|---|---|
| Measurement height (m) | 50.3 | 49.7 | 39.6 | 40.1 | 32 | 24.3 |
| Mean wind speed (m/s) | 6.91 | 6.32 | 6.46 | 6.36 | 6.26 | 6.19 |
| MoMM wind speed (m/s) | 6.88 | 6.31 | 6.45 | 6.37 | 6.25 | 6.20 |
| Median wind speed (m/s) | 5.90 | 5.40 | 5.50 | 5.40 | 5.30 | 5.10 |
| Max wind speed (m/s) | 30.1 | 29.7 | 30.2 | 29.6 | 30.8 | 31.5 |
| Weibull k | 1.39 | 1.52 | 1.54 | 1.48 | 1.48 | 1.46 |
| Weibull c (m/s) | 7.52 | 7.00 | 7.18 | 7.03 | 6.92 | 6.83 |
| Mean power density (W/m²) | 494 | 358 | 387 | 388 | 370 | 371 |
| MoMM power density (W/m²) | 488 | 356 | 384 | 388 | 368 | 372 |
| Mean energy content (kWh/m²/yr) | 4,329 | 3,139 | 3,386 | 3,400 | 3,237 | 3,252 |
| MoMM energy content (kWh/m²/yr) | 4,276 | 3,122 | 3,364 | 3,401 | 3,222 | 3,260 |
| Energy pattern factor | 2.73 | 2.61 | 2.61 | 2.75 | 2.75 | 2.86 |
| Frequency of calms (%) | 32.0 | 35.1 | 33.6 | 36.0 | 36.0 | 37.7 |
| Data recovery rate (%) | 44.3 | 69.2 | 86.6 | 79.0 | 90.5 | 91.8 |

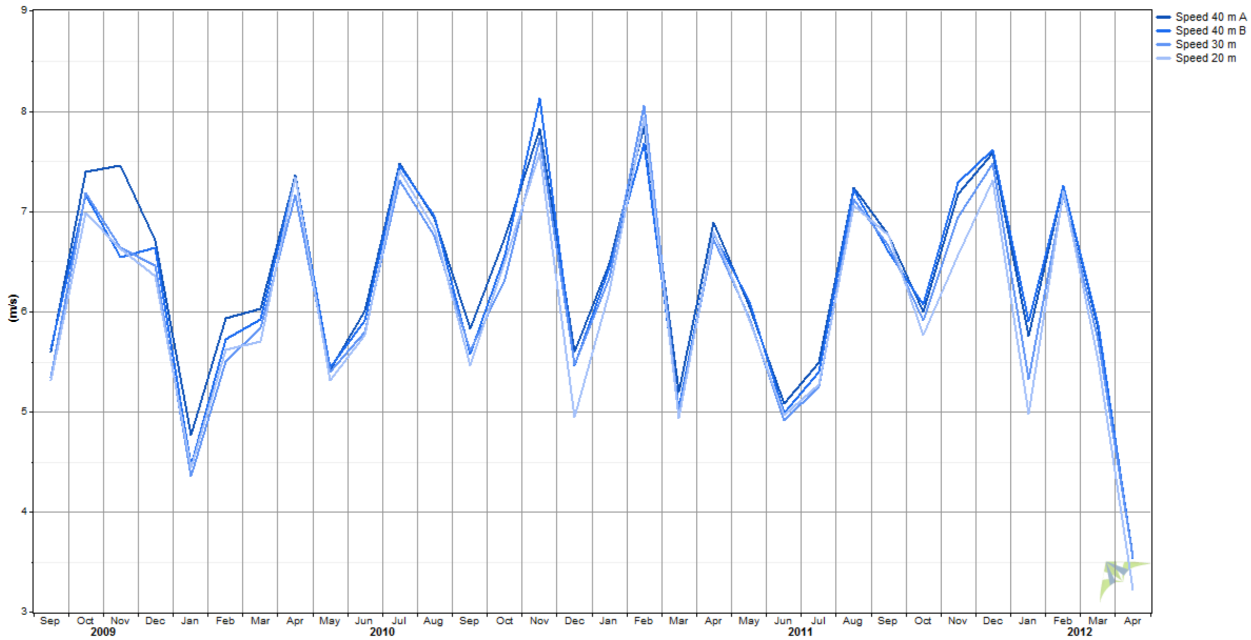
## Time Series

Time series calculations indicate higher wind speeds during the winter months with more moderate wind speeds during summer months, although interestingly there is significant variation from month-to-month throughout the 31 month data set. This is indicative of the often temperamental nature of mountain winds. The daily wind profiles indicate relatively even wind speeds throughout the day with slightly higher wind speeds during night hours.

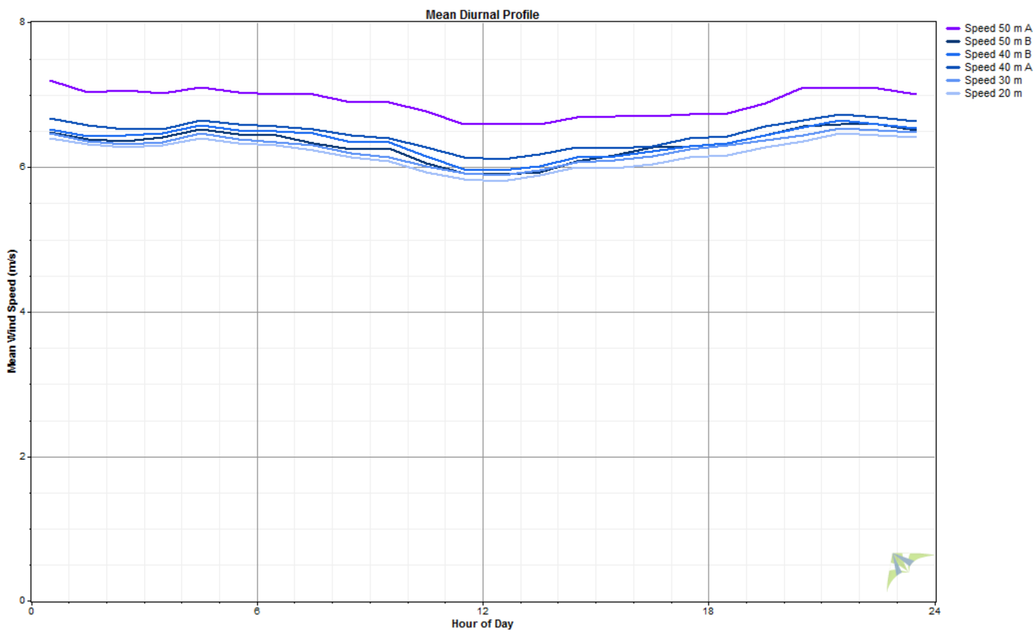
### 40 m A anemometer data summary

| Month | Mean (m/s) | Median (m/s) | Max 10-min avg (m/s) | Max gust (2 sec.) (m/s) | Std. Dev. (m/s) | Weibull k (-) | Weibull c (m/s) |
|---|---|---|---|---|---|---|---|
| Jan | 5.83 | 5.30 | 23.7 | 29.1 | 3.54 | 1.64 | 6.49 |
| Feb | 7.09 | 6.30 | 30.2 | 41.6 | 4.46 | 1.66 | 7.94 |
| Mar | 5.68 | 4.80 | 23.0 | 31.4 | 3.78 | 1.57 | 6.33 |
| Apr | 6.99 | 5.80 | 29.8 | 40.1 | 4.57 | 1.58 | 7.79 |
| May | 5.73 | 4.90 | 26.8 | 35.2 | 3.73 | 1.61 | 6.41 |
| Jun | 5.54 | 4.50 | 21.7 | 26.5 | 4.04 | 1.42 | 6.11 |
| Jul | 6.48 | 5.40 | 26.2 | 32.2 | 4.46 | 1.48 | 7.18 |
| Aug | 7.08 | 6.60 | 23.9 | 29.1 | 4.33 | 1.66 | 7.91 |
| Sep | 6.16 | 5.50 | 25.0 | 30.3 | 4.02 | 1.52 | 6.82 |
| Oct | 6.67 | 6.20 | 21.3 | 29.5 | 3.68 | 1.85 | 7.48 |
| Nov | 7.49 | 6.20 | 28.5 | 39.3 | 4.99 | 1.54 | 8.34 |
| Dec | 6.74 | 5.60 | 27.0 | 36.3 | 4.85 | 1.37 | 7.35 |
| Annual | 6.45 | 5.50 | 30.2 | 41.6 | 4.28 | 1.54 | 7.18 |

