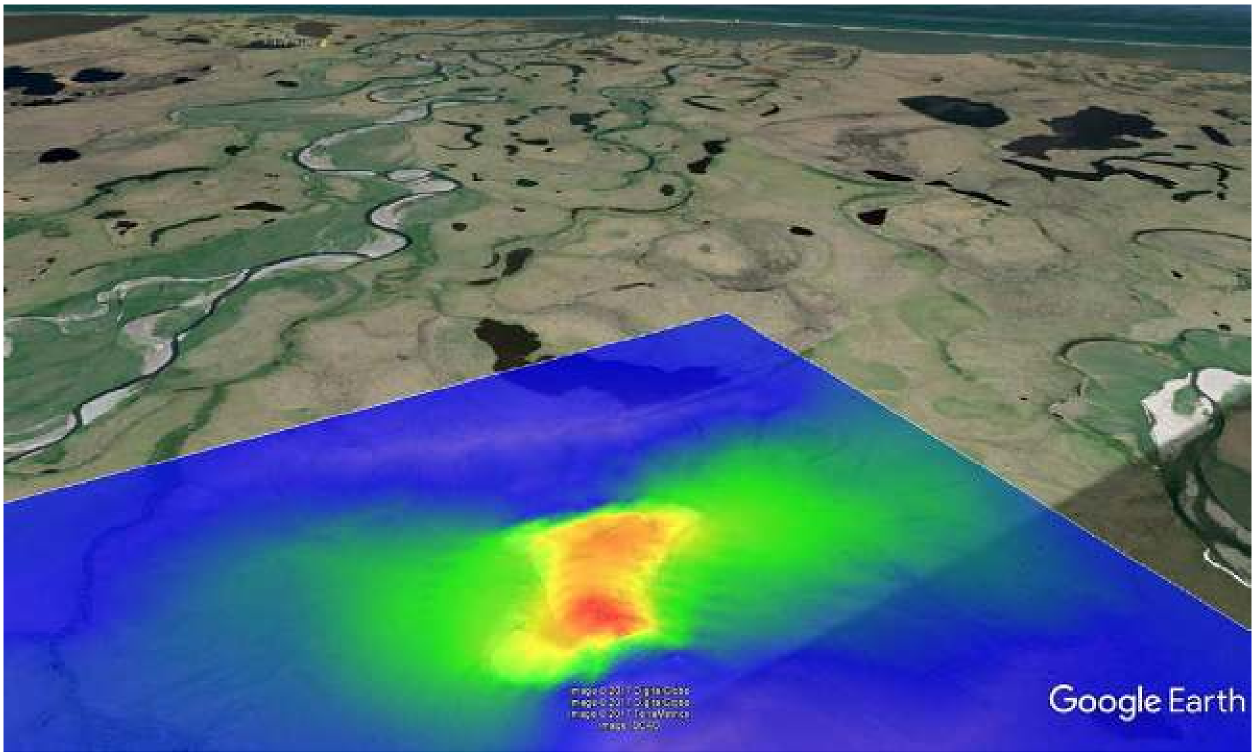
Kisimigiuktuk Hill (Kivalina), Alaska Wind Resource Assessment and Wind Flow Modeling Report



Kisimigiuktuk Hill and Kivalina, Google Earth image with WAsP model wind speed overlay, view south

May 26, 2017

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Summary

Kisimigiuktuk Hill (K-Hill for short), located approximately 7 miles northeast of the native village of Kivalina in the Northwest Arctic Borough of Alaska, is the preferred site for re-location of the village due to erosion of the beach strand that comprises the present location of the community. This beach erosion is due to the battering and erosive effects autumn and early winter storms and the lack of protective sea ice; the latter a consequence of rapid climate change in the high arctic in recent decades.

The wind resource measured at the K-Hill met tower site is superb with a mean annual wind speed of 7.94 m/s and a wind power density of 754 W/m^2 at approximately 32 meters above ground level. In all respects the K-Hill wind resource is highly suitable for wind power and further development is highly encouraged. This wind resource assessment report was prepared by V3 Energy, LLC under contract to Northwest Arctic Borough.

Met tower data synopsis

Data dates	5/10/2015 to 5/18/2016 (12.25 months); missing data: 6/2/15 to 6/4/15, 7/11/15 to 7/13/15, 7/26/15 to 7/28/15, and 10/12/15 to 10/14/15
Wind speed mean, 32 m, annual	7.94 m/s (17.7 mph)
Wind power density mean, 32 m	754 W/m^2
Wind power class	Class 7 (superb); based on wind power density
Max. 10-min wind speed	29.7 m/s
Maximum 2-sec. wind gust	33.2 m/s (74.2 mph), November 2015
Weibull distribution parameters	k = 1.67, c = 8.88 m/s
Wind shear power law exponent	0.039 (low shear)
Surface roughness	0 meters (very smooth, ice or mud)
IEC 61400-1, 3rd ed. classification	Class I or II-C
Turbulence intensity, mean (at 32 m)	0.018 (at 15 m/s)

Test Site Location

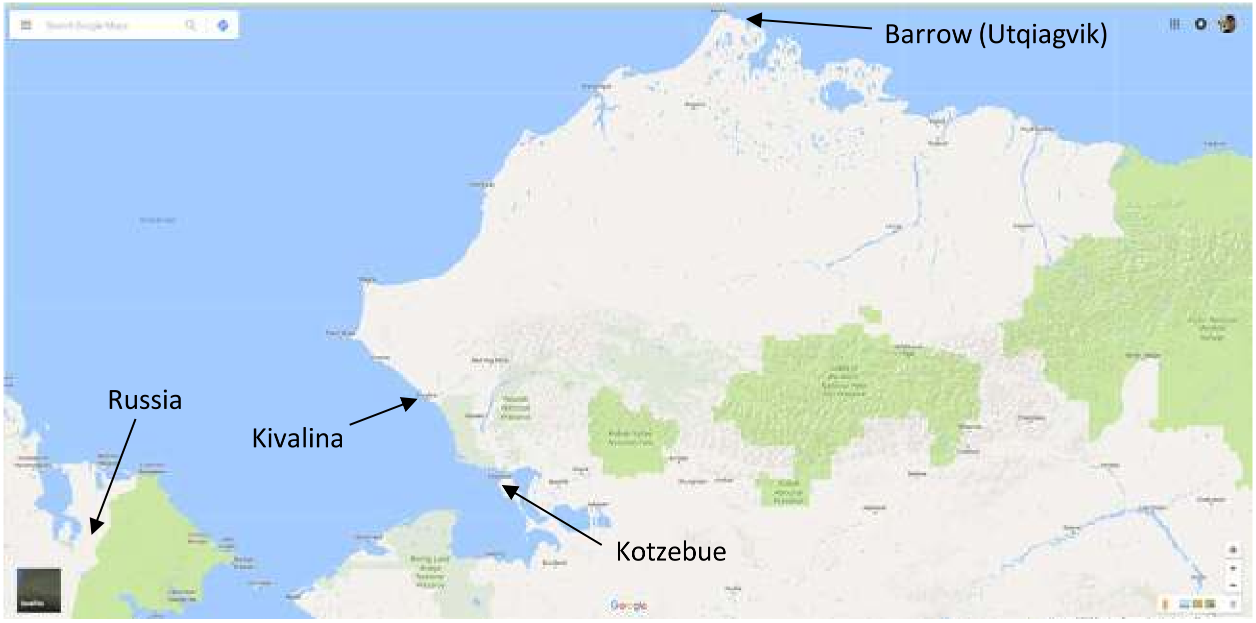
A 34 meter NRG Systems, Inc. tubular-type meteorological (met) tower was installed in May 2015 on K-Hill by Remote Solutions, a Kotzebue-based company. Kivalina is at the tip of an 8-mile barrier reef located between the Chukchi Sea and Kivalina River. It is located 80 air miles northwest of Kotzebue, Alaska. Kivalina falls within the arctic climate zone, characterized by seasonal extremes in temperature. Winters are long and harsh, and summers are short but warm. The Chukchi Sea is ice-free and open to boat traffic from mid-June to the first of November.[1]

The K-Hill test site was chosen by Northwest Arctic Borough given its proximity to the planned replacement Kivalina school location and eventual new community site. Also, following analysis of data from a 2011-2012 met tower that had been located 2.5 miles southeast of Kivalina, wind flow modeling

[1] Community data obtained from State of Alaska DCCED Community and Regional Affairs website

work accomplished in 2012 by V3 Energy, LLC indicated a high mean annual wind speed on the summit of K-Hill and hence strong potential for wind power development there.

Northern Alaska and Kivalina



Google Maps Image

Met Tower Installation

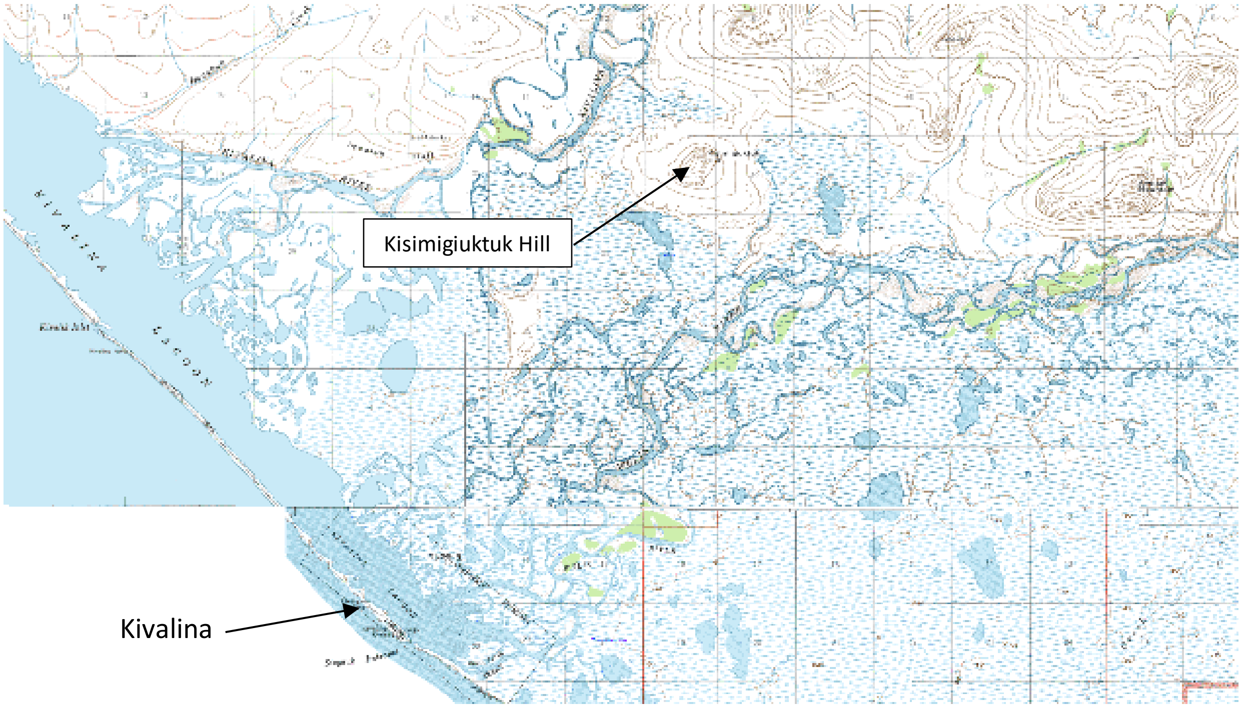
Installation details of the K-Hill met tower are documented in Remote Solutions' report, *Kisimigiuktuk Hill Meteorological Tower Installation*, dated May 15, 2015, which are excerpted for this wind resource assessment and wind flow modeling report.

