JBER Site Summit Wind Power Assessment Report

Site Summit met tower, photo by Douglas Vaught

October 26, 2016

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Summary

This report is provided to Pacific Northwest National Laboratory (PNNL) as part of a project to measure the wind resource on Site Summit area of Joint Base Elmendorf Richardson (JBER) in Anchorage, Alaska and provide the Air Force with an assessment of wind power potential and options for the site area.

V3 Energy, LLC was contracted by PNNL to assist with site selection, install a meteorological (met) test tower, maintain the tower and review data periodically, compare the met tower data to a nearby reference station, create a wind flow model of the Site Summit area, recommend a wind turbine array for the site, and estimate energy production from the wind farm. This report is a summary and compilation of those objectives.

Site Summit Met Tower

A 10-meter high met tower, factory painted aviation orange and white, was installed near the communications compound of Site Summit in summer, 2015. The met tower was equipped with an NRG Symphonie data logger, a communications modem, two anemometers, a wind vane, plus temperature and relative humidity sensors. The met tower was also equipped with two red FAA-compliant LED obstruction lights, batteries to power the lights, and a small wind turbine to charge the batteries.

Met tower data synopsis

Data dates	6/17/2015 to 6/24/2016 (12 months)
Wind speed, mean, 9 m, annual	5.81 m/s (13.0 mph)
Wind power density, mean, 9 m	365 W/m^2
Max. 10-minute average wind speed	36.6 m/s (81.8 mph)
Maximum 2-second wind gust	51.2 m/s (114.5 mph), December 30, 2015
Weibull distribution parameters	k = 1.38, c = 6.37 m/s
Wind shear power law exponent	Not measured
Surface roughness	Not measured
IEC 61400-1, 3rd ed. classification	Class I-S
Turbulence intensity, mean	0.138 (at 15 m/s)
Calm wind frequency (wind <4 m/s)	43% (12 mo. measurement period)

Test Site Location

The project site is on a narrow ridge immediately west of the fenced Site Summit communications compound. This met tower installation was the culmination of an effort to identify a suitable site that represented the area wind resource and satisfied the restrictions of JBER Range Control Department. With this, the chosen location is a compromise in that it is not a particularly suitable location for a met tower due to typically complex airflow on ridgelines with high topographic relief, but it is the only site that Range Control would approve.

Met tower site photographs

View to north

View to northeast

View to east

View to southeast

View to south

View to southwest

View to west

View to northwest

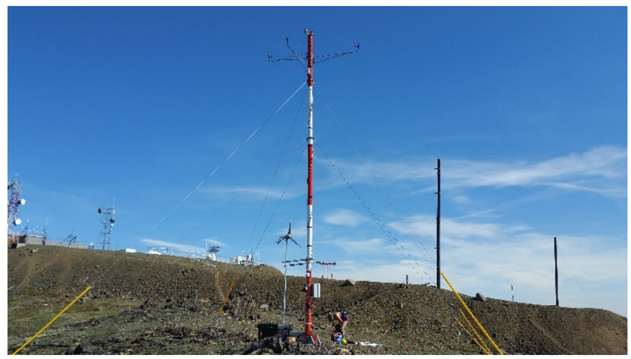
Site information

Site number (logger ID)	9612
Latitude/longitude	N 61° 15’ 30.9”, W 149° 31’ 53.7”
Time offset	-9 hours from UTC (Yukon/Alaska time zone)
Site elevation	1,173 meters (3,850 ft.)
Datalogger type	NRG SymphoniePLUS3, 10-minute averaging time step
Tower type	Tubular, ~15 cm (6 in.) diameter, 10-meter height

Met tower photographs

View to north

View to southeast



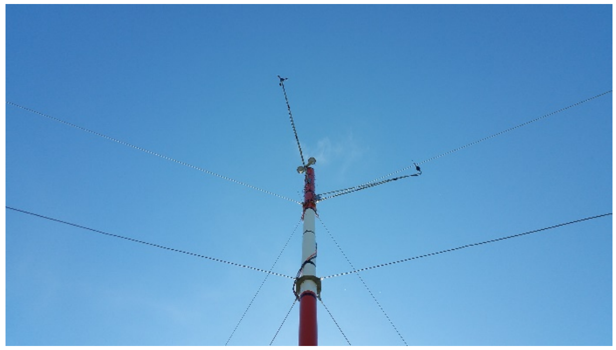
View to west

Battery charging turbine

Up-tower sensor photographs

North side

East side



South side

West side

Tower sensor information

Logger Channel	Sensor type	Sensor Designation	Serial Number	Height AGL	Multiplier	Offset[1]	Orientation[2]
1	NRG #40C anemometer	10m A	247374	9.5 m	0.761	0.33	090 T
2	NRG #40C anemometer	10m B	247373	9.5 m	0.760	0.36	240 T
7	NRG #200P wind vane	Direction	n/a	9.0 m	0.351	000	000 T
9	NRG #110S Temp C	Temp	n/a	2 m	0.136	-86.38	000 T
11	NRG RH5X relative humidity	RH	n/a	2 m	0.097	0	045 T
12	Voltmeter	Volts	n/a	2 m	0.021	0	n/a

[1] Multiplier and offset are variables of the straight-line transfer function to calculate sensor value from its raw data inputs with the equation $y = mx + b$ where y is sensor value, m is multiplier and b is offset.
[2] In true degrees (reference pt. is Earth's geographic North Pole)