### *Monthly time series, mean wind speeds*



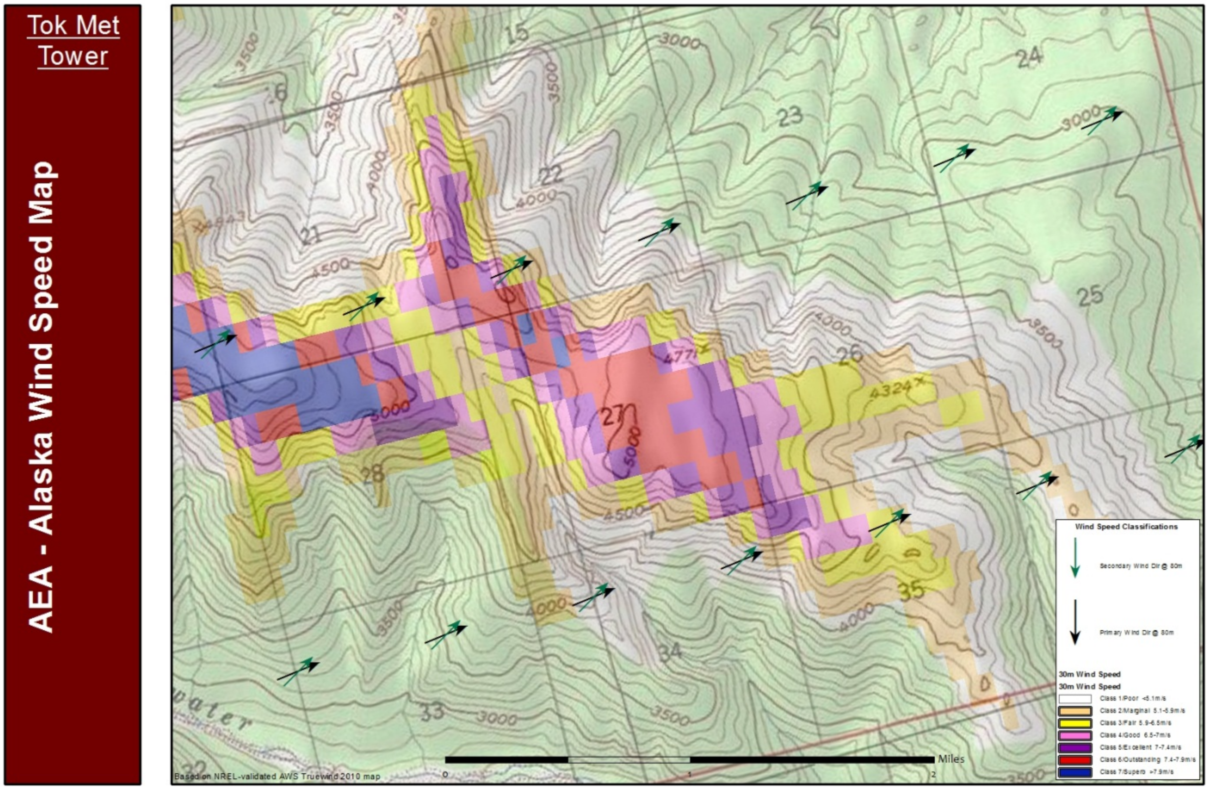

### *Daily wind profile*



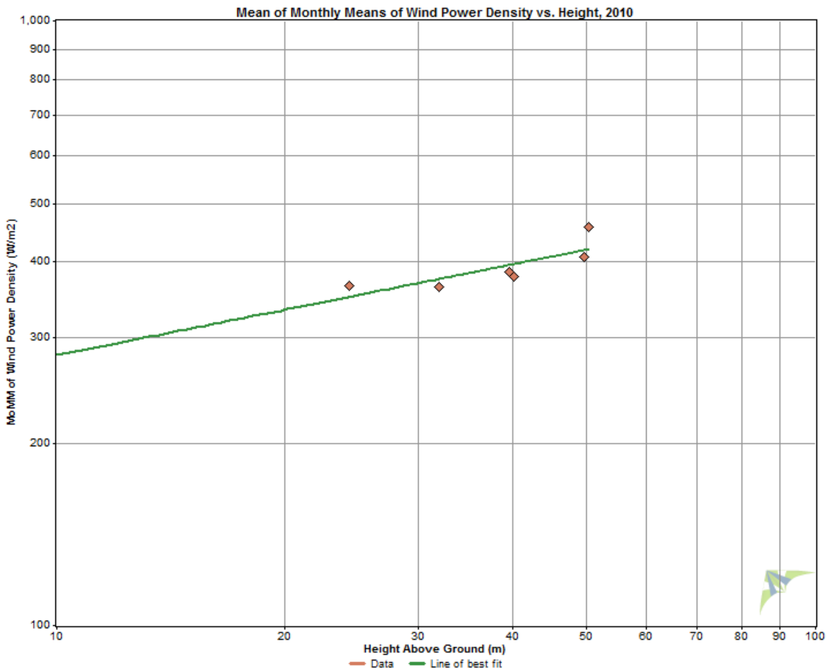

## Wind Power Density

Wind power density at the Tok 0051 met tower site was predicted to be Class 6 (description: outstanding) by reference to Alaska Energy Authority high resolution wind map. This map was created with assistance from National Renewable Energy Laboratory to help guide efforts to prospect for wind resources in Alaska. Actual measured wind resource, though, appears to be Class 4 (description: good) by review of the 50 meter, 40 meter and 30 meter anemometer data. This is likely due to a modeling discrepancy with the high resolution wind map that over-predicted speed-up effects of the wind across the ridgeline where the site is located.

### *AEA high resolution wind map*



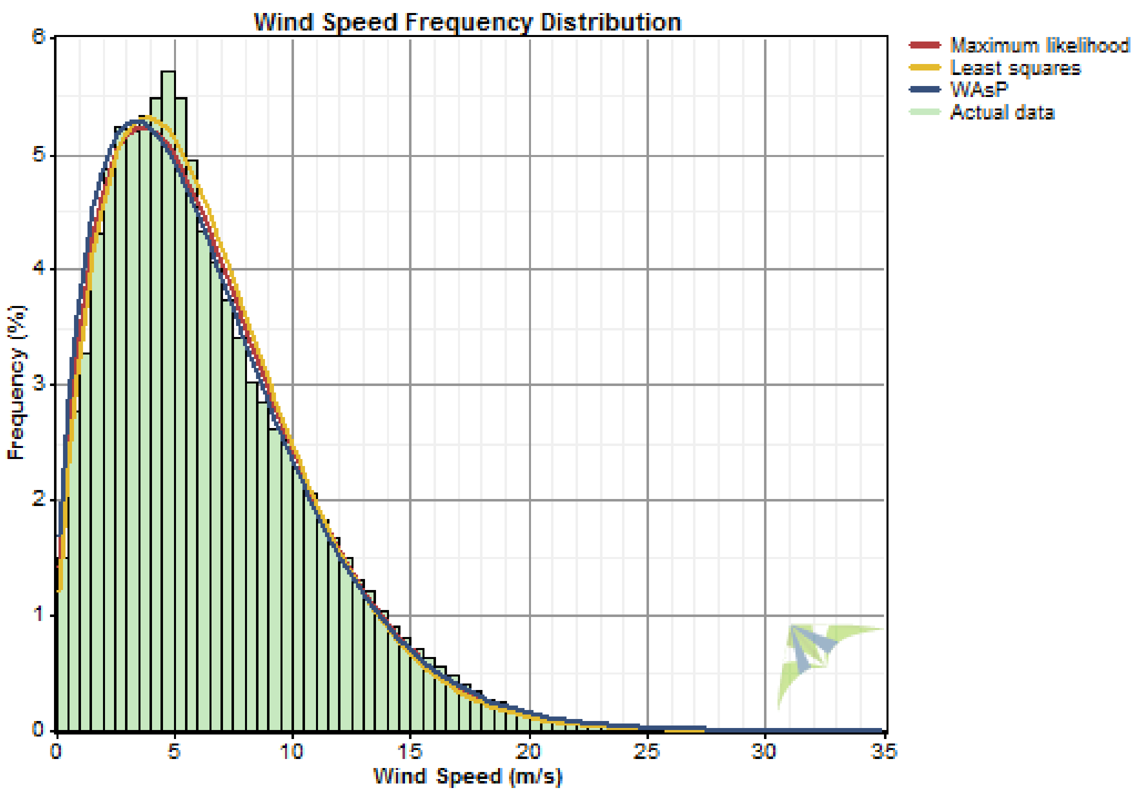

### *Met tower wind power density*



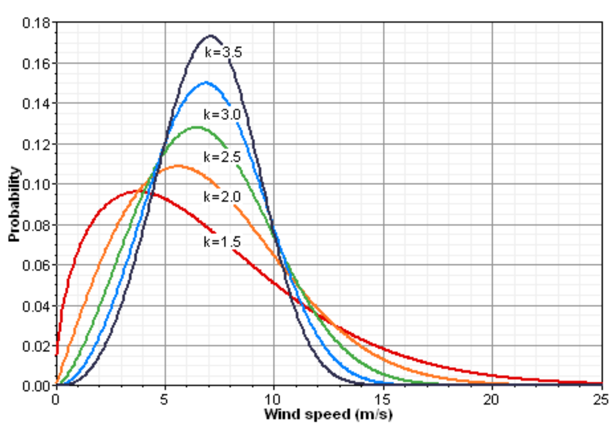
## Probability Distribution Function

The probability distribution function (PDF), or histogram, of the Tok 0051 met tower site wind speed indicates a shape curve dominated by moderate to lower wind speeds compared to a "normal" shape curve, known as the Rayleigh distribution (Weibull k = 2.0), which is defined as the standard wind distribution for wind power analysis. As seen below in the wind speed distribution of the 40 meter A anemometer, the most frequently occurring wind speeds are between 2 and 6 m/s with very few wind events exceeding 25 m/s (the cutout speed of most wind turbines; see following wind speed statistical table).