Met tower details

Site number	1002
Latitude/longitude	N 67° 48' 52.80", W 164° 23' 12.66"[2]
Time offset	-9 hours from UTC (Yukon/Alaska time zone)
Site elevation	122 meters (400 ft.)
Datalogger type	NRG SymphoniePLUS3, 10 minute time step
Tower type	Guyed tubular, 15 cm (6 in.) diameter, 34 meter (112 ft.) height

[2] Documented on pg. 3 of the met tower installation report; geographic datum is not noted, although it is most likely NAD27, NAD83, or WGS84

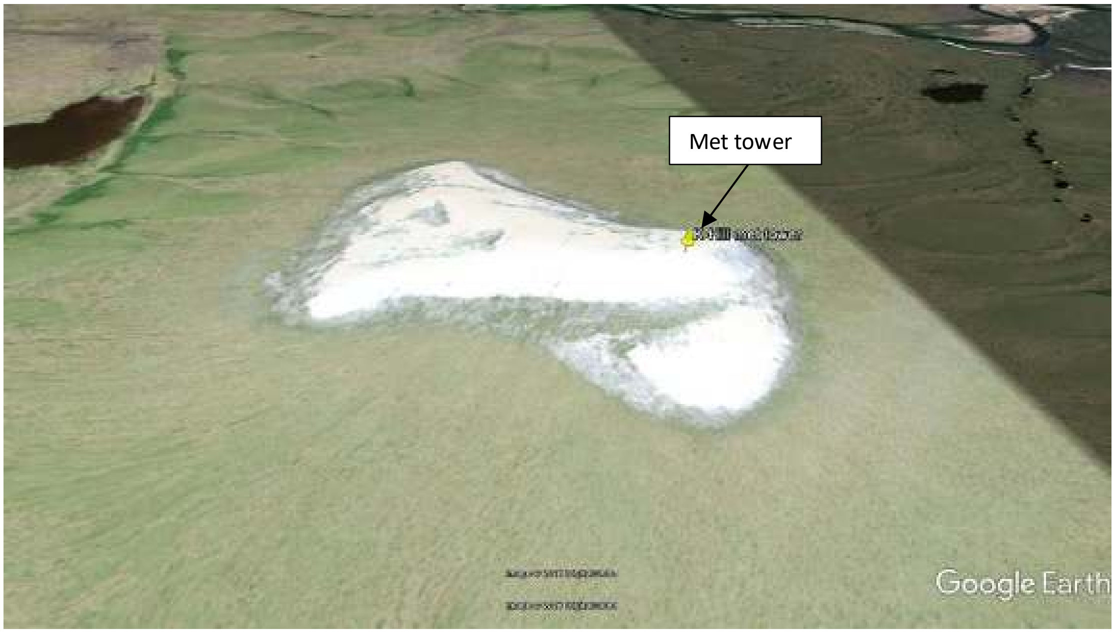
Kivalina and K-Hill, USGS topographic map



Kivalina and K-Hill, view north, Google Earth image

The met tower site location documented in the installation report was input to Google Earth, which operates with a WGS84 datum. This shows the met tower position as the extreme northeast point of the summit area of K-Hill. A Google Earth image in the met tower installation report, however, shows that the met tower was located approximately 190 meters to the southwest of the latitude/longitude information provided (see page 4 of the report and the image below). This may be validated by a photograph on page 11 of met tower installation report which appears to show higher K-Hill terrain beyond the met tower to the north. This contradictory information is inconclusive though and the met tower is assumed to have been located at the latitude and longitude noted in the met tower installation report, using a WGS84 datum reference.

K-Hill Met Tower, view west, Google Earth image



Installation report, met tower location

Google Earth image from page 4 of the met tower installation report

Sensor heights were documented in met tower installation report as 34 meters for the upper-level anemometers and the wind vane, and 20 meters for the lower level anemometer. These are nominal heights though; actual measured heights were not noted. By review of photographs in the installation report and with reference to the NRG Systems 34 meter met tower installation manual, actual sensor heights were estimated as 31.5 and 31.0 meters for the upper-level anemometers, 31.0 meters for the wind vane, and 18.5 meters for the lower level anemometer.

Met tower sensor information

Channel	Sensor type	Designation	SN[3]	Height	Multiplier	Offset	Orientation
1	NRG #40C anem.	19 m	238047	18.5 m	0.756	0.38	N/R[4]
2	NRG #40C anem.	32 m A	238046	31.5 m	0.759	0.33	N/R
3	NRG #40C anem.	32 m B	238045	31.0 m	0.757	0.37	N/R
7	NRG #200P vane	Direction		31.0 m	0.351	000[5]	N/R
9	NRG #110S Temp C	Temp		3 m	0.136	-86.38	N/R

Tower sensors, up-tower views (Remote Solutions, LLC photographs)

Figure 10: Tower Raising at 60%

View of north side (left image) and south side (right image) of met tower (from pg. 8 of the met tower installation report)

[3] Anemometer serial number

[4] Not recorded in the met tower installation report; orientation is normally documented as degrees true (relative to Earth's geographic North Pole) or degrees magnetic (relative to Earth's magnetic North Pole)

[5] Datalogger default value of 000 was referenced in the met tower installation report, but actual measured wind vane orientation was not noted

K-Hill met tower site (Remote Solutions, LLC photographs)

Figure 15: Installation View North

Site view to north (from pg. 11 of the met tower installation report)

Figure 16: Installation View East

Site view to east (from pg. 12 of the met tower installation report)

Figure 17: Installation View South

Site view to south (from pg. 13 of the met tower installation report)

Figure 18: Installation View West

Site view to west (from pg. 13 of the met tower installation report)

By all indications, the K-Hill met tower was properly installed with excellent anchoring and recovered data indicates that it operated normally during its one year service life. Omission of sensor orientation information in the installation report, however, is problematic. Interpretation of the up-tower photographs from the installation report indicates the wind direction vane was oriented slightly west of the north reference point of the tower. It is not known though if the north reference in the met tower installation report (see photos above) is precise true north, precise magnetic north, or a general northerly direction. This has considerable bearing with documentation of wind direction on K-Hill and will be discussed further in the wind rose section of this report.

A similar orientation issue exists with respect to the anemometers. The direction of the 20-meter-level anemometer can be deduced from the up-tower photographs as east, and orientation of the higher-level anemometers can be deduced as north and east, but the met tower installation report does not indicate which datalogger channel (2 or 3) is north or east. In other words, it is not possible from the installation report or the data to determine individual orientations of the upper-level anemometers. This has some bearing on the wind shear calculation which will be discussed later in this report.

Data Quality Control

K-Hill met tower 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 identify, and invalid or low quality data for situations such as logger initialization and other situations.

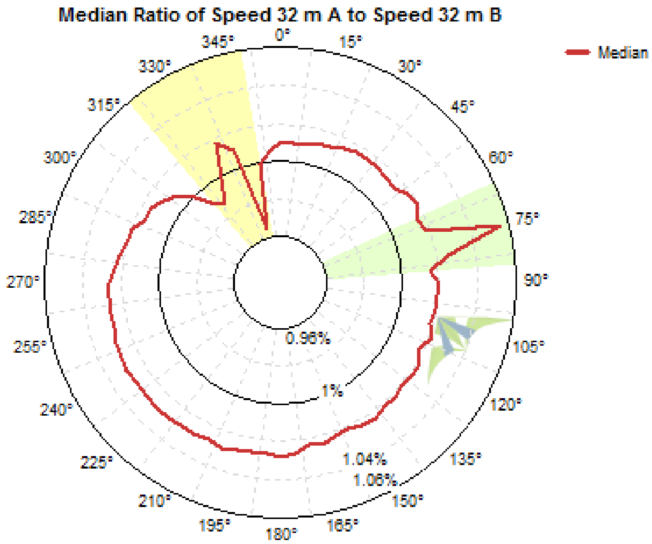
- Anemometer icing – data filtered if temperature < 1°C, speed SD = 0, and speed changes < 0.25 m/s for minimum 2 hours
- Vane icing – data filtered if temperature < 1°C and vane SD = 0 for minimum of 2 hours
- Tower shading of 32 meter A and B paired anemometers – data filtered when winds from ± 15° of behind tower; refer to graphic below

Surprisingly considering the proximity of Kivalina and K-Hill to the Chukchi Sea coast, icing conditions were very infrequent, indicating minimal concern for wind turbine energy production loss due to ice. This assumes of course that 2016/17 was representative of typical winters, but icing detected in data from a met tower located near Kivalina (operational one year, including winter 2011/12) also was very minimal. Kivalina apparently is too cold and dry to experience North Pacific-origin, moisture-laden maritime storms that cause significant atmospheric icing in the Bering Straits and Yukon-Kuskokwim Delta regions of Alaska.

With frequent northwesterly winds[6], tower shadow affected the northwest-facing[7] 32 meter-level anemometer very significantly more often than the east-facing 32 meter level anemometer. Applying the tower shading filter though would essentially eliminate the northwest-facing anemometer from the data. Given the very robust nature of the K-Hill wind resource and otherwise excellent data recovery, filtering for tower shading was considered not necessary in this analysis. For future reference though, paired anemometers should be oriented 60 degrees either side of a prevailing wind (for a 120 degree sensor separation). A NRG System, Inc. technical bulletin indicates that this configuration yields optimally-representative wind speed data.

[6] Note documentation problem regarding wind vane orientation; actual prevailing wind north to north-northeast; see wind rose section of report for discussion
[7] This anemometer likely faced north to north-northeast

Tower shading plot (data filter not employed)



Sensor data recovery table

Data Column	Possible Records	Valid Records	Recovery Rate	Icing	Invalid[8]
Speed 19 m	52,488	52,009	99.1%	334	145
Speed 32 m A	52,488	51,982	99.0%	361	145
Speed 32 m B	52,488	51,965	99.0%	378	145
Temperature 3 m	52,488	52,342	99.7%	0	146
Direction 32 m	52,488	51,973	99.0%	371	144

Data Synthesis

Filtering removes compromised sensor readings from the data set. This is desirable for icing in that it eliminates the negative speed bias of false "zero" data. Filtering for tower shadow is more nuanced in that filtered data biases both paired anemometers, but the direction of bias is not apparent for either. One solution is to remove filtered data and fill the missing gaps with synthesized data using a gap-filling subroutine contained in Windographer Pro software. Gap-filling, or data synthesis, can yield a more representative and realistic data set, especially for tower shadow-filtered data in that flagged data from one paired anemometer can be reconstructed with data from the other anemometer of the pair. The result is a more true representation of wind speeds for both paired anemometers.

Gap-filling icing-flagged data is more complex in that often all anemometers and/or wind vanes freeze simultaneously and hence Windographer software must use a Markov transition matrix[9] to create a probable result for the flagged period. For short icing periods, the inherent uncertainty of this approach is low; for long periods, it is higher. Data synthesis using the Markov transition gap-fill subroutine was

[8] Invalid data from initialization of sensors during tower installation

[9] Described in the Windographer software Help section, or see https://en.wikipedia.org/wiki/Markov_chain

not employed for the K-Hill met tower data set due to minimal icing in the dataset and the decision not to filter for tower shadow.