Datalogger photographs

GPS reading

Wiring panel

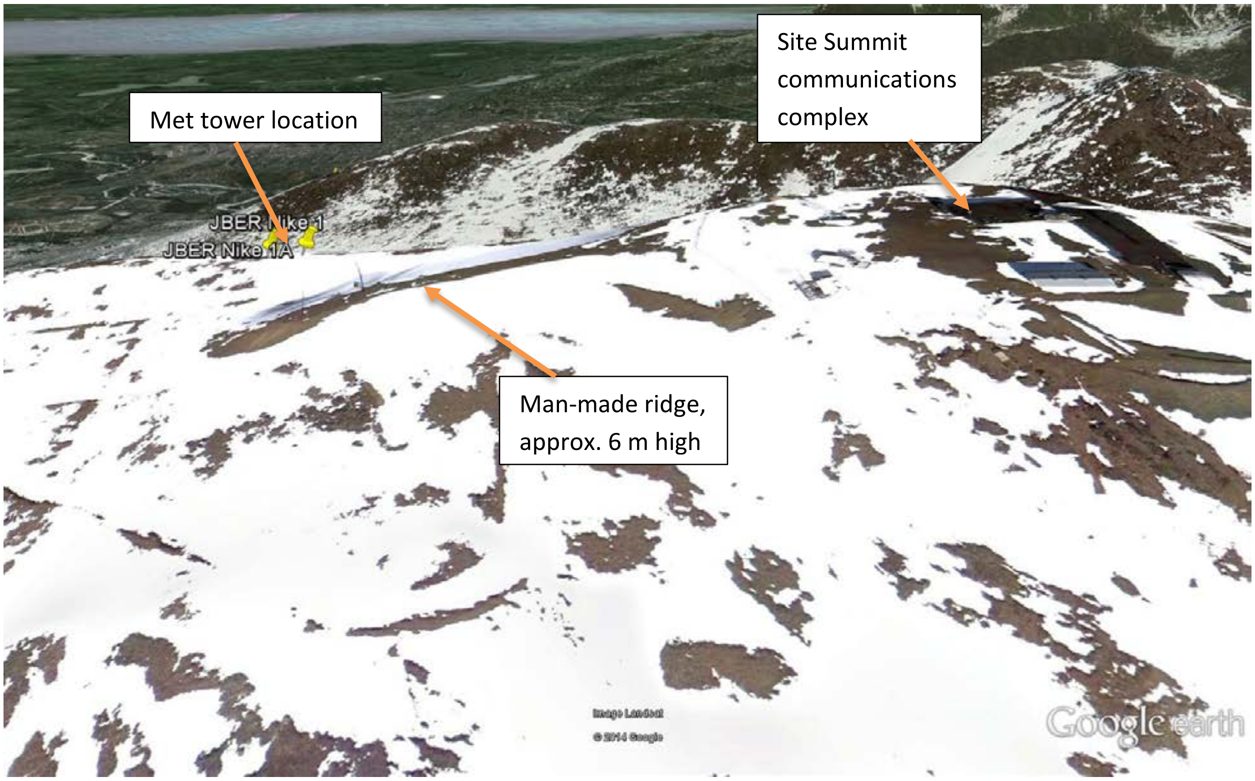
Channels 1 and 2, anemometers

Channel 7, wind vane

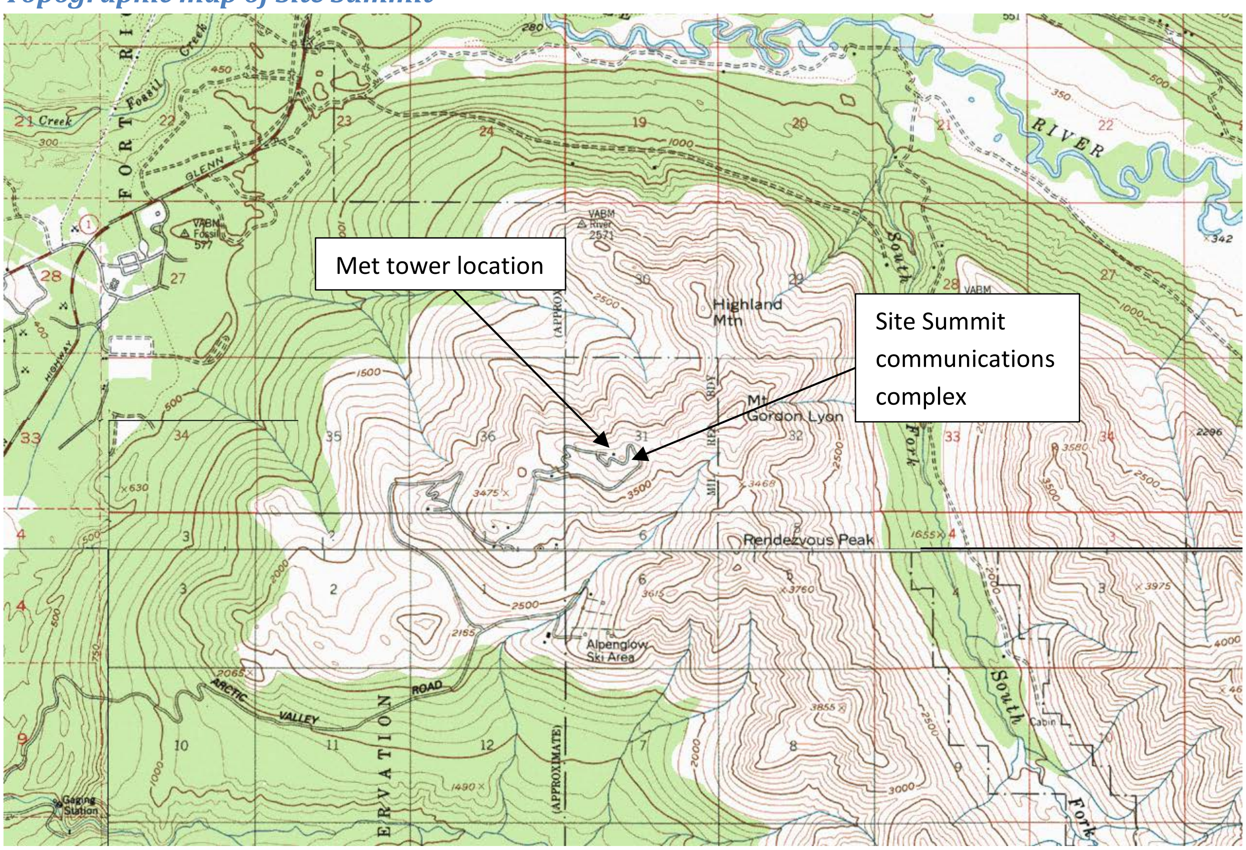
Channel 9, temperature

Channels 11 and 12, RH and voltmeter

Google Earth image, Site Summit, view north



Topographic map of Site Summit



Data Quality Control

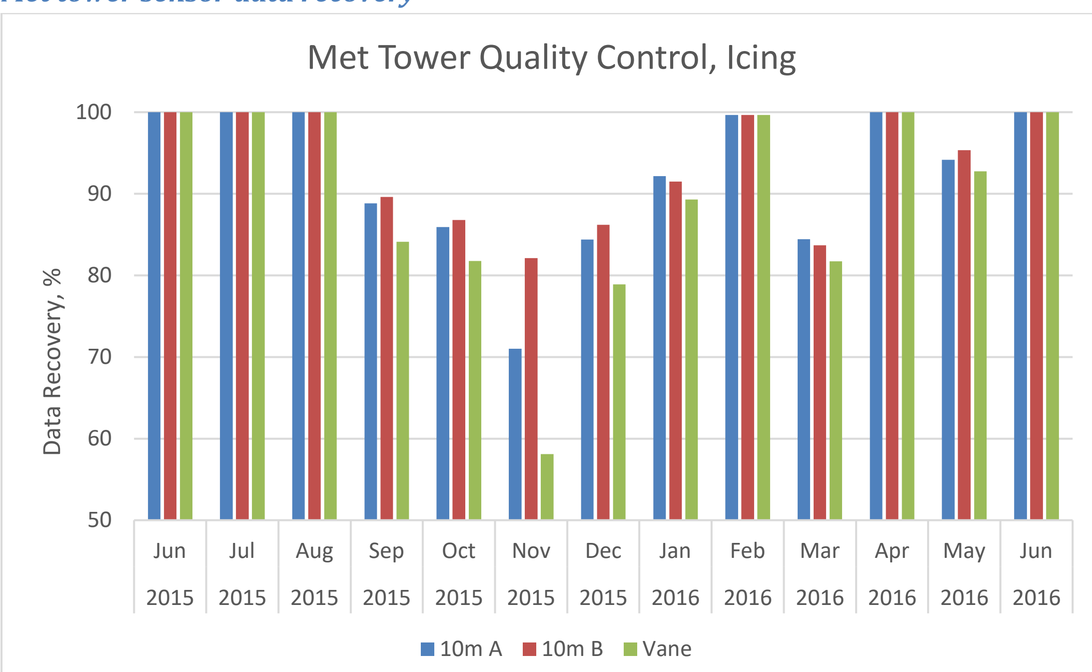
Data was filtered to remove presumed icing events that yield false zero wind speed data and non-variant wind direction data. Typically, data that meets the criteria listed below is automatically filtered:

- 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 10-meter A and B paired anemometers – data filtered when winds from ± 15° of behind tower

In addition to automatic data filtering, icing data was manually filtered in situations where the automatic filtering failed to detect obvious icing conditions or flagged data as icing where it did not appear to be so. Specifically, to aid manual filtering of icing data, a relative humidity sensor was installed to enhance the detection of icing conditions, but data recovery from it was problematic throughout the project with frequent and persistent data loss for unknown reasons. Relative humidity data was used for icing detection when possible, but often the data was too sporadic and hence not usable.

Note that in late December the charging turbine power cable was disconnected from the obstruction light batteries by either very strong wind or possible vandalism. Evidence at the site suggested the latter. At that time, the batteries backed up the modem battery, which powers the modem and the RH sensor. With loss of battery voltage, modem communication and RH function failed, as well as the obstruction lights. Modem and RH sensor functionality was restored in mid-February when a 15 W solar panel was installed to charge the modem battery. The obstruction lights remained out of service and functionality was not restored before decommissioning the met tower.

Met tower sensor data recovery



Sensor data recovery table

Data Column	Possible Records	Icing	Invalid	Low Quality	Valid Records	Recovery Rate (%)
Speed 10m A	53,464	4,221	13	0	49,230	92.1%
Speed 10m B	53,464	3,559	13	0	49,892	93.3%
Direction	53,464	4,947	13	0	48,504	90.7%
Temperature	53,464	0	7	0	53,457	100.0%
RH	53,464	0	8,237	5,497	39,730	74.3%
Voltmeter	53,464	0	0	0	53,464	100.0%

Wind Speed

Anemometer data obtained from the Site Summit met tower, from the perspectives of both mean wind speed and mean wind power density, indicate a moderate wind resource. The table below displays wind both raw and filtered (for icing events) wind data.