### *PDF of 40 m A anemometer*




### *Weibull k shape curve table*



### *Weibull values table, 40 m A anemometer*

| Algorithm | Weibull k (-) | Weibull c (m/s) | Mean (m/s) | Proportion Above 6.460 m/s | Power Density (W/m2) | R Squared (-) |
|---|---|---|---|---|---|---|
| Maximum likelihood | 1.544 | 7.18 | 6.46 | 0.428 | 430 | 0.992 |
| Least squares | 1.598 | 7.16 | 6.42 | 0.428 | 402 | 0.991 |
| WAsP | 1.496 | 7.05 | 6.37 | 0.416 | 431 | 0.991 |
| Actual data | (116,196 time steps) | | 6.46 | 0.416 | 431 | |

### *Occurrence by wind speed bin (40 m A anemometer)*

| Bin Endpoints (m/s) | | Occurrences | | | Bin Endpoints (m/s) | | Occurrences | | |
|---|---|---|---|---|---|---|---|---|---|
| Lower | Upper | No. | Percent | Cumul. | Lower | Upper | No. | Percent | Cumul. |
| 0 | 1 | 4,971 | 4.3% | 4.3% | 16 | 17 | 1,214 | 1.0% | 97.6% |
| 1 | 2 | 8,806 | 7.6% | 11.9% | 17 | 18 | 884 | 0.8% | 98.4% |
| 2 | 3 | 11,725 | 10.1% | 21.9% | 18 | 19 | 603 | 0.5% | 98.9% |
| 3 | 4 | 12,218 | 10.5% | 32.5% | 19 | 20 | 432 | 0.4% | 99.3% |
| 4 | 5 | 13,018 | 11.2% | 43.7% | 20 | 21 | 276 | 0.2% | 99.5% |
| 5 | 6 | 12,107 | 10.4% | 54.1% | 21 | 22 | 170 | 0.1% | 99.7% |
| 6 | 7 | 9,752 | 8.4% | 62.5% | 22 | 23 | 131 | 0.1% | 99.8% |
| 7 | 8 | 8,288 | 7.1% | 69.6% | 23 | 24 | 81 | 0.1% | 99.9% |
| 8 | 9 | 6,818 | 5.9% | 75.5% | 24 | 25 | 45 | 0.0% | 99.9% |
| 9 | 10 | 5,961 | 5.1% | 80.6% | 25 | 26 | 44 | 0.0% | 99.9% |
| 10 | 11 | 5,028 | 4.3% | 84.9% | 26 | 27 | 30 | 0.0% | 100.0% |
| 11 | 12 | 4,076 | 3.5% | 88.4% | 27 | 28 | 20 | 0.0% | 100.0% |
| 12 | 13 | 3,279 | 2.8% | 91.3% | 28 | 29 | 11 | 0.0% | 100.0% |
| 13 | 14 | 2,633 | 2.3% | 93.5% | 29 | 30 | 13 | 0.0% | 100.0% |
| 14 | 15 | 1,987 | 1.7% | 95.2% | 30 | 31 | 1 | 0.0% | 100.0% |
| 15 | 16 | 1,574 | 1.4% | 96.6% | 31 | 32 | 0 | 0.0% | 100.0% |

## Wind Shear and Roughness

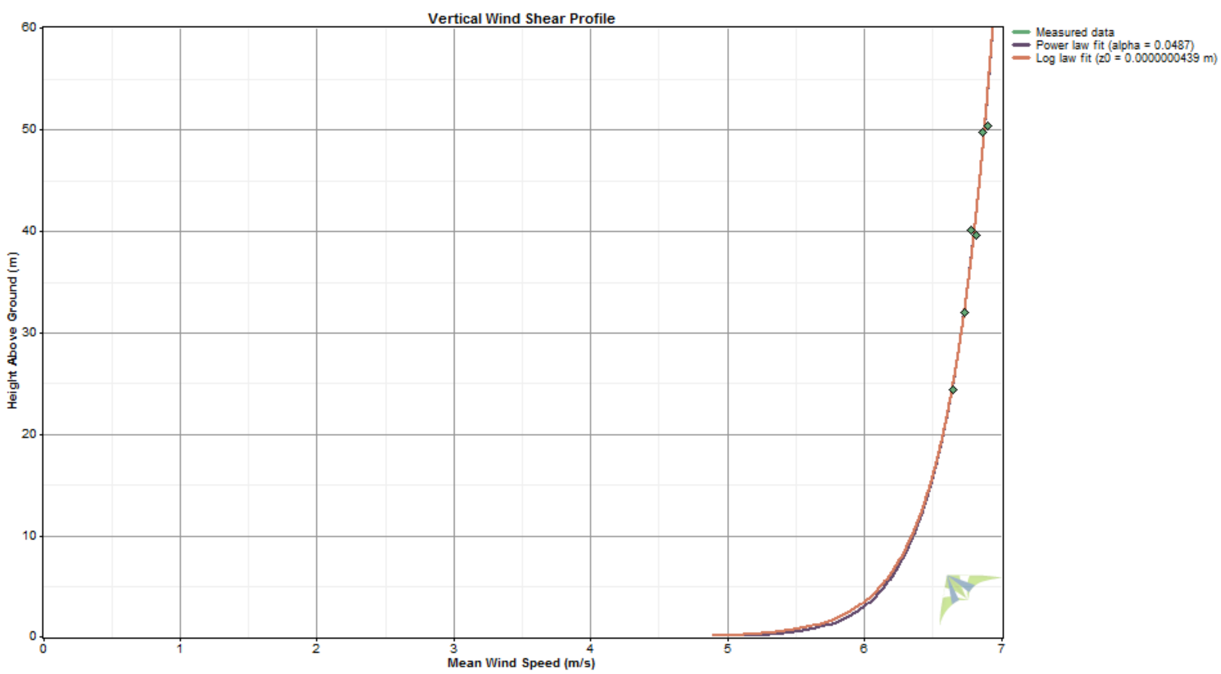
Wind shear at the Tok 0051 met tower site was calculated with *concurrent* data from all six standard anemometers. Noted in the quality control discussion were the problems with the 50 meter level anemometers. For this reason, plus other data loss including icing and tower shadow, only 45,545 data steps out of a possible 134,148 (34.0%) data steps in the entire data package were included in the shear calculations. This is interesting by itself in that it indicates a different view of mean wind speed than the individual anemometer averages that include more data, but with the highly variable anemometer data recovery from the met tower, seasonal representation in the data set, especially with the 50 meter anemometers, is not complete.

In any event, the calculated power law exponent of 0.049 indicates extremely low wind shear at the site, which is expected given the site location of a mountain ridgeline where little ground drag of the wind is possible. Calculated surface roughness at the site is 0 m (the height above ground where wind speed would be zero) for a roughness class of 0.00 (description: smooth). The practical consideration of this data is that wind turbines could be constructed at low hub heights and still generate nearly as much energy as would be possible at much higher hub heights.

### *Vertical wind shear data table*

| Wind Speed Sensor | Height (m) | Time Steps | Mean Wind Speed (m/s) |
|---|---|---|---|
| Speed 50 m A | 50.3 | 45,545 | 6.91 |
| Speed 50 m B | 49.7 | 45,545 | 6.87 |
| Speed 40 m B | 40.1 | 45,545 | 6.78 |
| Speed 40 m A | 39.6 | 45,545 | 6.82 |
| Speed 30 m | 32.0 | 45,545 | 6.73 |
| Speed 20 m | 24.3 | 45,545 | 6.65 |

### *Vertical wind shear profile*




### *Wind shear by direction sector table*

Mean Wind Speed (m/s)

| Direction Sector | Time Steps | Speed 50 m A | Speed 50 m B | Speed 40 m B | Speed 40 m A | Speed 30 m | Speed 20 m | Best-fit Power Law Exp | Surface Roughness (m) |
|---|---|---|---|---|---|---|---|---|---|
| 345° - 15° | 6,649 | 5.58 | 5.57 | 5.40 | 5.44 | 5.33 | 5.04 | 0.132 | 0.0179 |
| 15° - 45° | 6,806 | 6.12 | 6.06 | 5.96 | 5.97 | 5.75 | 5.37 | 0.169 | 0.0907 |
| 45° - 75° | 2,574 | 5.20 | 5.22 | 5.04 | 5.08 | 4.86 | 4.61 | 0.170 | 0.0954 |
| 75° - 105° | 3,243 | 7.64 | 7.60 | 7.43 | 7.46 | 7.42 | 7.54 | 0.019 | 0.0000 |