Wind Speed

Anemometer data obtained from the met tower, from the perspectives of both mean wind speed and mean wind power density, indicate a very strong wind resource. Note that cold temperatures contributed to a higher wind power density than standard conditions would yield for the measured mean wind speeds. This is reflected in the CRMC (cubed root mean cubed) wind speed, which reflects a calculation of a steady wind speed, at the measured mean air density, that would yield the measured mean wind power density. In other words, given the cold temperatures on K-Hill, the winds punch above their weight.

Filtered anemometer data summary

Variable	Speed 32 m A	Speed 32 m B	Speed 19 m
Measurement height (m)	31.5[10]	31.0	18.5
Mean wind speed (m/s)	7.94	7.89	7.75
Max 10-min avg. wind speed (m/s)	29.4	29.7	29.1
Max gust wind speed (m/s)	31.8	33.2	33.1
CRMC[11] wind speed (m/s)	10.5	10.5	10.2
Weibull k	1.67	1.65	1.70
Weibull c (m/s)	8.88	8.80	8.68
Mean power density (W/m²)	754	745	694
Mean energy content (kWh/m²/yr)	6,608	6,530	6,077
Energy pattern factor	2.31	2.33	2.29
Frequency of calms (%)	23.0	23.3	23.5
Data recovery rate (%)	96.4[12]	96.4	96.5

Time Series

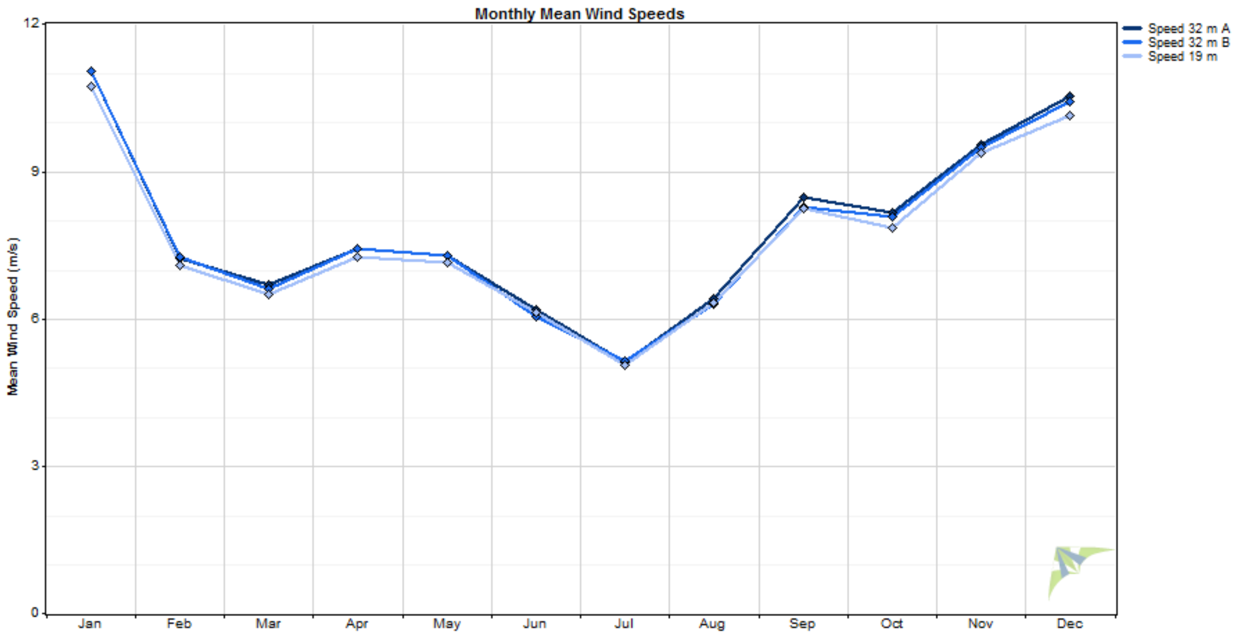
Time series calculations indicate substantially higher wind speeds during the winter months compared to summer. Interestingly, the daily wind speed profile (on an annual basis) of K-Hill indicates only a minimal diurnal variation of wind speeds. Monthly views of diurnal wind speed profile though indicate much more variability.

[10] As previously noted, anemometer identification was not noted in the installation documentation, hence the 32 m B anemometer could be at 31.5 m, not 32 m A

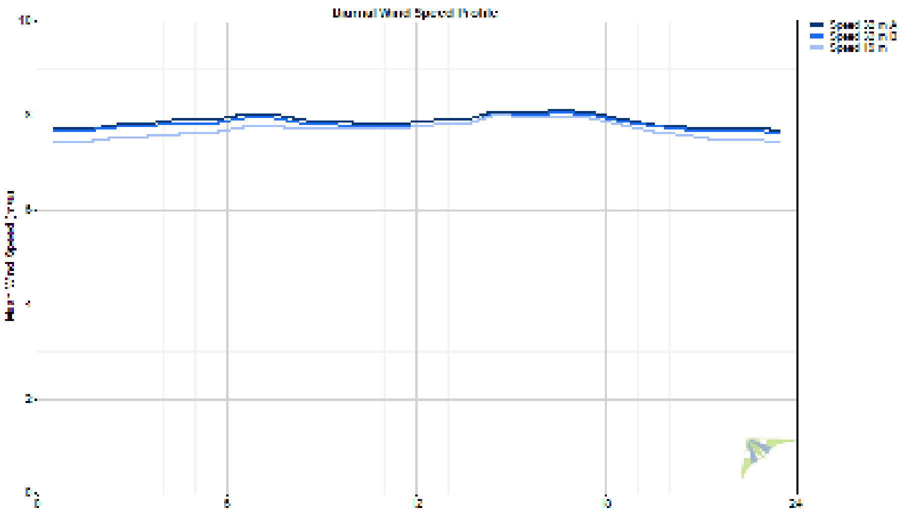
[11] Cubed root mean cube: a steady wind at CRMC wind speed has a wind power density equal to that measured; from Windographer software Help section

[12] Data recovery in this table includes missing days of data and hence differs from the sensor data recovery table

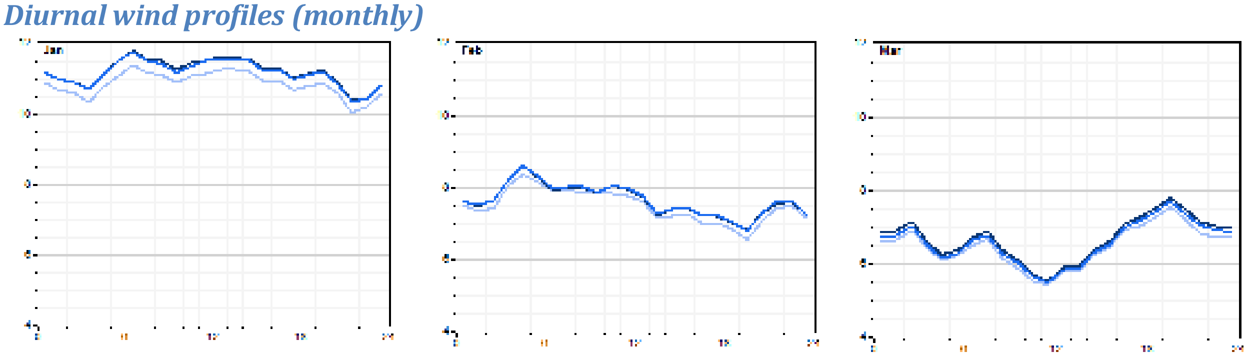
Monthly time series (annual), mean wind speeds

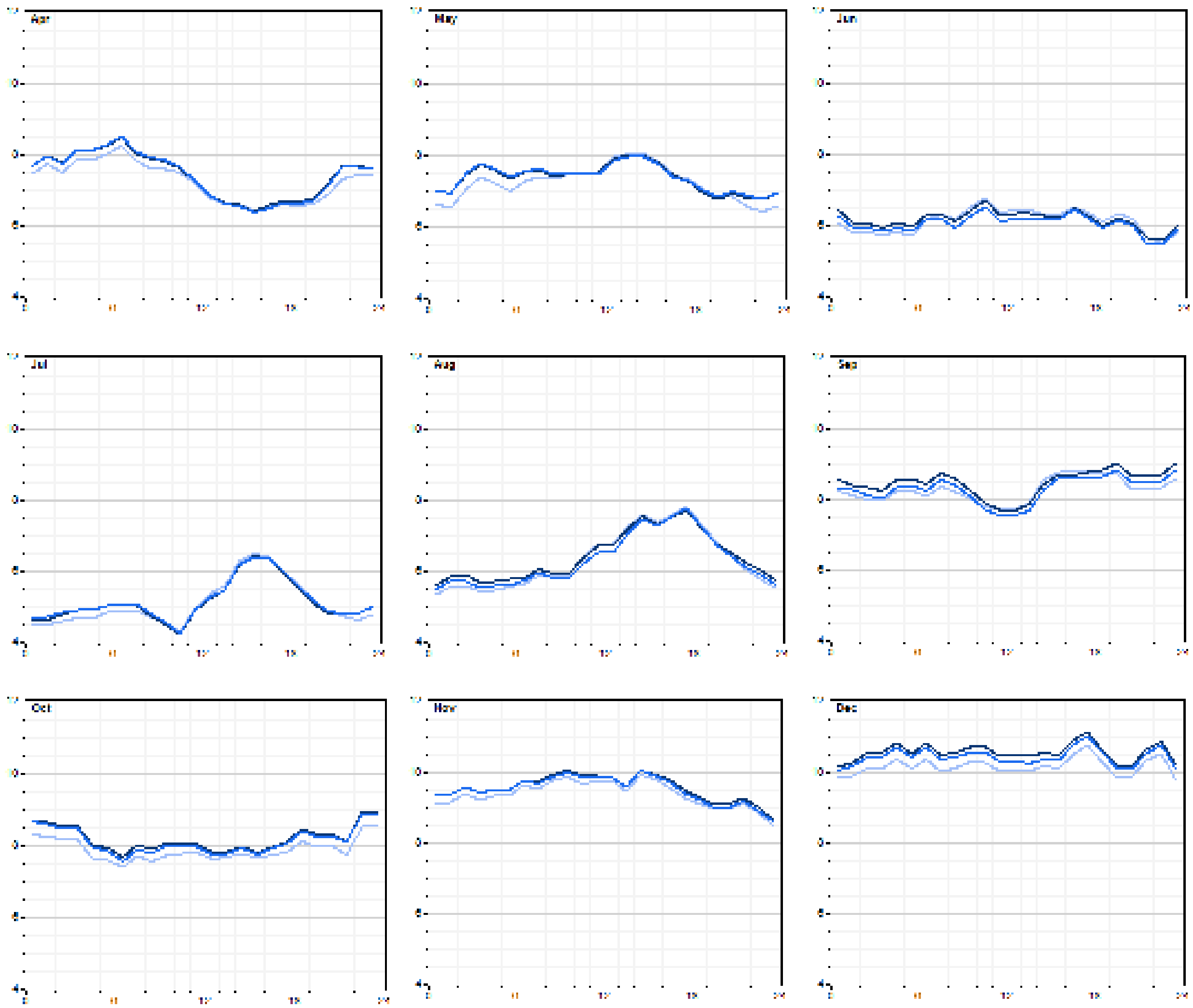


Diurnal wind profile (annual)



Diurnal wind profiles (monthly)





Detailed monthly data from the 32 m A anemometer is profiled because it recorded the highest wind speeds of the three anemometers on the met tower. Note again though that direction of this anemometer is not known. Likely though it is the east-facing anemometer of the 32 meter pair as wind flow at the anemometer facing the prevailing wind would be compromised somewhat by the tower immediately behind the sensor.