Anemometer data summary (raw and filtered)

Variable	Speed 10 m A		Speed 10 m B	
Measurement height (m)	raw	filtered	raw	filtered
Mean wind speed (m/s)	5.30	5.70	5.46	5.81
Median wind speed (m/s)	4.23	4.60	4.40	4.70
Max 10-min wind speed (m/s)	36.6	36.6	36.4	36.4
Max 2-second gust (m/s)	51.2	51.2	51.2	51.2
Weibull k	1.13	1.34	1.22	1.38
Weibull c (m/s)	5.51	6.20	5.82	6.37
Mean power density (W/m²)	330	358	342	367
Mean energy content (kWh/m²/yr.)	2,891	3,137	2,994	3,212
Energy pattern factor[3]	3.93	3.44	3.73	3.32
Frequency of calms (wind <4 m/s, %)	47.7	43.7	46.2	42.4

Time Series

Time series calculations indicate higher wind speeds during the winter months compared to the summer months. The daily wind profile (annual basis) indicates relatively even wind speeds throughout the day with slightly higher wind speeds during late afternoon hours.

10 m B anemometer data summary

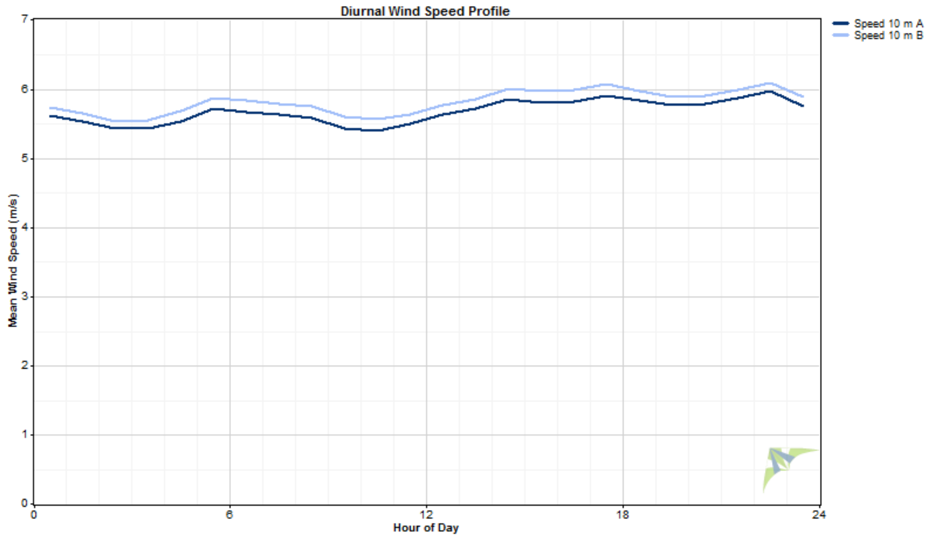
Month	Mean (m/s)	Max (m/s)	Gust (m/s)	Std. Dev. (m/s)	Weibull k (-)	Weibull c (m/s)
Jan	5.62	32.2	43.1	4.47	1.28	6.05
Feb	6.73	29.1	39.5	4.72	1.52	7.50

[3] With an assumption of constant air density, energy pattern factor is the ratio of the actual mean wind power density to the wind power density calculated from only the mean wind speed. Definition obtained from Windographer 4.0 Help file.

Month	Mean (m/s)	Max (m/s)	Gust (m/s)	Std. Dev. (m/s)	Weibull k (-)	Weibull c (m/s)
Mar	5.76	27.0	33.3	4.48	1.36	6.30
Apr	5.34	21.6	30.6	3.50	1.61	5.99
May	5.12	23.9	33.3	3.65	1.47	5.68
Jun	5.06	23.0	31.9	3.74	1.40	5.56
Jul	4.41	21.8	30.6	3.46	1.31	4.78
Aug	5.53	18.2	24.7	3.63	1.50	6.11
Sep	6.87	24.2	34.8	5.14	1.21	7.25
Oct	5.66	18.9	26.9	3.50	1.60	6.28
Nov	7.64	25.7	41.3	5.51	1.40	8.37
Dec	6.65	36.4	51.2	5.40	1.28	7.18
Annual	5.81	36.4	51.2	4.37	1.38	6.37