Mean Wind Speed (m/s)

| Direction Sector | Time Steps | Speed 50 m A | Speed 50 m B | Speed 40 m B | Speed 40 m A | Speed 30 m | Speed 20 m | Best-fit Power Law Exp | Surface Roughness (m) |
|---|---|---|---|---|---|---|---|---|---|
| 105° - 135° | 4,262 | 8.27 | 8.37 | 8.22 | 8.21 | 8.19 | 8.30 | 0.008 | |
| 135° - 165° | 2,121 | 4.42 | 4.44 | 4.30 | 4.32 | 4.20 | 4.00 | 0.140 | 0.0276 |
| 165° - 195° | 2,697 | 4.52 | 4.49 | 4.31 | 4.31 | 4.18 | 3.84 | 0.211 | 0.3014 |
| 195° - 225° | 1,714 | 4.62 | 4.53 | 4.41 | 4.45 | 4.27 | 3.83 | 0.232 | 0.4476 |
| 225° - 255° | 3,030 | 9.06 | 8.79 | 8.80 | 8.98 | 8.99 | 9.13 | -0.031 | |
| 255° - 285° | 8,784 | 10.58 | 10.48 | 10.59 | 10.61 | 10.64 | 10.92 | -0.046 | |
| 285° - 315° | 1,517 | 3.80 | 3.90 | 3.96 | 3.96 | 3.96 | 4.03 | -0.060 | |
| 315° - 345° | 1,652 | 2.87 | 2.94 | 2.75 | 2.82 | 2.67 | 2.53 | 0.192 | 0.1908 |

## Extreme Winds

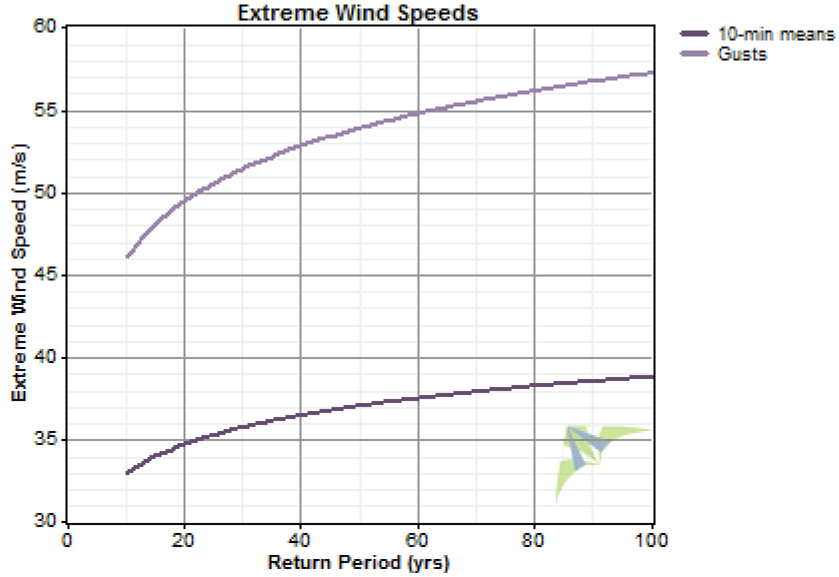
A modified Gumbel distribution analysis, based on monthly maximum winds vice annual maximum winds, was used to predict extreme winds at the Tok 0051 met tower site. The 40 meter A anemometer was chosen for this calculation because it is the highest elevation anemometer on the met tower with consistently good data recovery. With data available, the predicted Vref (maximum ten-minute average wind speed) in a 50 year return period (in other words, predicted to occur once every 50 years) is 39.7 m/s. This result classifies the site as Class II by International Electrotechnical Commission 61400-1, 3rd edition (IEC3) criteria. IEC extreme wind probability classification is one criteria – with turbulence the other – that describes a site with respect to suitability for particular wind turbine models. Note that the IEC3 Class II extreme wind classification, which applies to the Tok 0051 met tower site, indicates relatively energetic winds and turbines installed at this location should be IEC3 Class II rated.

Interestingly, however, is consideration of extreme wind probability at 20 meters. Although 20 meters is well below the hub height of utility-scale wind turbines, significant topographic Venturi effect speed-up results in extreme wind probability calculations high enough to classify the site as IEC3 Class 1 at 20 meters elevation.

### *Site extreme wind probability table, 40 meter A data*

| Period (years) | $V_{ref}$ (m/s) | Gust (m/s) | IEC 61400-1, 3rd ed. Class | $V_{ref}$, m/s |
|---|---|---|---|---|
| 3 | 30.3 | 38.7 | I | 50.0 |
| 10 | 35.0 | 44.7 | II | 42.5 |
| 20 | 36.2 | 46.2 | III | 37.5 |
| 30 | 38.2 | 48.7 | S | designer-specified |
| 50 | 39.7 | 50.6 | | |
| 100 | 41.7 | 53.2 | | |
| average gust factor: | 1.28 | | | |

### *Extreme wind graph, 40 meter level, by annual method*




### *Site extreme wind probability table, 20 meter data*

| Period (years) | $V_{ref}$ (m/s) | Gust (m/s) | IEC 61400-1, 3rd ed. Class | $V_{ref}$, m/s |
|---|---|---|---|---|
| 3 | 32.8 | 42.2 | I | 50.0 |
| 10 | 38.6 | 49.6 | II | 42.5 |
| 20 | 40.0 | 51.5 | III | 37.5 |
| 30 | 42.5 | 54.7 | S | designer-specified |
| 50 | 44.3 | 57.0 | | |
| 100 | 46.8 | 60.1 | | |
| average gust factor: | 1.29 | | | |

## Temperature, Density, and Relative Humidity

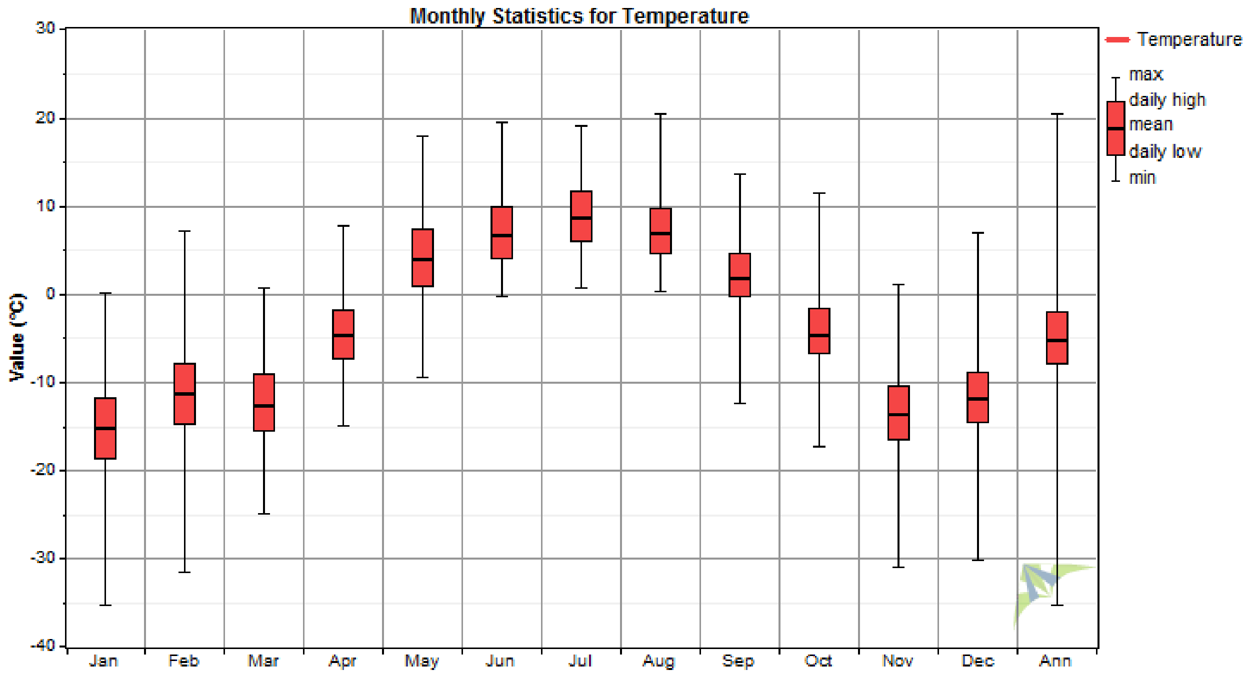
The Tok met tower site experiences cool summers and cold winters with resulting higher than standard air density. Calculated mean-of-monthly-mean (or annual) air density during the met tower test period exceeds the 1.058 kg/m$^3$ standard air density for a 1,503 meter elevation by 3.5 percent. This is advantageous in wind power operations as wind turbines produce more power at low temperatures (high air density) than at standard temperature and density.