32 m A anemometer data summary

Year	Month	Raw Mean (m/s)	Filtered Mean (m/s)	Max 10-min Avg (m/s)	Max Gust (m/s)	Std. Dev. (m/s)	Weibull k (-)	Weibull c (m/s)
2015	May	7.67	7.67	22.4	25.7	4.51	1.77	8.63
2015	Jun	6.19	6.19	17.7	19.9	3.00	2.17	6.99
2015	Jul	5.12	5.12	12.7	15.4	2.45	2.15	5.75
2015	Aug	6.43	6.43	19.9	24.6	3.58	1.80	7.19
2015	Sep	8.48	8.48	22.0	25.7	4.91	1.78	9.53

Year	Month	Raw Mean (m/s)	Filtered Mean (m/s)	Max 10-min Avg (m/s)	Max Gust (m/s)	Std. Dev. (m/s)	Weibull k (-)	Weibull c (m/s)
2015	Oct	8.20	8.17	21.7	25.7	3.88	2.25	9.27
2015	Nov	9.55	9.55	27.2	31.8	5.15	1.94	10.78
2015	Dec	10.56	10.56	25.1	29.2	5.42	2.04	11.91
2016	Jan	11.20	11.05	26.5	29.2	5.13	2.32	12.63
2016	Feb	7.65	7.25	29.4	31.8	5.42	1.48	8.49
2016	Mar	6.70	6.70	21.8	24.6	5.59	1.11	6.95
2016	Apr	7.43	7.43	21.1	23.6	3.91	1.98	8.38
2016	May	6.95	6.87	22.9	25.7	4.57	1.54	7.73
Annual		7.94	7.89	29.4	31.8	4.86	1.67	8.88

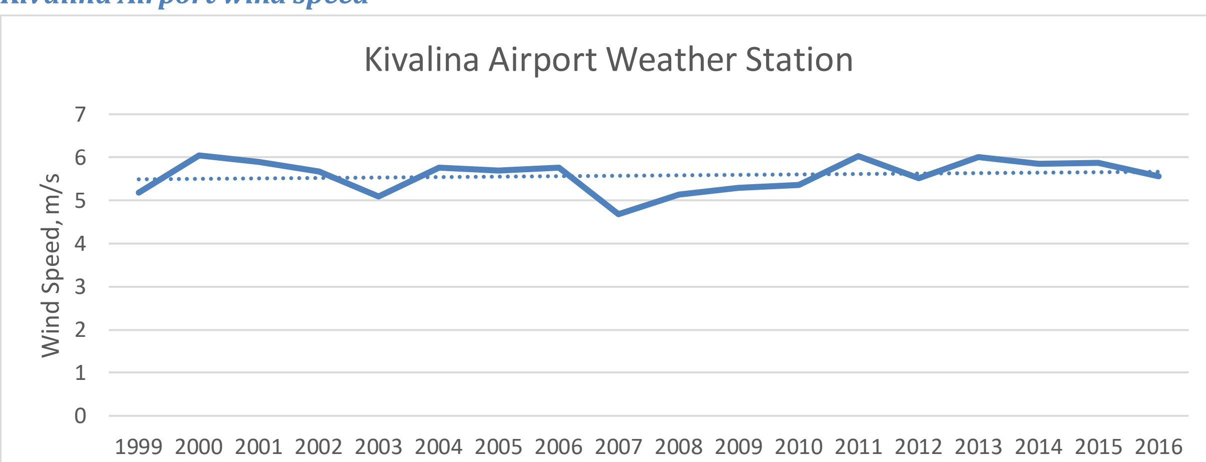
Long-term Wind Speed Average

Comparing the 12 months of measured wind speed data at the K-Hill met tower is possible by reference to the nearby Kivalina Airport automated weather station. Data for this station was obtained for the period of January 1999 through December 2016. For this 17 year time period, the weather station recorded an average wind speed of 5.61 m/s (at a 10 meter measurement height).

In 2015 and 2016, of which the K-Hill met tower was operational partially for each, the Kivalina airport weather station wind speed average was 5.71 m/s, which is 1.8% higher than the 17 year average back to 1999. But, given distance to the airport, partial years of K-Hill data for 2015 and 2016, and the significantly different wind measurement methodology of the airport weather station, K-Hill met tower wind speed data was not adjusted accordingly.

Note a very slight increasing trend in wind speed over the 17-year period of the Kivalina airport weather station, although there is significant variability year-to-year. Recent years – since about 2010 – have been relatively windy compared to the preceding four or five years.

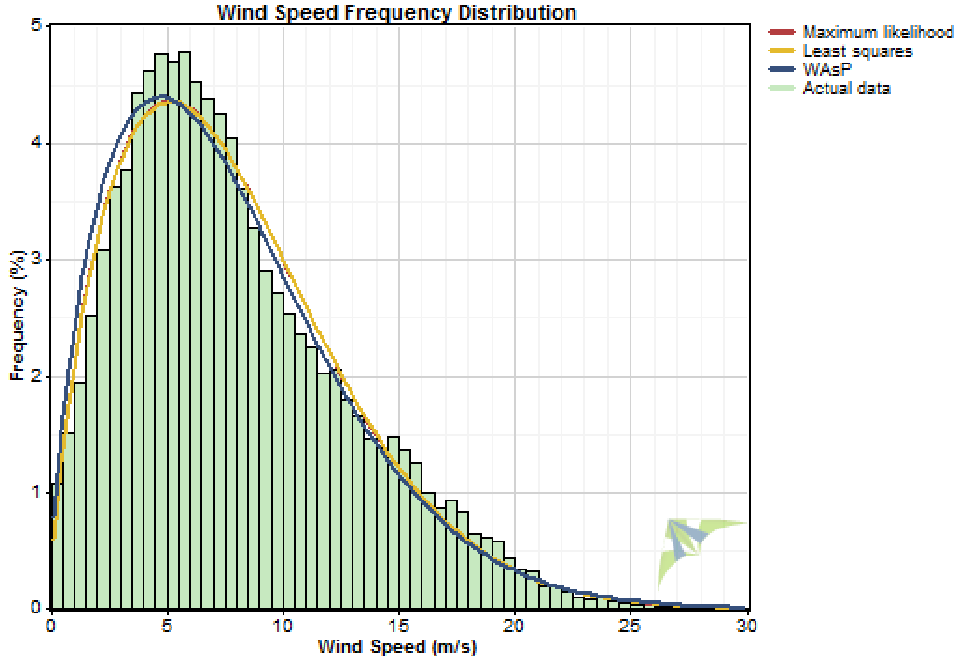
Kivalina Airport wind speed



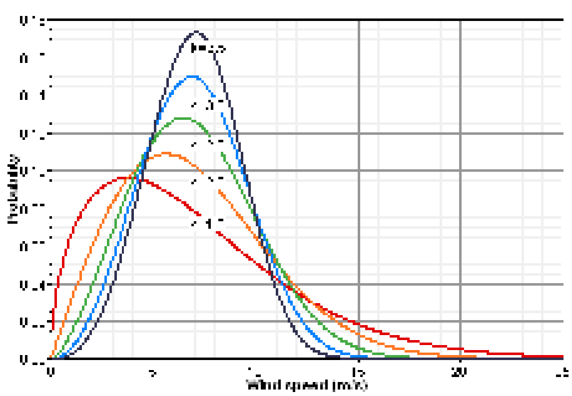
Probability Distribution Function

The probability distribution function (PDF), or histogram, of the K-Hill met tower site wind speed indicates a shape curve dominated by relatively high wind speeds and is mostly reflective of 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 32 meter A anemometer, the most frequently-occurring wind speeds are between 4 and 8 m/s with few wind events exceeding 25 m/s, the cutout speed of most wind turbines.

PDF of 32 m A anemometer



Weibull k shape curve table



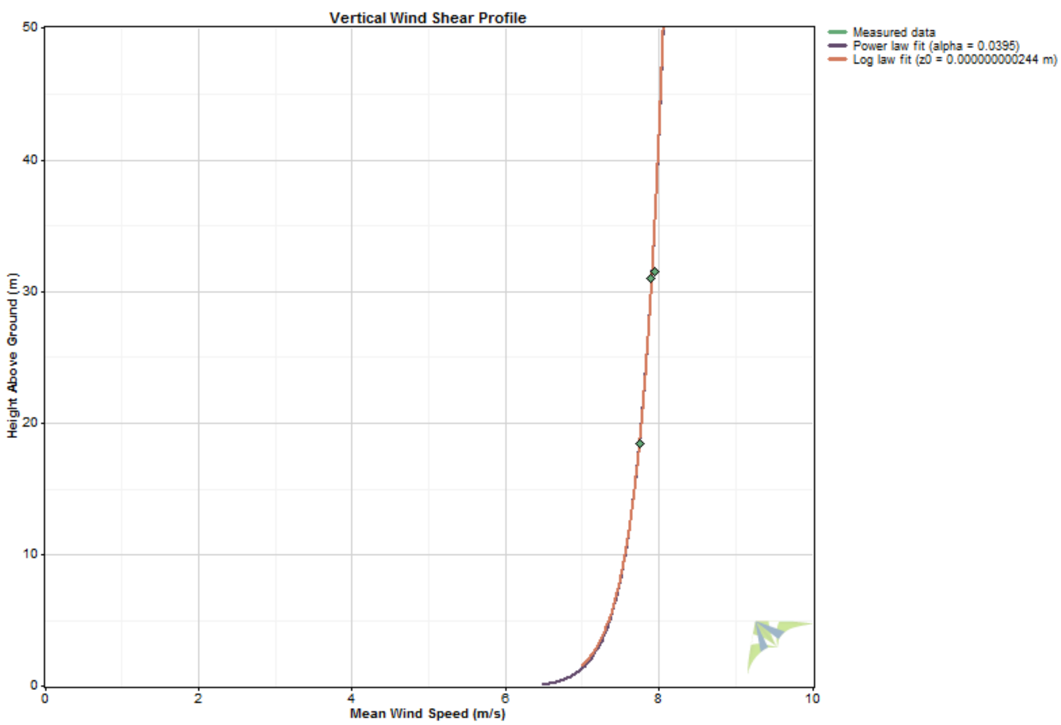
Weibull values table, 32 m A anemometer

Algorithm	Weibull k	Weibull c (m/s)	Mean (m/s)	Proportion Above 7.94 m/s[13]	Power Density (W/m2)	R Squared[14]
Maximum likelihood	1.67	8.88	7.94	0.437	716	0.981
Least squares	1.67	8.90	7.95	0.437	720	0.981
WAsP	1.61	8.67	7.77	0.419	709	0.979
Actual data			7.94	0.419	709	

Wind Shear and Roughness

Wind shear at the K-Hill met tower site was calculated with both 32 m anemometers and the 19 m anemometer. This is not ideal in that typically wind shear is measured with "stacked" anemometers – one (or more) directly above the other – but the met tower installation report did not identify orientation of the anemometers, hence the use of both 32 meter level anemometer for the shear calculation in this analysis. The calculated power law exponent of 0.039 indicates extremely low wind shear at the site, which is typical of mountain-top locations. Calculated surface roughness at the site is 0 meters (the height above ground where wind speed would be zero) for a roughness class of 0 (description: water surface).