Per month time series, mean and maximum (10-minute average) wind speeds

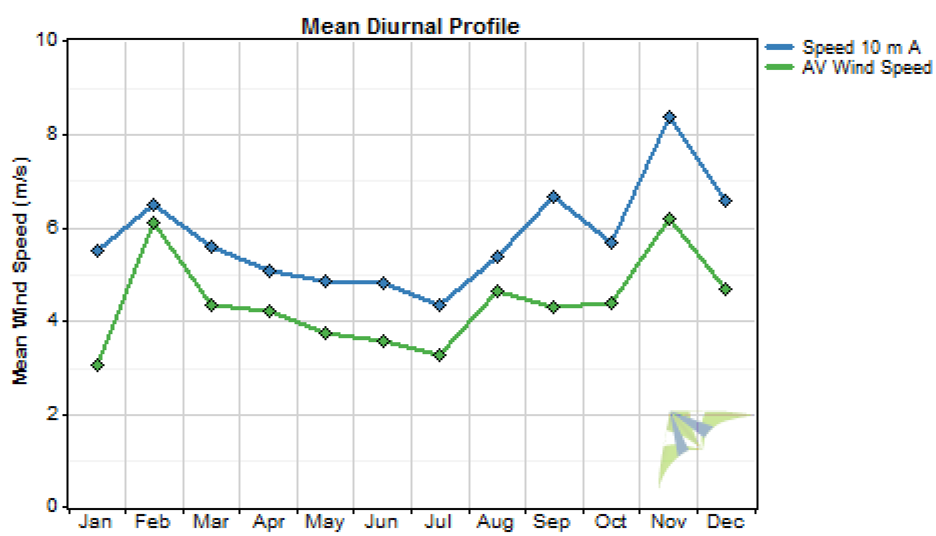
Daily wind profile



Long-term Wind Speed Comparison

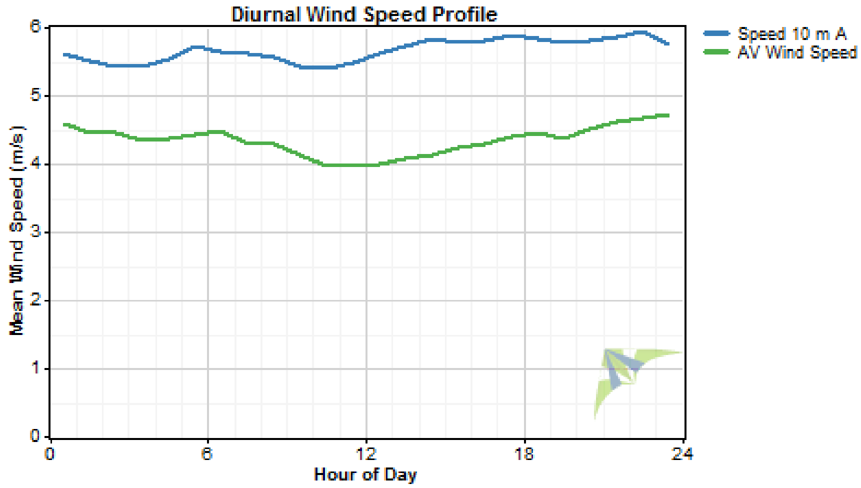
Comparing the twelve months of measured wind speed data at the Site Summit met tower to a long-term reference source is possible with the nearby Arctic Valley mesonet[4] weather station, located on the ridge across the valley immediately east of Site Summit. The Arctic Valley weather station is located near the top of Chairlift no. 2 of the Arctic Valley Ski Area. It was installed in 2009 but data was sporadic until August 2011 from which consistent data is available. In comparing the data overlap period of the Site Summit met tower to the Arctic Valley mesonet weather station, one can see reasonably well correlated wind speeds, although note than met tower mean wind speeds average about 1 m/s faster than the weather station. Diurnal variation between the two agree as well.

Site Summit met tower and Arctic Valley weather station monthly wind speed comparison



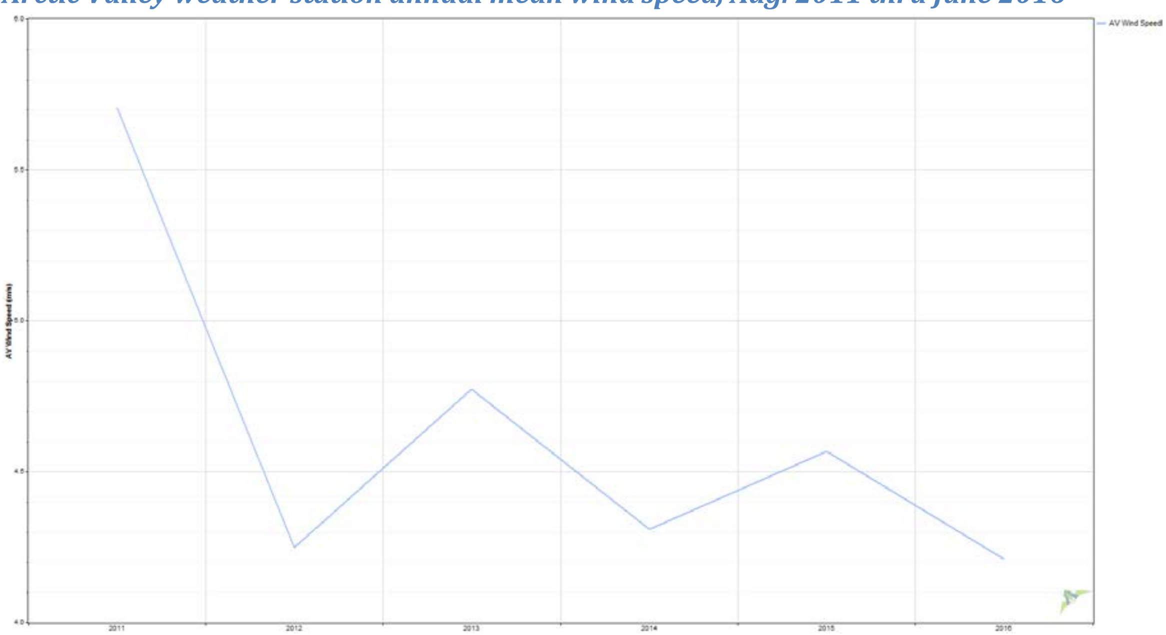
[4]A mesonet is a network of automated weather stations designed to measure mesoscale (intermediate scale: 10 to 1,000 km horizontal extent) meteorological conditions

Site Summit met tower vs. Arctic Valley diurnal profile comparison



Data for five years of Arctic Valley weather station data – from August 2011 through June 2016 – is a short-term timeframe and somewhat inconclusive with respect to determination of a long-term average. In the graph below, 2011 and 2016 data must be ignored as those years' data are incomplete, leaving four complete years: 2012 through 2015. The Arctic Valley data indicates that 2015 was relatively windy compared to 2014; hence possibly Site Summit met tower data reflects a relatively windy year as well, but because the met tower data is comprised of two partial years, from June 2015 to June 2016, this comparison is imperfect. Winter 2015/2016 in Anchorage was El Niño-influenced, much warmer than normal, and included more warm North Pacific Ocean-origin storms than typical. This indicates at least the potential for windier-than-typical conditions compared to a long-term average, which presumably is reflected in the met tower data.