### *Temperature and density table*

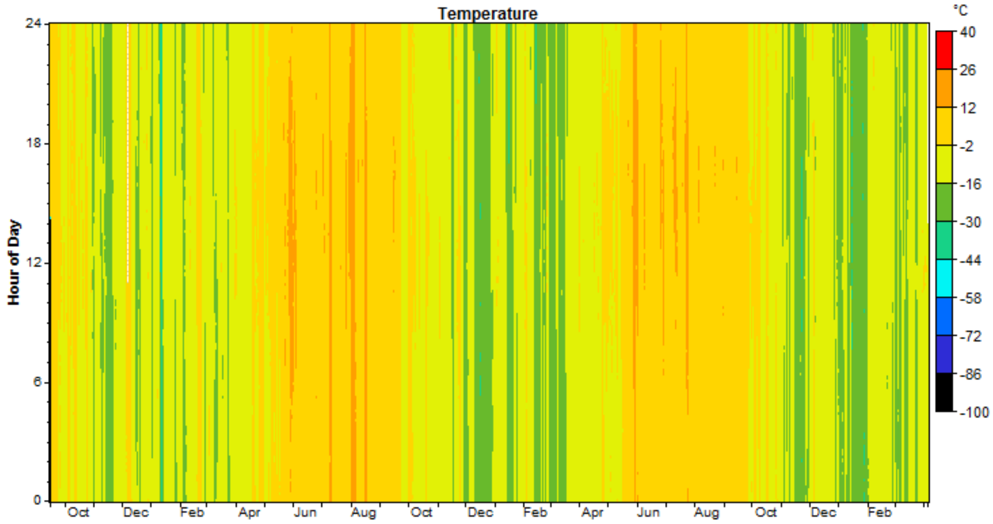
| | Temperature | | | | | | Density | | |
|---|---|---|---|---|---|---|---|---|---|
| Month | Mean (°F) | Min (°F) | Max (°F) | Mean (°C) | Min (°C) | Max (°C) | Mean (kg/m³) | Min (kg/m³) | Max (kg/m³) |
| Jan | 4.7 | -31.5 | 32.2 | -15.2 | -35.3 | 0.1 | 1.143 | 1.078 | 1.239 |
| Feb | 11.8 | -24.9 | 45.0 | -11.2 | -31.6 | 7.2 | 1.126 | 1.051 | 1.220 |
| Mar | 9.1 | -13.0 | 33.1 | -12.7 | -25.0 | 0.6 | 1.132 | 1.076 | 1.187 |
| Apr | 23.6 | 5.0 | 46.0 | -4.7 | -15.0 | 7.8 | 1.098 | 1.049 | 1.141 |

| | Temperature | | | | | | Density | | |
|---|---|---|---|---|---|---|---|---|---|
| Month | Mean (°F) | Min (°F) | Max (°F) | Mean (°C) | Min (°C) | Max (°C) | Mean (kg/m³) | Min (kg/m³) | Max (kg/m³) |
| May | 39.2 | 15.1 | 64.2 | 4.0 | -9.4 | 17.9 | 1.064 | 1.012 | 1.117 |
| Jun | 44.0 | 31.3 | 67.1 | 6.7 | -0.4 | 19.5 | 1.053 | 1.007 | 1.080 |
| Jul | 47.5 | 33.1 | 66.2 | 8.6 | 0.6 | 19.0 | 1.046 | 1.009 | 1.076 |
| Aug | 44.5 | 32.4 | 68.7 | 7.0 | 0.2 | 20.4 | 1.052 | 1.004 | 1.078 |
| Sep | 35.2 | 9.5 | 56.5 | 1.8 | -12.5 | 13.6 | 1.072 | 1.028 | 1.131 |
| Oct | 23.9 | 0.7 | 52.5 | -4.5 | -17.4 | 11.4 | 1.097 | 1.036 | 1.152 |
| Nov | 7.6 | -24.0 | 33.8 | -13.6 | -31.1 | 1.0 | 1.136 | 1.075 | 1.217 |
| Dec | 10.7 | -22.4 | 44.6 | -11.9 | -30.2 | 7.0 | 1.128 | 1.052 | 1.213 |
| Annual | 25.2 | -31.5 | 68.7 | -3.8 | -35.3 | 20.4 | 1.095 | 1.004 | 1.239 |

## *Tok 0051 site temperature boxplot graph*



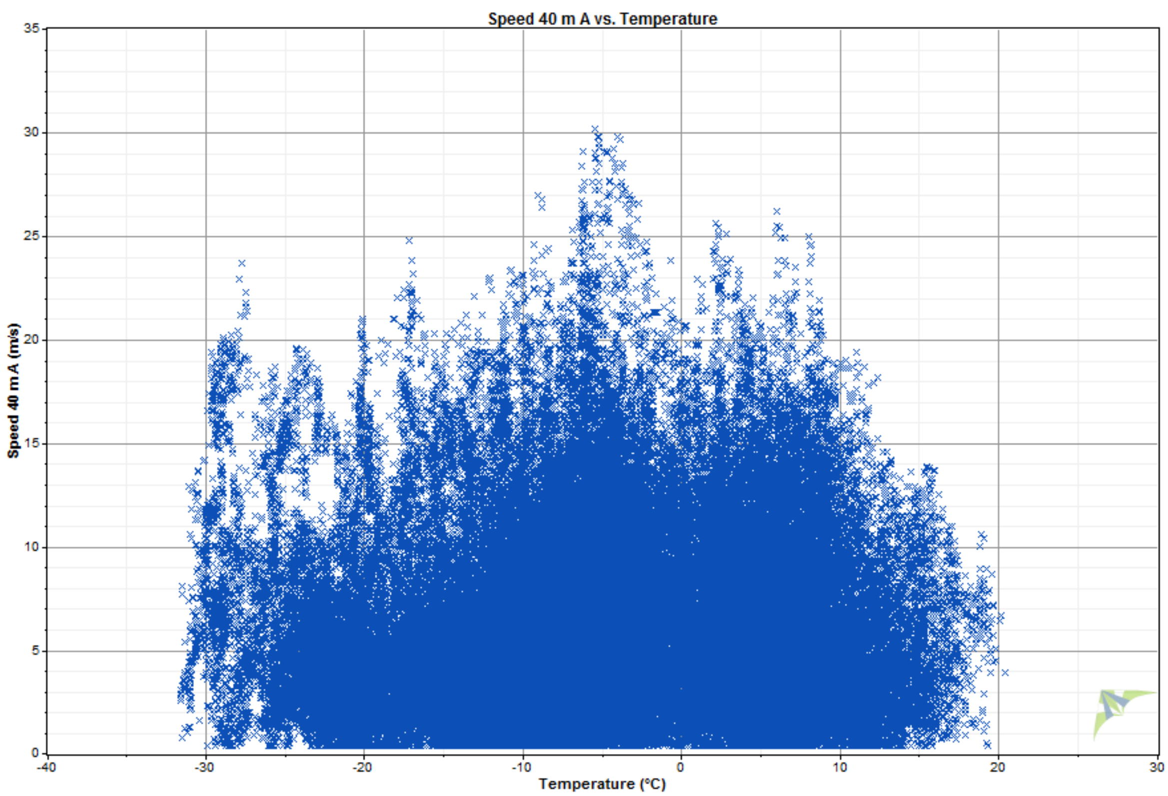
### *Temperature DMap*




## Wind Speed Scatterplot

The wind speed versus temperature scatterplot below indicates cold temperatures at the Tok met tower site with a preponderance of below freezing temperatures. During the met tower test periods, temperatures were often below -20° C (-4° F), the minimum operating temperature for most standard-environment wind turbines. Note that arctic-capable (ratings to -40°C) wind turbines would be required at this site.

### *Wind speed/temperature*

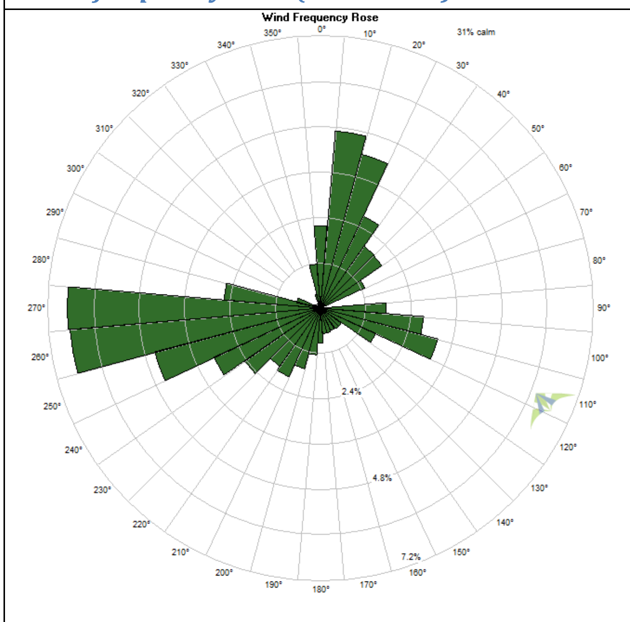
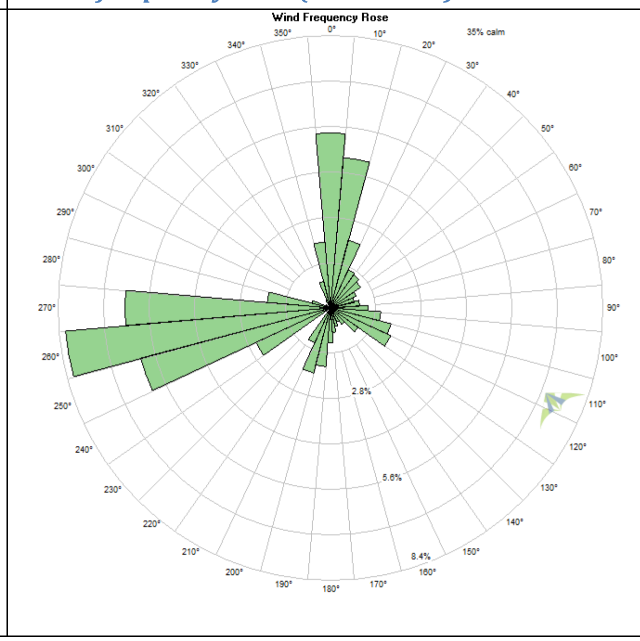