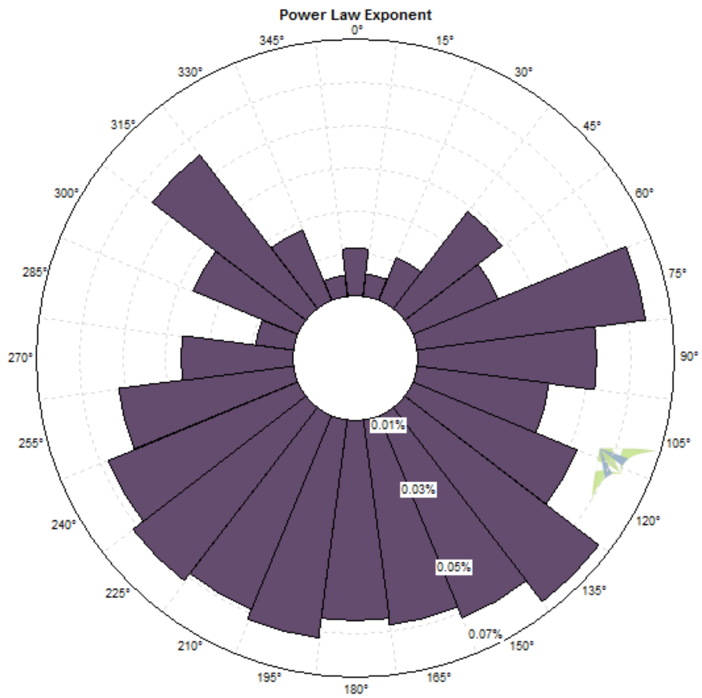
Vertical wind shear profile



[13] 7.94 m/s is the mean annual wind speed
[14] Relatedness or correlation of Weibull approximation algorithm with actual data

The wind shear rose indicates virtually no wind shear with northerly winds and higher shear from infrequent easterly, southerly and westerly winds. This can be understood by reference to the topography of Kisimigiuktuk Hill with a steep gradient on the north side, which is the direction of the prevailing wind.

Wind shear by direction graph[15]



Extreme Winds

International Electrotechnical Commission (IEC) 61400-1, 3rd edition extreme wind probability classification is one criteria – with turbulence the other – that describes site suitability for wind turbine models. Extreme wind is described by the 50 year, 10-minute average V_{ref}, or reference velocity in a 50 year return period; in other words, V_{ref} is the 10-minute average wind speed predicted to occur once every 50 years.

IEC 61400-1 extreme wind classification

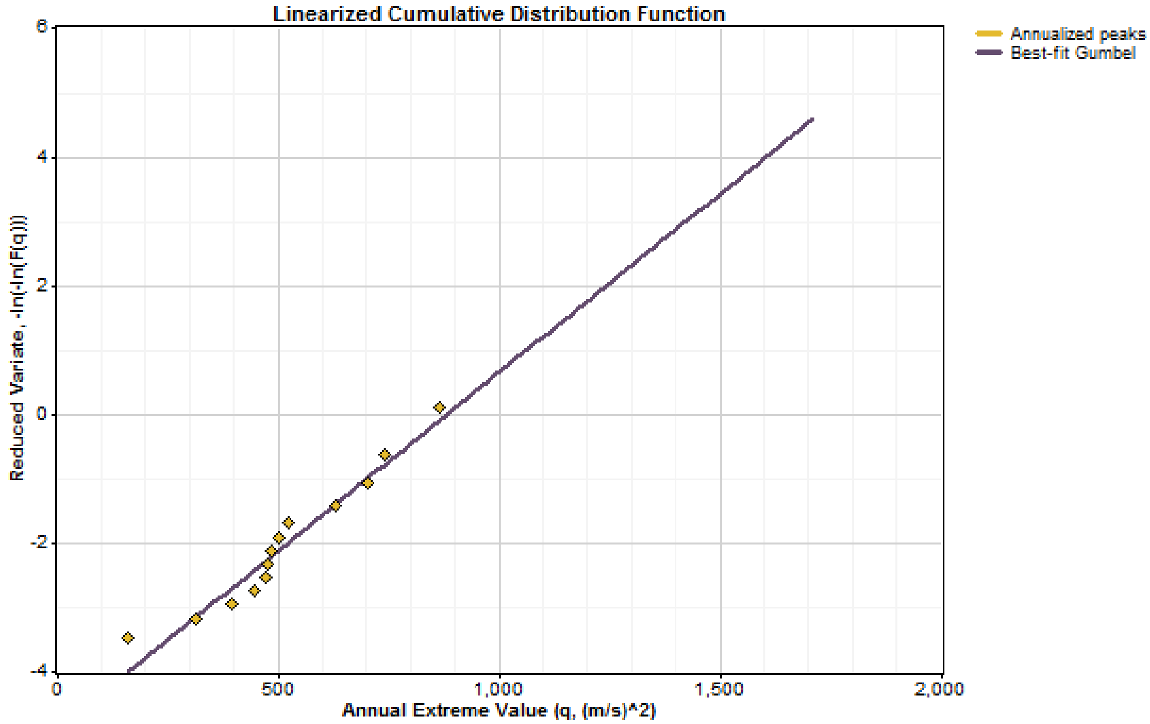
IEC 61400-1, 3rd ed.	
Class	V_{ref}, m/s
I	50
II	42.5
III	37.5
S	designer-specified

[15] Note uncertainty regarding wind vane orientation; see wind rose section for more information

One method to estimate V_{ref} is a periodic maximum, or Gumbel distribution, analysis modified for monthly maximum winds versus annual maximum winds, which are typically used for this calculation. Twelve months of wind data in the met tower data set are extremely minimal for this analysis, but useful information may be gleaned nonetheless.

For this analysis, the 32 meter level A anemometer is referenced because it recorded the highest wind speeds of the three anemometers on the tower. With filtered and preconditioned data[16] (by squaring maximum measured monthly wind speeds), the predicted V_{ref} by this method is 39.8 m/s. This result meets IEC 3rd edition Class II criteria, the middle category of extreme wind speed probability.

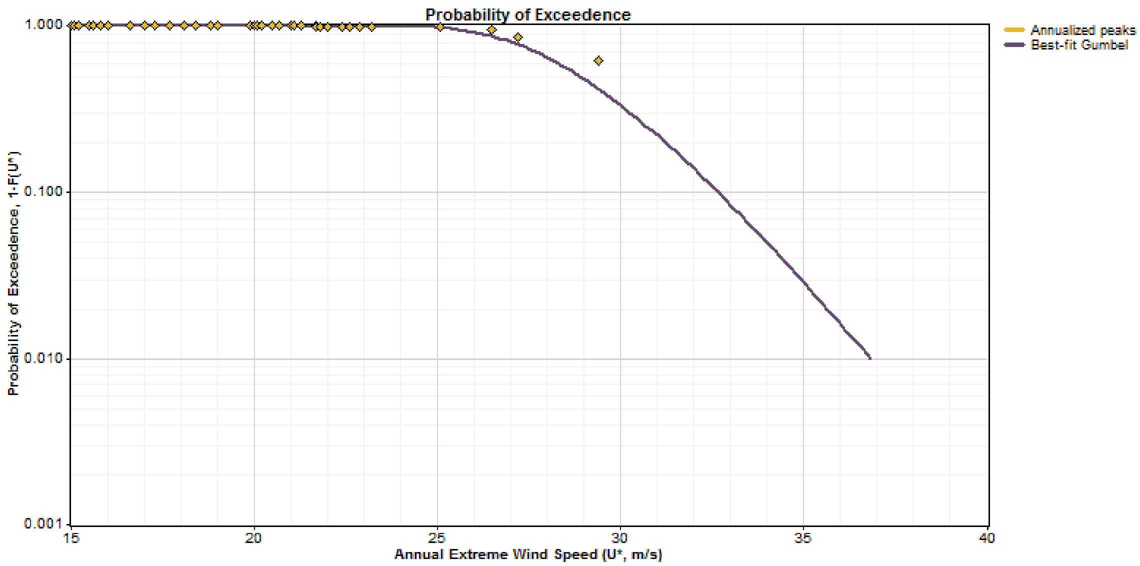
Periodic maxima cumulative distribution, 32 m A anemometer



A second technique, Method of Independent Storms, yields a V_{ref} estimate of 35.6 m/s, lower than that predicted by the periodic maxima method and which would classify the site as an IEC 61400-1 Class III extreme wind, the lowest defined category.

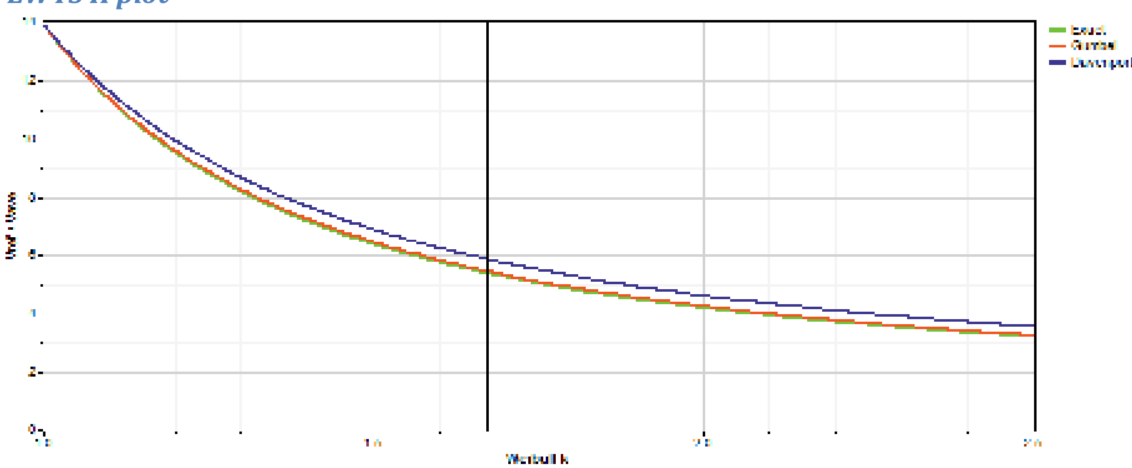
[16] Preconditioning improves the accuracy of 50-year extreme wind speed estimates; Windographer Help (references 1996 (Harris) and 2009 (Langreder et al.) studies).

Method of Independent Storms



A third method, known as EWTS II (European Wind Turbine Standards II), ignores recorded peak wind speeds and calculates V_{ref} from the Weibull k factor. There are three variations of this method – Exact, Gumbel and Davenport – which yields a V_{ref} between 42.9 and 46.8 m/s for K-Hill. These are mostly in-line with, but also higher than, the periodic maxima method and high enough to classify K-Hill as IEC 3rd edition Class I, which is the highest-defined category of extreme wind.

EWTS II plot



EWTS II table

Method	Vref (50 yr) (m/s)
Periodic Maxima	39.8
Method of Independent Storms	35.6
EWTS II (Exact)	42.9
EWTS II (Gumbel)	43.5
EWTS II (Davenport)	46.8

Extreme Wind Summary

The calculated V_{ref} wind speeds by the three methods described above indicate IEC 61400-1, 3rd edition Class I, II and III wind classification. Note again that twelve months of wind data is very minimal for an extreme wind analysis and additional data would add confidence to the extreme wind analysis. That said, the practical importance is that wind turbines installed on K-Hill ought to be IEC 61400-1 Class I certified. A IEC Class I turbine model, compared to a Class III variant, would be equipped with a smaller rotor diameter. This could be discussed with prospective turbine manufacturers, however, as they may take a less conservative view of the K-Hill data.