Arctic Valley weather station annual mean wind speed, Aug. 2011 thru June 2016



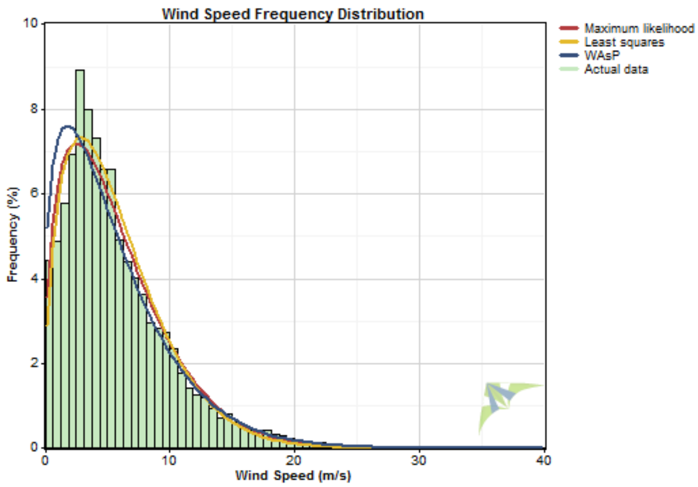
Probability Distribution Function

The probability distribution function (PDF), or histogram, of the Site Summit met tower site wind speed indicates a shape curve dominated by lower wind speeds and is not particularly reflective of a standard curve, known as the Rayleigh distribution[5] where Weibull k = 2.0. The Rayleigh distribution is defined as the default wind probability distribution for wind power analysis.

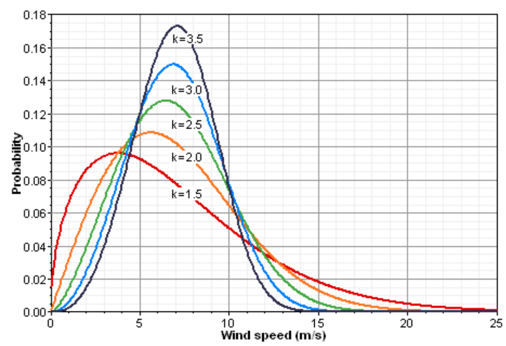
Weibull values table, 10 m B anemometer, all data

Algorithm	Weibull k	Weibull c (m/s)	Mean (m/s)	Proportion Above 5.803 m/s	Power Density (W/m2)	R Squared (-)
Maximum likelihood	1.38	6.37	5.82	0.415	373	0.979
Least squares	1.46	6.31	5.72	0.413	323	0.981
WAsP	1.26	6.07	5.64	0.389	397	0.959
Actual data			5.80	0.389	397	

PDF of 10m B anemometer (all data)



Weibull k shape curve table



Wind Shear and Roughness

Wind shear and roughness at the Site Summit met tower site cannot be calculated as the two anemometers were installed at the same height (10 meters) above ground level. It should be noted that measurement of the wind resource at the met tower site with a taller met tower equipped with multi-level anemometers likely would yield confusing information or shear data not reflective of the general Site Summit area where wind turbines would be located. On sharp mountain ridges with significant topographic relief, negative shear is often measured at lower heights and minimal positive shear above that. The negative shear is due to the speed-up of wind rushing over the ridge, acting somewhat as a

[5] One form of the Weibull distribution is the Rayleigh, which occurs when k = 2.0. This is equivalent to a standard deviation of 52% of the mean wind speed. Wind turbine manufacturers provide standard performance data based on a wind resource with a Rayleigh distribution. Definition from www.wind-power-program.com and www.windpower.org.

venture. For this reason, measured shear in such locations, even if available, should be regarded with considerable suspicion.

Extreme Winds

International Electrotechnical Commission (IEC) 61400-1, 3rd edition extreme wind probability classification is one criteria – with turbulence the other – that describes a site with respect to suitability for wind turbine models.

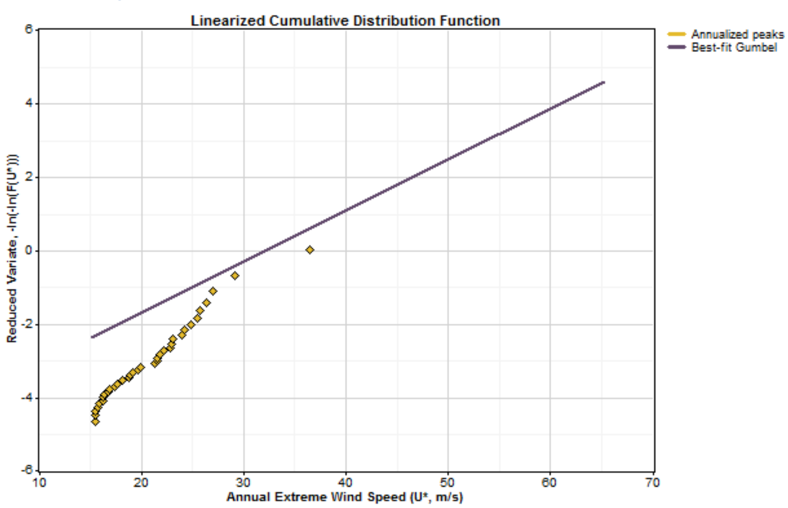
One method to estimate V_{ref}, or the maximum 50-year, 10-minute average wind speed is a Gumbel distribution analysis modified for monthly maximum winds versus annual maximum winds, which are typically used for this calculation. Twelve months of data however are minimal at best and hence results should be viewed with caution. Nevertheless, with data available the predicted V_{ref} in a 50-year return period (in other words, predicted to occur once every 50 years) by this method is 52.4 m/s at 10 meters above ground level. This result exceeds IEC 3rd edition Class I criteria and hence would be considered Class S.