## Wind Direction

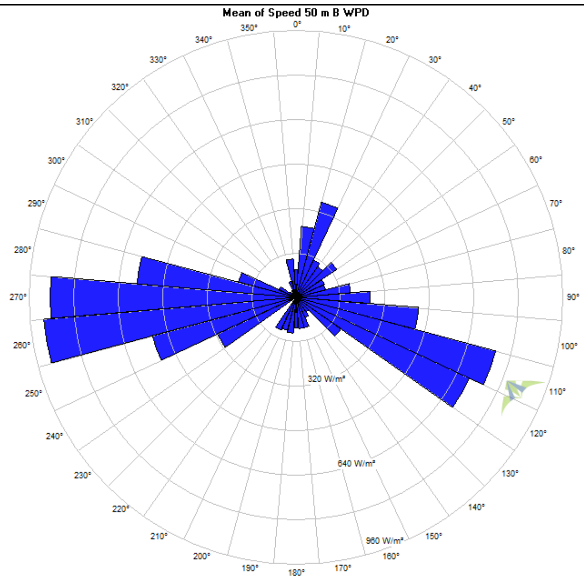
Wind frequency rose data indicates that winds at the Tok 0051 met tower site are tri-directional, with predominately westerly winds and north-northeasterly and east-southeasterly winds to a lesser extent. The mean value rose indicates that westerly winds are also of the highest intensity although east-southeasterly winds, when they do occur, are of relatively high intensity. North-northeasterly winds, however, are of relatively low intensity. The wind energy roses indicate that a significant majority of the power-producing winds at the site are westerly.

Calm wind frequency (the percent of time that winds at the 50 meter level are less than 4 m/s, a typical cut-in speed of larger wind turbines) was a moderate 31 percent during the 31 month test period. Calm wind frequency at the 40 meter level was a slightly higher 35 percent during the test period.

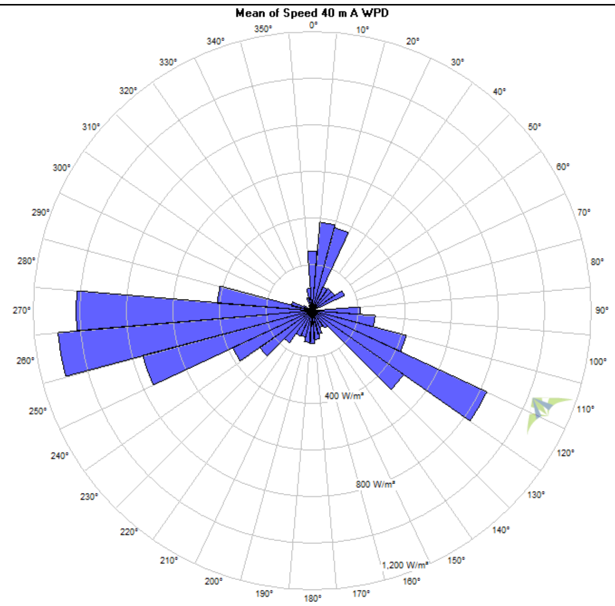
Note that the 50 meter and 40 meter wind roses don't exactly match each other. After an April, 2012 field check, both vanes were reported as facing 305° M, which after consideration of reported winds and magnetic declination, yields a 146° True offset (zero point of the vane), but in reality there likely is a slight offset error, probably less than ten degrees, with one or both wind vanes.

| ***Wind frequency rose (50 m vane)*** | ***Wind frequency rose (40 m vane)*** |
| --- | --- |
|  |  |