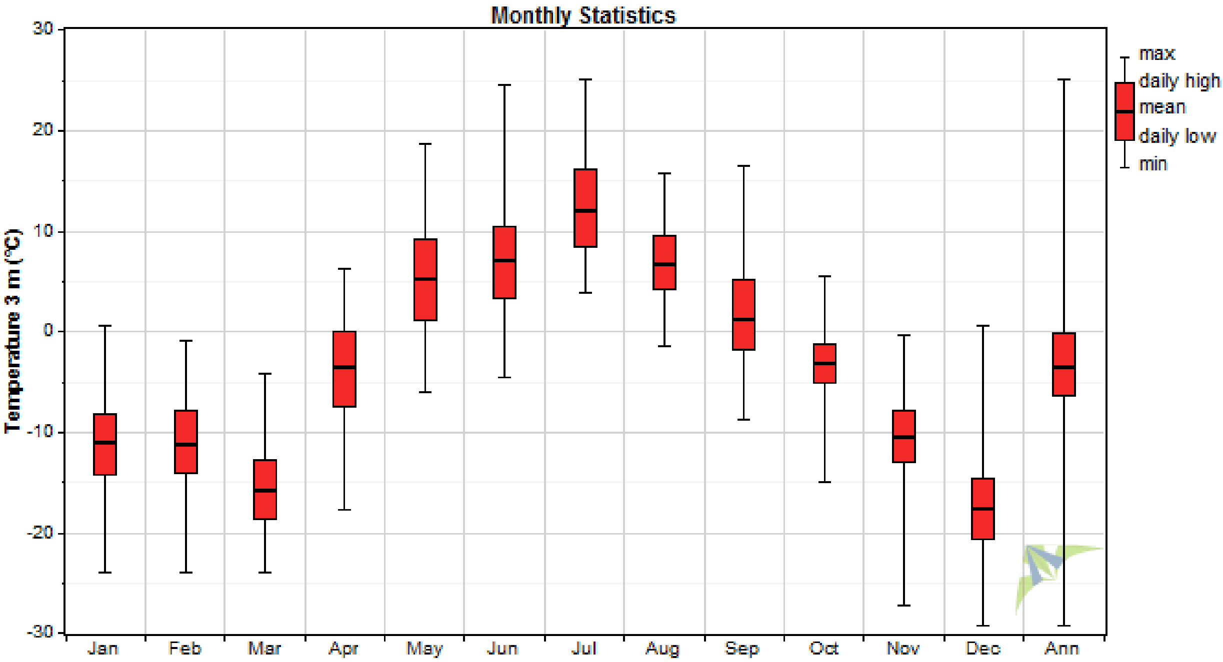
Temperature, Density, and Relative Humidity

During the 12-month measurement period, K-Hill experienced a cold winter and warm summer, with resulting higher than standard air density. Calculated mean-of-monthly-mean (or annual) air density during the met tower test period exceeds by 6.4 percent the 1.210 kg/m^3 standard air density for a 122 meter elevation. 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 (°C)	Min (°C)	Max (°C)	Mean (°F)	Min (°F)	Max (°F)	Mean (kg/m3)	Min (kg/m3)	Max (kg/m3)
Jan	-10.8	-23.8	0.6	12.6	-10.8	33.1	1.326	1.269	1.395
Feb	-11.1	-23.9	-0.9	12.0	-11.0	30.4	1.327	1.276	1.395
Mar	-15.7	-23.9	-4.1	3.7	-11.0	24.6	1.351	1.292	1.395
Apr	-3.4	-17.6	6.3	25.9	0.3	43.3	1.289	1.242	1.361
May	5.5	-6.0	18.8	41.9	21.2	65.8	1.245	1.186	1.301
Jun	7.1	-4.4	24.6	44.8	24.1	76.3	1.236	1.161	1.293
Jul	12.2	4.0	25.1	54.0	39.2	77.2	1.214	1.159	1.253
Aug	6.8	-1.3	15.9	44.2	29.7	60.6	1.240	1.199	1.278
Sep	1.4	-8.6	16.5	34.5	16.5	61.7	1.266	1.196	1.314
Oct	-3.0	-14.9	5.5	26.6	5.2	41.9	1.280	1.207	1.346
Nov	-10.3	-27.1	-0.2	13.5	-16.8	31.6	1.323	1.273	1.413
Dec	-17.5	-29.2	0.7	0.5	-20.6	33.3	1.361	1.268	1.426
Annual	-3.3	-29.2	25.1	26.1	-20.6	77.2	1.287	1.159	1.426

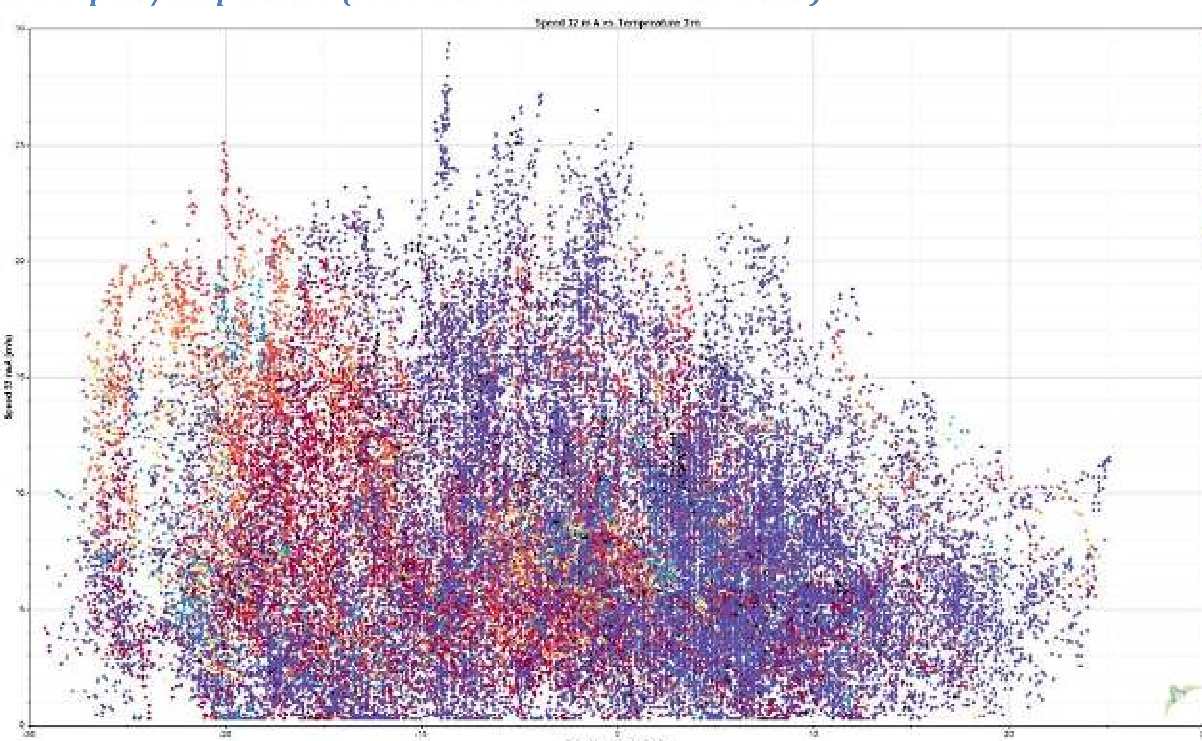
K-Hill temperature boxplot graph



Wind Speed vs. Temperature Scatterplot

A wind speed versus temperature scatterplot indicates cool to very cold temperatures at the K-Hill met tower site with many strong winds occurring when temperatures are less than -20° C (-4° F). With this, only wind turbine models with an arctic option – designed for -40° C operations – are suitable for K-Hill.

Wind speed/temperature (color code indicates wind direction)



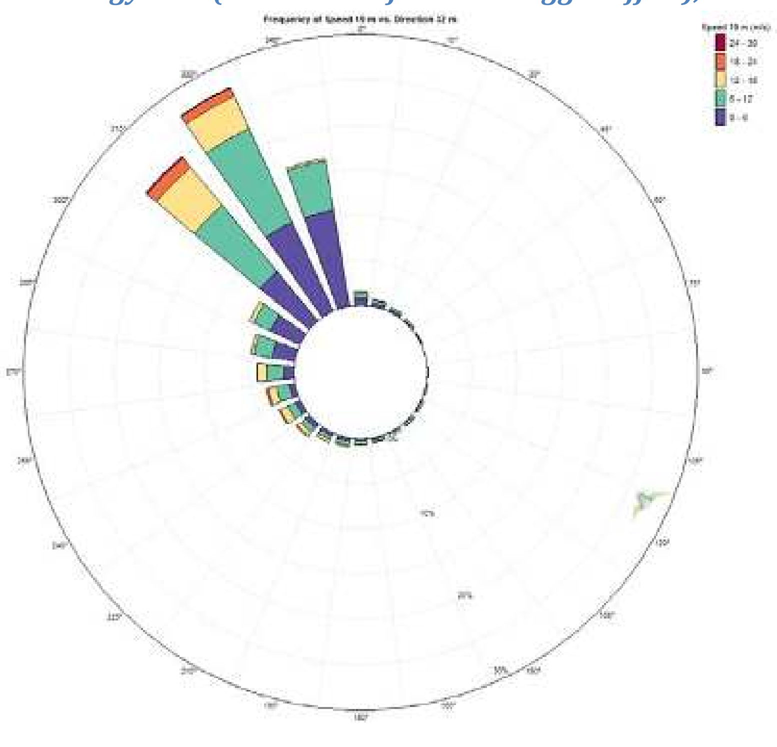
Wind Direction

The met tower installation report did not document wind vane orientation other than by reference to the datalogger offset default of 000°, which most likely is a carryover from previous use of the datalogger at the Quarry Road site in Noorvik. As noted previously in this report, met tower installation report photographs show the wind vane oriented perhaps 25 degrees northwest of a photograph indicating a north view. It is not known, however, if the north reference is true or magnetic, although the latter is a reasonable assuming use of a magnetic compass for orientation.

If the direction photographs in the met tower installation report are based on a magnetic reference, 20 degrees of declination must be added to achieve to a true geographic reference. With this, a 045° wind vane offset (025° orientation of the vane from the north reference of the tower, and 020° magnetic declination) was added to the Windographer data file to correct wind vane orientation. This aligns the K-Hill wind rose with that documented by the ASOS[17] weather station at the nearby Kivalina airport and the wind rose measured by the Kivalina Site 9750 met tower located two miles southeast of Kivalina, which was operational May 2011 through May 2012.