Site extreme wind probability table, 10m B data

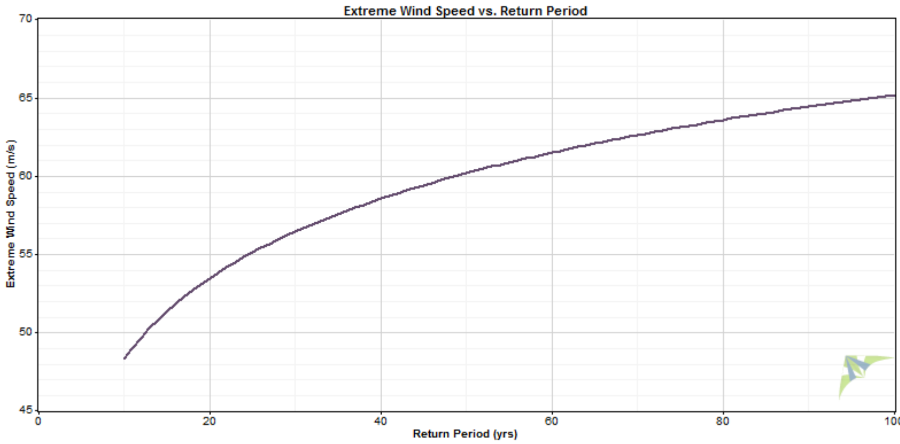
	V_{ref}	Gust	IEC 61400-1, 3rd ed.	
Period (years)	(m/s)	(m/s)	Class	V_{ref}, m/s
3	36.5	51.1	I	50.0
10	44.5	62.3	II	42.5
20	46.5	65.1	III	37.5
30	49.9	69.9	S	designer-specified
50	52.4	73.4		
100	55.8	78.2		
average gust factor:	1.40			

A second technique, Method of Independent Storms, yields a similar, but even higher, calculation of V_{ref} as 60.2 m/s.

Method of Independent Storms, cumulative distribution

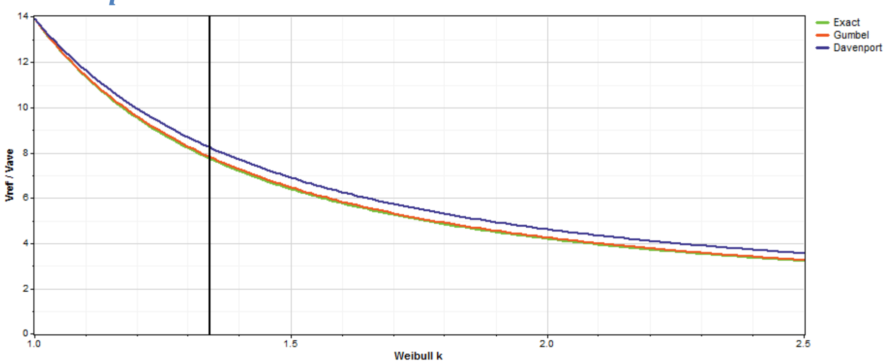


Method of Independent Storms, extreme wind vs. return period



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 yield a V_{ref} between 44.0 and 46.8 m/s. This is much lower than the other methods and within IEC 3rd edition Class I extreme wind criteria (noting of course that Class 1 is the highest defined category, indicating a strongly energetic or storm-prone wind resource).

EWTS II plot



EWTS II table

Method	V_{ref} / V_{ave}	V_{ref} (m/s)
Exact	7.75	44.1
Gumbel	7.83	44.5
Davenport	8.25	46.9

Note again the minimal measured wind data for these calculations and the fact that these calculations are at a very low 10-meter elevation on a mountain ridge which due to topographic constraints acts somewhat as a venturi. It is entirely possible that extreme wind behavior higher at higher elevations above ground level at the met tower site is much different and perhaps would yield lower V_{ref} estimations. In other words, V_{ref} measured with the met tower data may not be representative of the general Site Summit area. The calculations are, however, included in this report for reference and documentation.

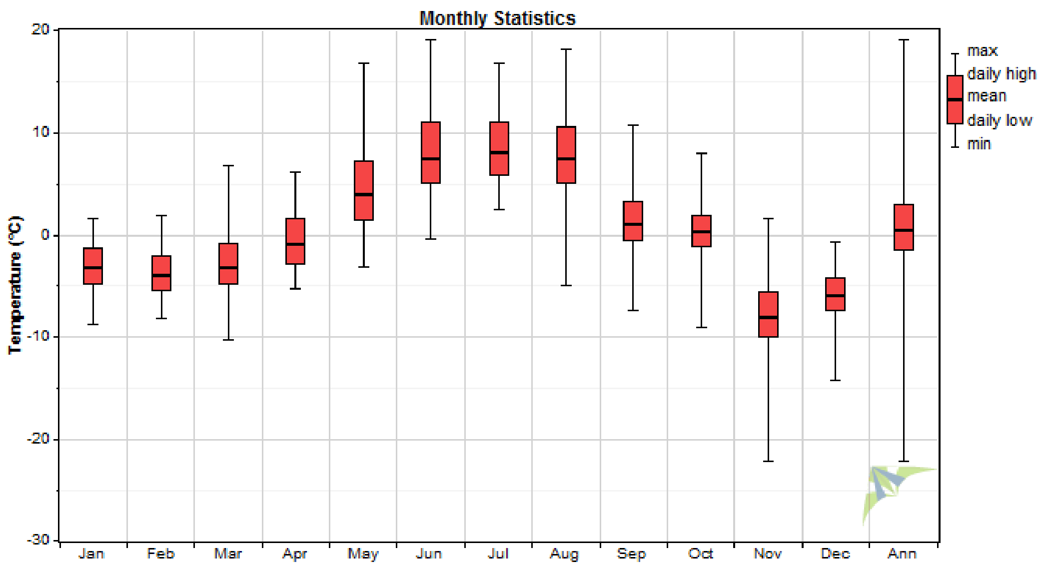
Temperature, Density, and Relative Humidity