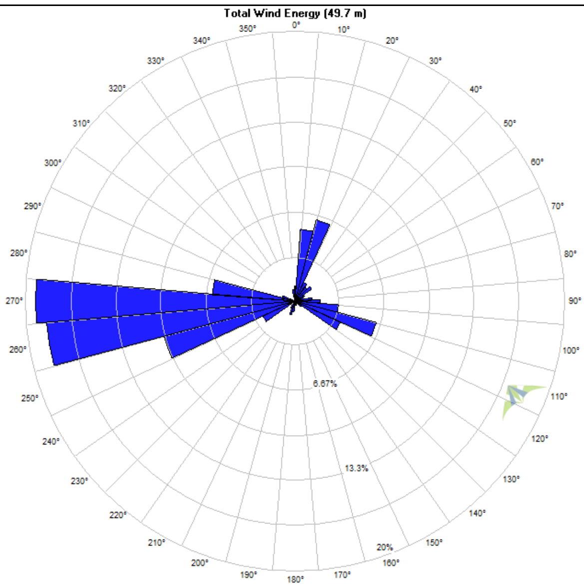
***Mean value rose (50 m B anem.)***



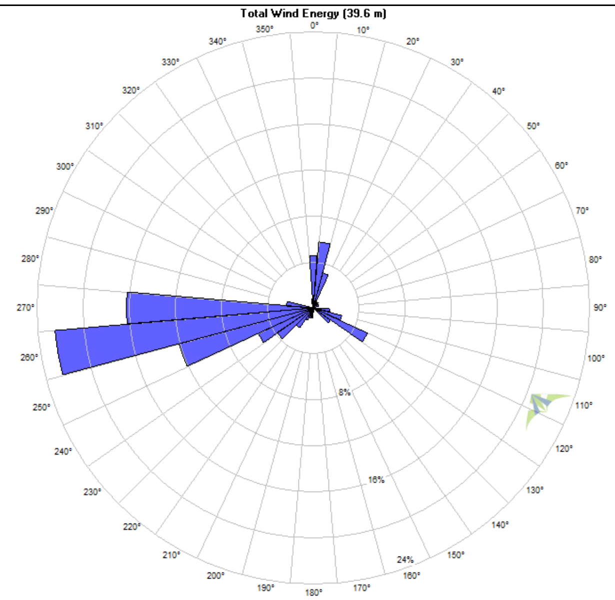

***Mean value rose (40 m A anem.)***



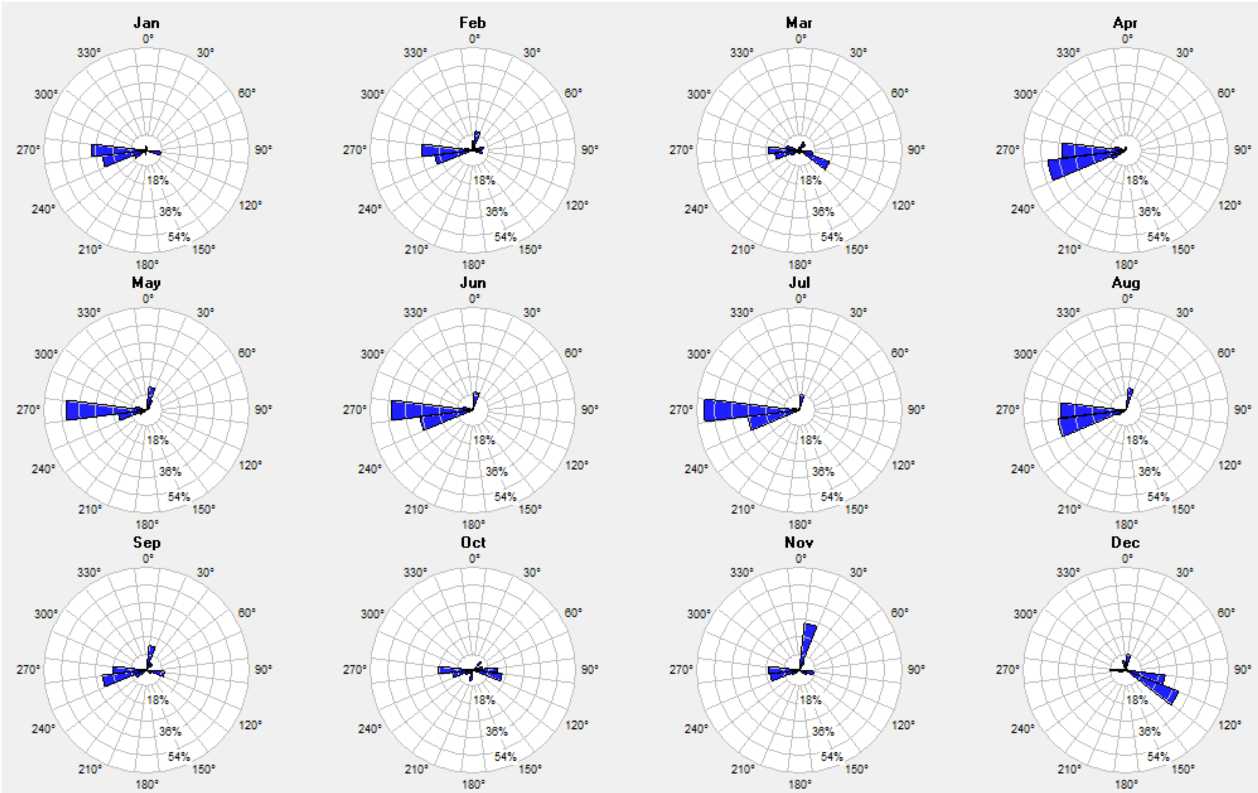

***Wind energy rose (50 m B anem.)***




***Wind energy rose (40 m A anem.)***



### *Wind density (50 meter height) roses by month (common scale)*



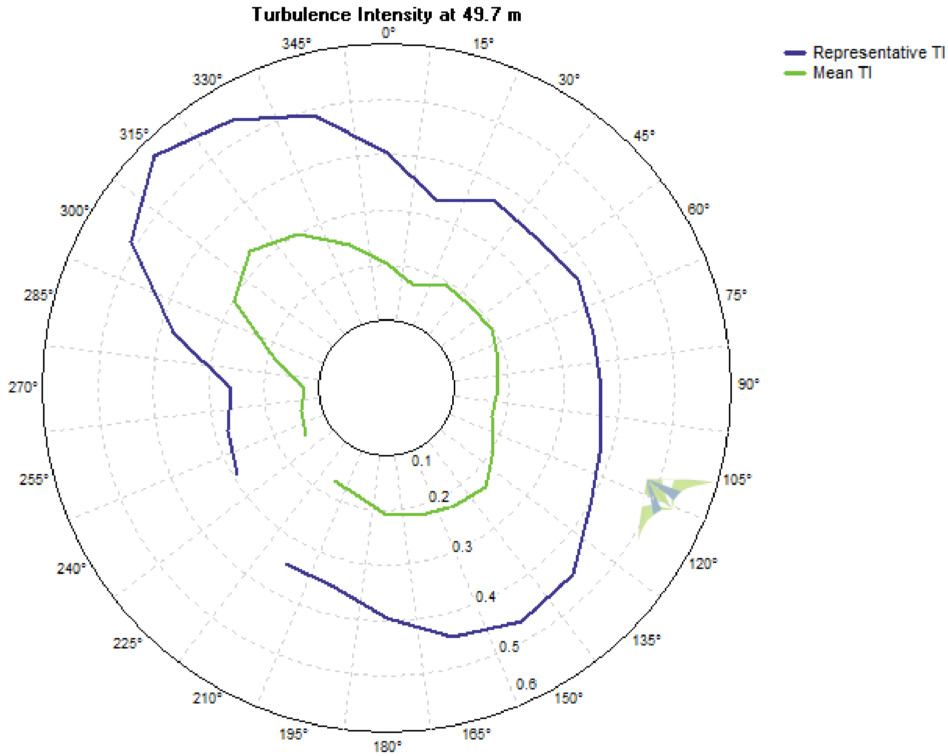

## Turbulence

The turbulence intensity (TI) is acceptable with a mean turbulence intensity of 0.102 and a representative turbulence intensity of 0.159 at 15 m/s wind speed at 50 meters, indicating reasonably smooth air for wind turbine operations, especially in a mountain environment. This equates to an International Electrotechnical Commission (IEC) 3rd Edition (2005) turbulence category C, which is the lowest defined category. These data are shown in the turbulence intensity graph below. As seen, representative TI (90th percentile of the turbulence intensity values, assuming a normal distribution) at 15 m/s is well under IEC Category C criteria at the Tok 0051 met tower site.

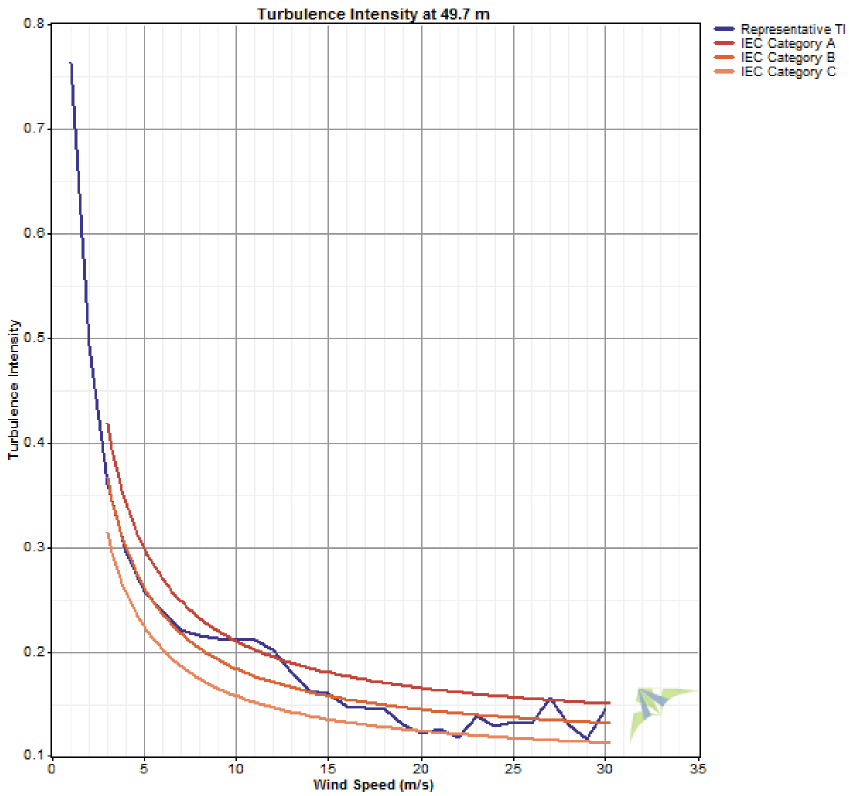
### *Turbulence synopsis*

| | 50 m B anem. | | | 40m A anem. | | | Legend | |
|---|---|---|---|---|---|---|---|---|
| Sector | Mean TI at 15 m/s | Repres. TI at 15 m/s | IEC3 Category | Mean TI at 15 m/s | Repres. TI at 15 m/s | IEC3 Category | IEC3 Categ. | Mean TI at 15 m/s |
| all | 0.102 | 0.159 | C | 0.100 | 0.145 | C | S | >0.16 |
| 315° to 045° | 0.100 | 0.141 | C | 0.111 | 0.151 | C | A | 0.14-0.16 |
| 045° to 135° | 0.100 | 0.149 | C | 0.097 | 0.143 | C | B | 0.12-0.14 |
| 135° to 225° | 0.107 | 0.166 | C | 0.113 | 0.166 | C | C | 0-0.12 |
| 045° to 135° | 0.102 | 0.166 | C | 0.098 | 0.143 | C | | |

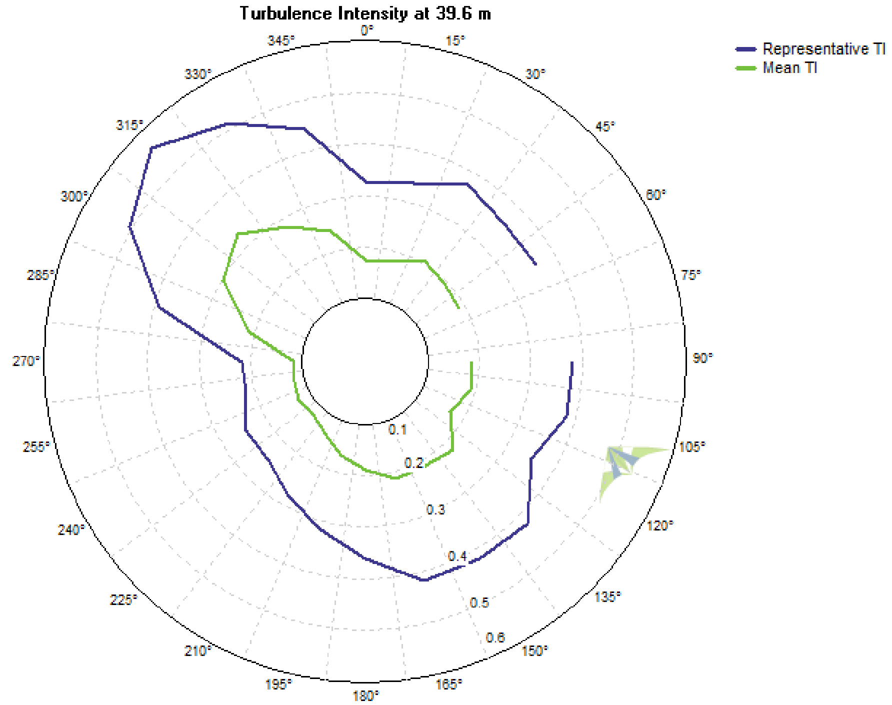
## *Turbulence rose, 50 m B anemometer, 50 m vane*