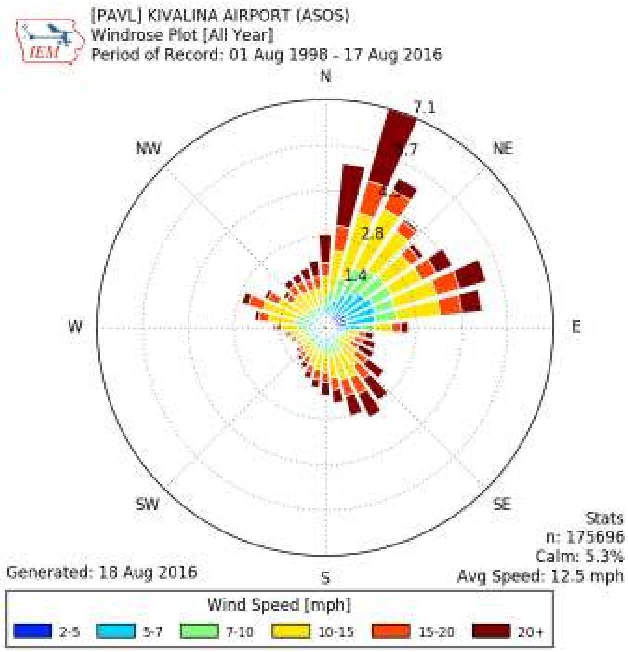
With the revised wind rose, wind frequency rose data indicates that winds at the K-Hill met tower site are very strongly northerly/northeasterly.

Wind frequency and energy rose (with 000° default datalogger offset), not corrected

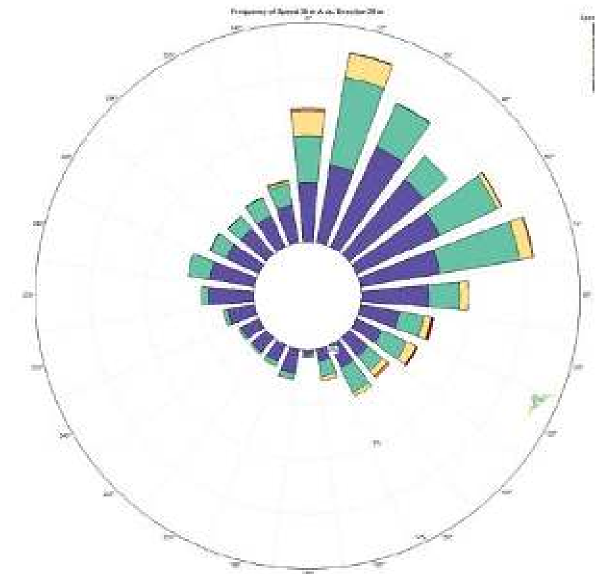


[17] Automatic Surface Observing System

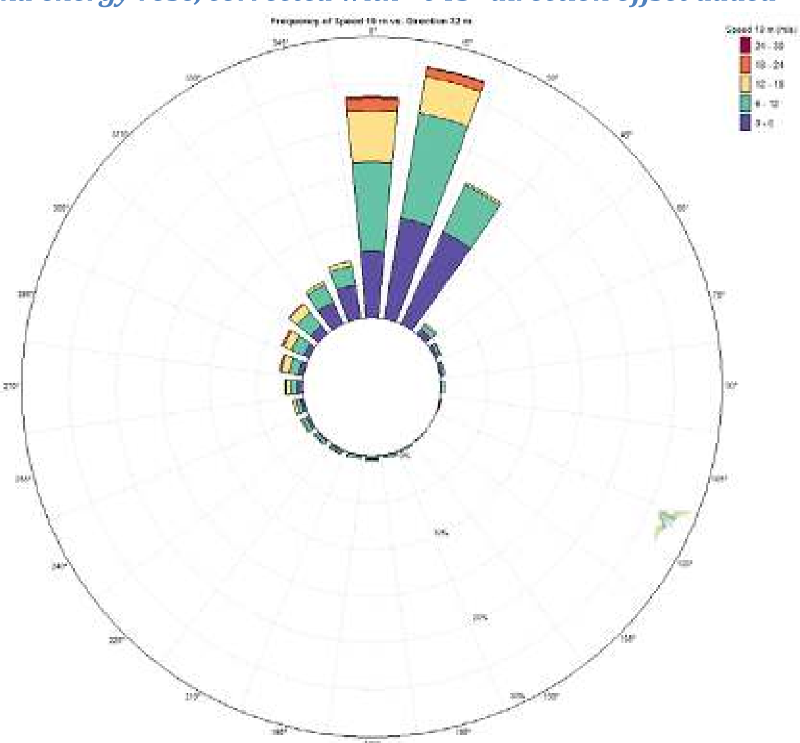
Kivalina Airport wind rose



Kivalina (Site 9750) met tower wind rose



Wind frequency and energy rose, corrected with +045° direction offset added



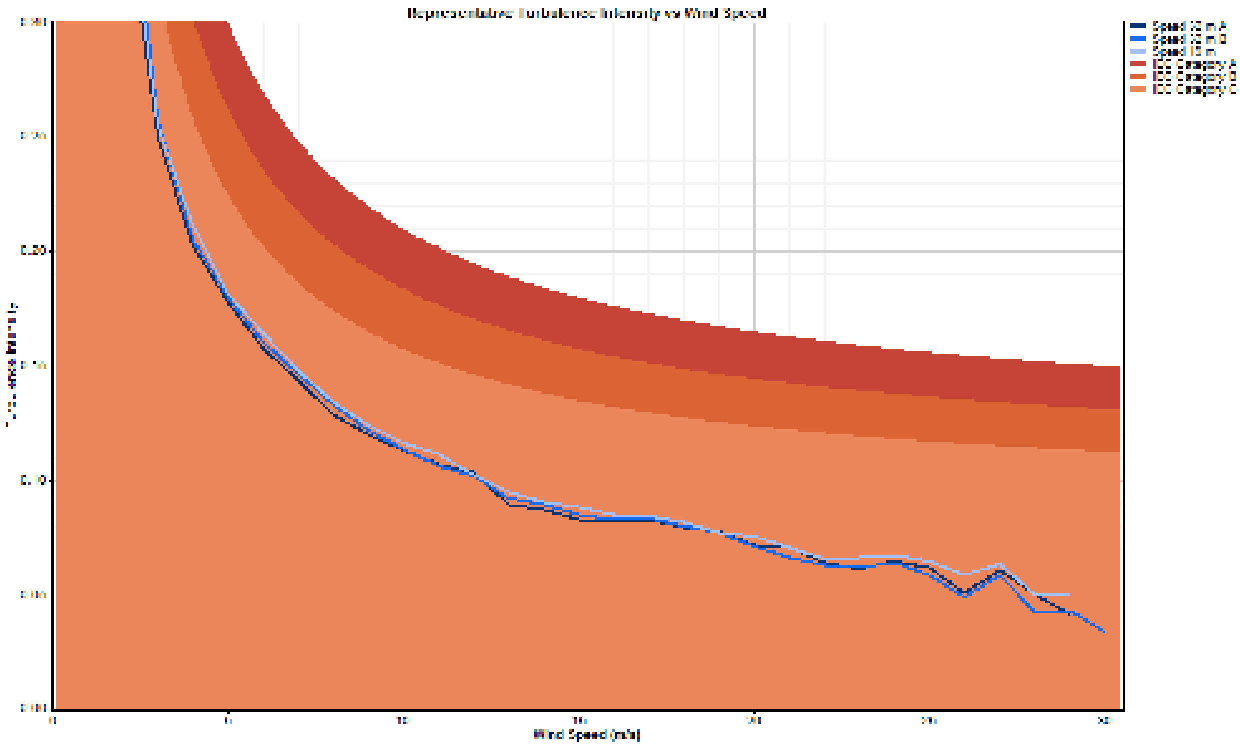
Turbulence

The turbulence intensity (TI) at the K-Hill met tower site is extremely low with a mean turbulence intensity of 0.061 and a representative turbulence intensity of 0.084 at 15 m/s wind speed at the 32 meter level, indicating very smooth air for wind turbine operations. This equates to an International Electrotechnical Commission (IEC) 61400-1, 3rd Edition (2005) turbulence category C, the lowest defined category.

Turbulence Intensity table

	All Speed Bins				15 m/s Speed Bin			
	Mean TI	SD of TI	Representative TI	Peak TI	Mean TI	SD of TI	Representative TI	IEC 3 ed. Turb. Cat.
Speed 32 m A	0.120	0.101	0.250	1.10	0.061	0.018	0.084	C
Speed 32 m B	0.123	0.104	0.256	1.11	0.063	0.018	0.086	C
Speed 19	0.124	0.097	0.248	1.29	0.068	0.017	0.090	C

Turbulence intensity, all direction sectors



WAsP Wind Flow Model

WAsP (Wind Atlas Analysis and Application Program) is a PC-based software designed to estimate wind resource and power production for individual wind turbines and/or wind turbine farms.

Orographic Modeling

WAsP modeling begins with import of a digital elevation map (DEM) of the subject site and surrounding area and conversion of coordinates to Universal Transverse Mercator (UTM). UTM is a geographic coordinate system that uses a two-dimensional Cartesian coordinate system to identify locations on the surface of Earth. UTM coordinates reference the meridian of its particular zone (60 longitudinal zones are further subdivided by 20 latitude bands) for the easting coordinate and distance from the equator for the northing coordinate. Easting and northing units are meters and elevations of the DEMs are converted to meters if necessary for import into WAsP software.

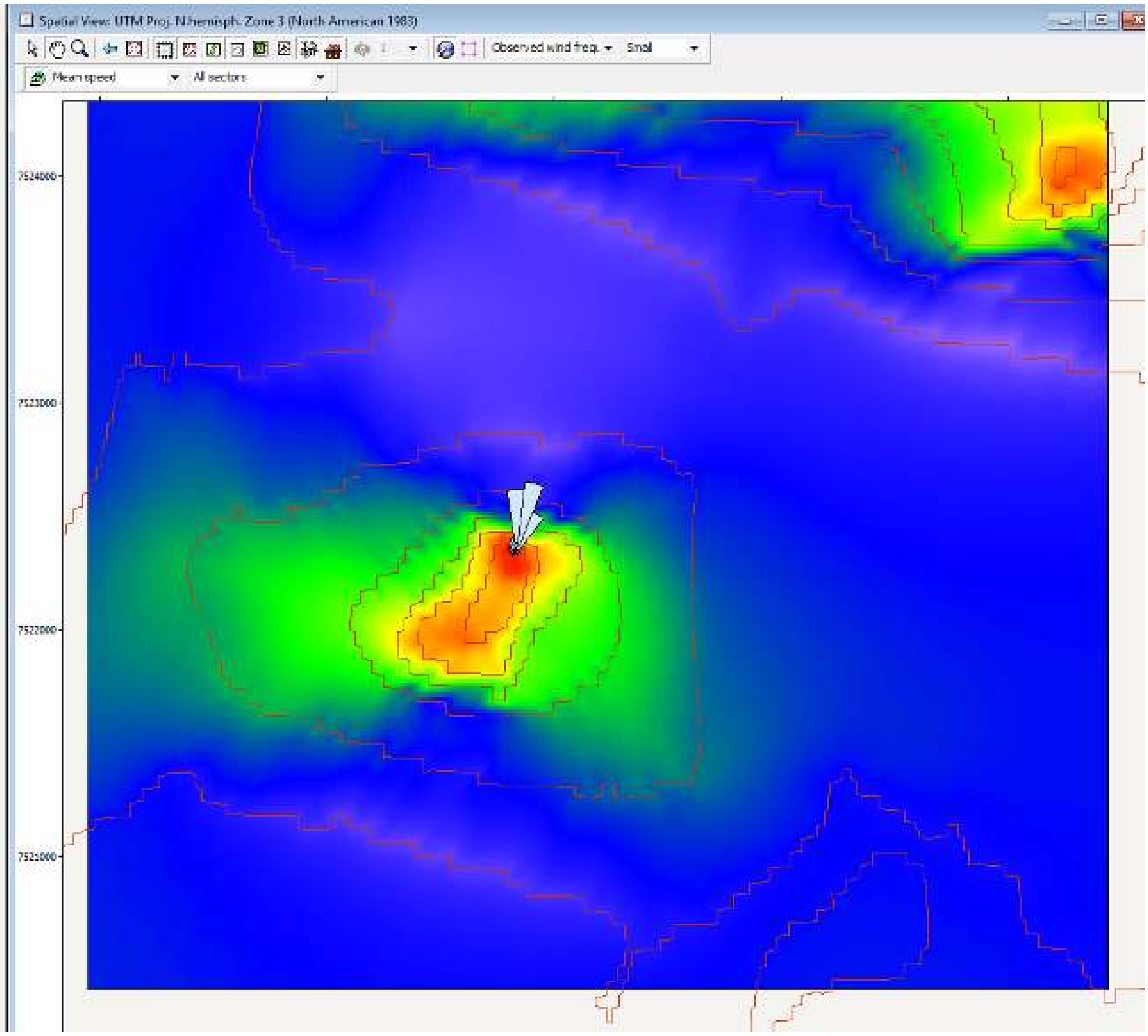
A met tower reference point is added to the digital elevation map, wind turbine locations identified, and a wind turbine model selected to perform the calculations. WAsP considers the orographic (terrain) effects on the wind, plus surface roughness variability and obstacles if added, and calculates wind speed increase or decrease at each node of the DEM grid. The mathematical model, although robust, has several limitations, including an assumption that the wind flow regime at the turbine site is like that at the met tower reference site, prevailing weather conditions are stable over time, and the surrounding terrain at both locations is sufficiently gentle and smooth to ensure laminar, attached wind flow.