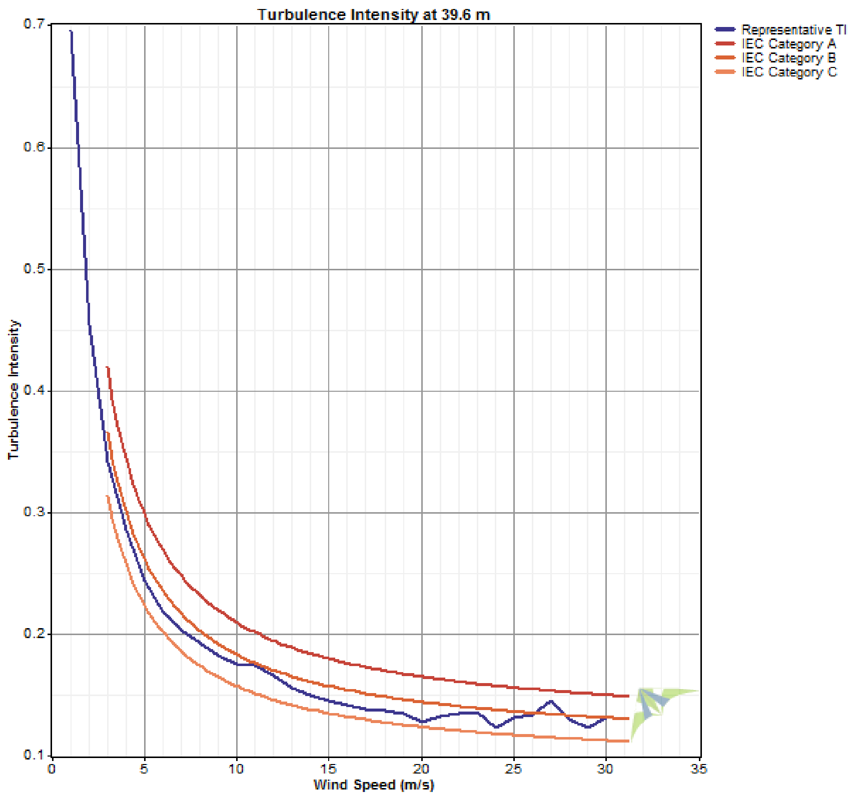

## *Turbulence intensity, 50 m B, all direction sectors*



## *Turbulence rose, 40 m A anemometer, 40 m vane*




## *Turbulence intensity, 40 m A, all direction sectors*



### *Turbulence table, 40 m A data, all sectors*

| Bin Midpoint (m/s) | Bin Endpoints Lower (m/s) | Upper (m/s) | Records In Bin | Mean TI | Standard Deviation of TI | Representative TI | Peak TI |
|---|---|---|---|---|---|---|---|
| 1 | 0.5 | 1.5 | 7,021 | 0.462 | 0.183 | 0.696 | 2.000 |
| 2 | 1.5 | 2.5 | 10,652 | 0.269 | 0.144 | 0.454 | 1.118 |
| 3 | 2.5 | 3.5 | 12,107 | 0.199 | 0.111 | 0.341 | 1.303 |
| 4 | 3.5 | 4.5 | 12,568 | 0.166 | 0.093 | 0.285 | 1.205 |
| 5 | 4.5 | 5.5 | 13,006 | 0.141 | 0.081 | 0.244 | 0.979 |
| 6 | 5.5 | 6.5 | 10,767 | 0.127 | 0.071 | 0.218 | 0.655 |
| 7 | 6.5 | 7.5 | 9,059 | 0.122 | 0.064 | 0.204 | 0.632 |
| 8 | 7.5 | 8.5 | 7,469 | 0.118 | 0.059 | 0.193 | 0.636 |
| 9 | 8.5 | 9.5 | 6,340 | 0.116 | 0.052 | 0.182 | 0.414 |
| 10 | 9.5 | 10.5 | 5,554 | 0.112 | 0.049 | 0.175 | 0.406 |
| 11 | 10.5 | 11.5 | 4,526 | 0.112 | 0.048 | 0.174 | 0.438 |
| 12 | 11.5 | 12.5 | 3,703 | 0.111 | 0.043 | 0.166 | 0.530 |
| 13 | 12.5 | 13.5 | 2,941 | 0.106 | 0.038 | 0.155 | 0.359 |
| 14 | 13.5 | 14.5 | 2,266 | 0.103 | 0.036 | 0.150 | 0.372 |
| 15 | 14.5 | 15.5 | 1,765 | 0.100 | 0.035 | 0.145 | 0.333 |
| 16 | 15.5 | 16.5 | 1,398 | 0.098 | 0.034 | 0.142 | 0.278 |
| 17 | 16.5 | 17.5 | 1,037 | 0.097 | 0.033 | 0.139 | 0.207 |
| 18 | 17.5 | 18.5 | 723 | 0.097 | 0.031 | 0.137 | 0.223 |
| 19 | 18.5 | 19.5 | 528 | 0.094 | 0.032 | 0.135 | 0.268 |
| 20 | 19.5 | 20.5 | 346 | 0.090 | 0.030 | 0.128 | 0.197 |
| 21 | 20.5 | 21.5 | 235 | 0.092 | 0.031 | 0.132 | 0.210 |
| 22 | 21.5 | 22.5 | 120 | 0.097 | 0.029 | 0.135 | 0.199 |
| 23 | 22.5 | 23.5 | 118 | 0.100 | 0.028 | 0.136 | 0.173 |
| 24 | 23.5 | 24.5 | 54 | 0.093 | 0.024 | 0.123 | 0.162 |
| 25 | 24.5 | 25.5 | 46 | 0.094 | 0.028 | 0.131 | 0.151 |
| 26 | 25.5 | 26.5 | 39 | 0.100 | 0.026 | 0.134 | 0.151 |
| 27 | 26.5 | 27.5 | 26 | 0.113 | 0.026 | 0.146 | 0.146 |
| 28 | 27.5 | 28.5 | 12 | 0.107 | 0.018 | 0.131 | 0.141 |
| 29 | 28.5 | 29.5 | 13 | 0.097 | 0.020 | 0.123 | 0.133 |
| 30 | 29.5 | 30.5 | 7 | 0.106 | 0.020 | 0.131 | 0.138 |
| 31 | 30.5 | 31.5 | 0 | | | | |

## Wind Turbine Production

Although not typically addressed in a wind resource report, annual energy production from a General Electric 1.5 sle (1.5 MW) wind turbine is included here for planning purposes. Note that a 95 percent turbine availability (percent of time the wind turbine is operational) is assumed.

### *GE 1.5 sle energy output, 95% turbine availability*

| Month | Hub Height Wind Speed (m/s) | Time At Zero Output (%) | Time At Rated Output (%) | Mean Net Power Output (kW) | Mean Net Energy Output (kWh/yr) | Net Capacity Factor (%) |
|---|---|---|---|---|---|---|
| Jan | 5.97 | 23.5 | 0.5 | 312 | 232,110 | 20.8 |
| Feb | 7.25 | 16.6 | 3.1 | 420 | 281,922 | 28.0 |
| Mar | 5.98 | 22.9 | 1.1 | 298 | 221,879 | 19.9 |
| Apr | 6.93 | 19.9 | 2.9 | 401 | 288,439 | 26.7 |
| May | 5.82 | 23.5 | 0.9 | 263 | 195,737 | 17.5 |
| Jun | 5.62 | 30.5 | 1.2 | 267 | 192,535 | 17.8 |
| Jul | 6.51 | 26.4 | 2.0 | 364 | 270,509 | 24.2 |
| Aug | 7.09 | 21.7 | 1.6 | 438 | 325,671 | 29.2 |
| Sep | 6.30 | 25.4 | 0.8 | 350 | 252,085 | 23.3 |
| Oct | 6.79 | 18.9 | 0.8 | 394 | 293,159 | 26.3 |
| Nov | 7.76 | 18.3 | 7.4 | 488 | 351,066 | 32.5 |
| Dec | 7.18 | 21.6 | 4.1 | 448 | 333,395 | 29.9 |
| Overall | 6.60 | 22.4 | 2.2 | 370 | 3,238,507 | 24.7 |