The version of WAsP software used for this analysis is capable of modeling turbulent wind flow resulting from sharp terrain features such as mountain ridges, canyons, shear bluffs, etc., with computational fluid dynamics (CFD) modeling, but this is only possible by accessing supercomputers (for a fee) on the DTU campus in Roskilde, Denmark. K-Hill terrain, however, appears conducive to laminar air flow and CFD modeling should not be necessary.

The vicinity of K-Hill is comprised of mildly undulating hills of equal and slightly higher elevation in an arc from due west to due east to the north, and flat tundra terrain across the southern arc with the Bering Sea coast approximately seven miles distant. The terrain surface in all directions is very smooth, even in summer, with low-lying tundra vegetation and no tree cover. K-Hill itself is an outlier of sorts amongst the higher terrain as it lies separate and disconnected from the nearby hills.

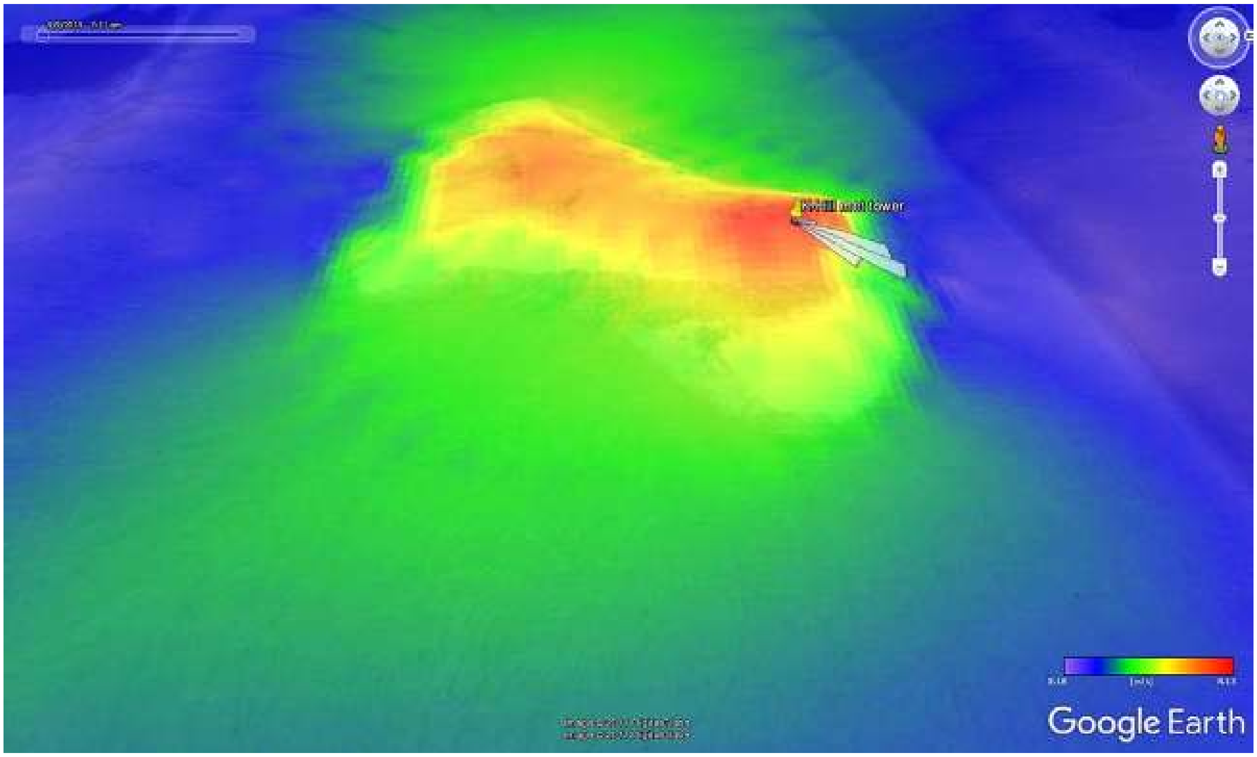
The WAsP image below shows a color-graduated wind speed overlay of a digital elevation map of K-Hill and surrounding terrain. As one can see, wind speeds at the foot of K-Hill directly north and south are very low, which is explained by wind flow theory. On the other hand, relatively high winds are found across the summit plateau and along the eastern and western slopes of K-Hill.

WAsP wind modeling of K-Hill in the digital elevation map, wind speed overlay



With reference to the following image, by overlaying the color-graduated wind speed modeling to Google Earth, wind flow speeds up and slow down across K-Hill in relation to measured winds at the met tower is apparent. This is a powerful tool for wind turbine siting as it allows one to make informed decisions regarding alternate wind turbine site options without initiating another expensive and time-consuming met tower study.

K-Hill wind speed overlay, Google Earth image, view to the west



Wind Turbine Performance

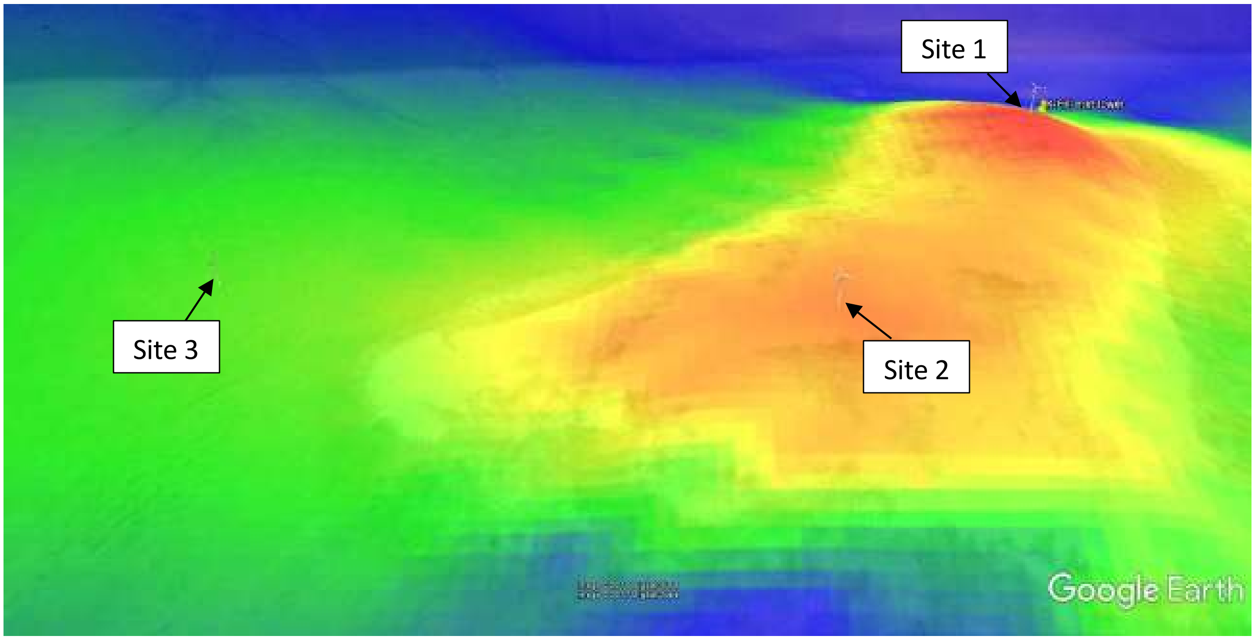
The purpose of a wind measurement study employing a met tower and wind flow modeling based on met tower data is to predict wind turbine energy production for one or more wind turbine models of interest. With later use of HOMER or similar software, a wind-diesel system model can be developed. This modeling provides insight into community energy production and usage, which directs later design efforts to achieve desired results for fuel savings and renewable energy production goals.

For this analysis, the 100 kW-rated Northern Power Systems NPS100C-21[18] wind turbine at a 30 meter hub height was chosen to compare three K-Hill site locations of interest. The 21 meter rotor model was chosen as this variant is IEC Class IA rated, which fits with the extreme wind probability calculate from the met tower data. Northern Power's 24 meter rotor variant may also be appropriate for K-Hill, but as an IEC Class III turbine, discussion with Northern Power System would be advisable to ensure suitability in the measured wind regime.

The three sites chose for comparison are identified in the following image and briefly are described as:

- Site 1 – highest and most northerly point of K-Hill, adjacent to the met tower
- Site 2 – flat plateau-like area on the south side of K-Hill
- Site 3 – broad, wide, higher terrain on western approach to K-Hill

[18] See http://www.northernpower.com/ for more information



The following table compares wind turbine performance at the three noted site locations. Although the Northern Power NPS100 is an excellent option for a rural Alaska wind-diesel system, note that other options exist which are highly suitable as well. These include the new 100 kW downwind Belgian XANT[19] turbine and remanufactured Vestas models in the 100 to 225 kW capacity range. Note also in the analysis below that AEP values are 100% or gross with no discounting for losses due to maintenance, curtailment, icing, wake, soiling, hysteresis and other. A HOMER software system model, if accomplished, should include a range of reasonable assumption losses to achieve a conservative estimate of wind turbine energy production.

K-Hill wind turbine site wind regime and NPS100C-21 energy production, 30 meter hub height

	Speed	WPD[20]	AEP[21]	CF[22]
Site	m/s	W/m^2	MWh/yr	%
1	8.04	744	358	41.4%
2	7.51	610	328	38.0%
3	6.48	392	261	30.2%

Sites 1 and 2 on K-Hill – the north side high point and the south side plateau – model very well indeed and even Site 3 on the western approach models well too. Note again the Northern Power (or XANT) may approve use of the larger 24 meter rotor variants for one or all three sites. If so, a 10 to 15 percent annual energy production increase over the 21 meter model can be expected.

[19] See http://xant.be/ for more information
[20] Wind power density
[21] Annual energy production
[22] Capacity factor (modeled AEP compared to maximum AEP possible)