Site Summit experiences very cool summers (below freezing temperatures occurred all months except July and August), but not especially cold winters by interior Alaska standards. Calculated mean air density during the met tower test period exceeds the 1.092 kg/m^3 standard air density for a 1,173-meter elevation by 2.5 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 (for the site elevation).

Temperature and density table

	Temp (°C)			Temp (°F)			Density		
Month	Mean (°C)	Min (°C)	Max (°C)	Mean (°F)	Min (°F)	Max (°F)	Mean (kg/m3)	Min (kg/m3)	Max (kg/m3)
Jan	-3.1	-8.7	1.7	26.4	16.3	35.1	1.134	1.114	1.159
Feb	-3.8	-8.1	1.9	25.2	17.4	35.4	1.137	1.091	1.156
Mar	-3.1	-10.2	6.8	26.4	13.6	44.2	1.134	1.093	1.165
Apr	-0.8	-5.2	6.3	30.6	22.6	43.3	1.124	1.095	1.143
May	4.1	-3.1	16.8	39.4	26.4	62.2	1.104	1.053	1.134
Jun	7.6	-0.4	19.2	45.7	31.3	66.6	1.090	1.044	1.123
Jul	8.2	2.5	16.9	46.8	36.5	62.4	1.087	1.053	1.111
Aug	7.6	-4.9	18.2	45.7	23.2	64.8	1.090	1.048	1.142
Sep	1.2	-7.3	10.8	34.2	18.9	51.4	1.116	1.077	1.152
Oct	0.4	-9.0	8.0	32.7	15.8	46.4	1.120	1.088	1.160
Nov	-7.9	-22.2	1.7	17.8	-8.0	35.1	1.156	1.114	1.221
Dec	-5.8	-14.2	-0.7	21.6	6.4	30.7	1.146	1.124	1.184
Annual	0.4	-22.2	19.2	32.7	-8.0	66.6	1.120	1.044	1.221

Site Summit temperature boxplot graph

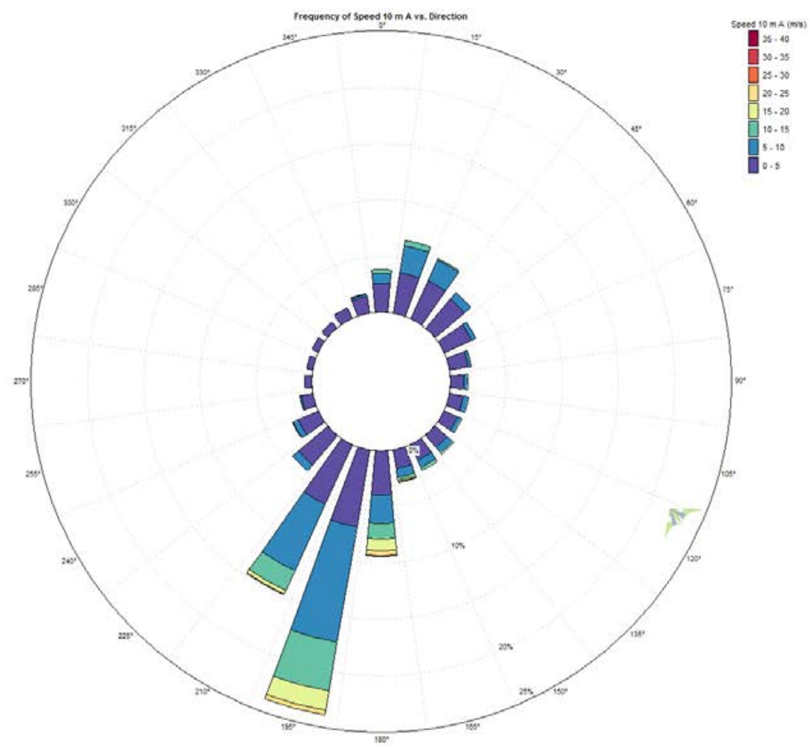


Wind Direction

Wind rose data indicates that winds at the Site Summit met tower site are primarily south-southwesterly (SSW) with a secondary north-northeasterly (NNE) component. The energy component of the wind rose indicates that the power-producing winds are strongly SSW.

It should be noted however that the wind rose measured at the Site Summit met tower site does not agree with that measured at the nearby Arctic Valley mesonet station which indicates south-southeasterly (SSE) prevailing winds. Given the constraints of the site location and nearby presence immediately to the south of a human-built ridge to house communication equipment (now largely abandoned), the SSW prevailing wind direction measured by the met tower should be viewed with caution as SSE winds are likely more representative of the larger Site Summit area. Note that accurate wind direction information is extremely important for wind turbine array design to avoid unknown wake shadowing and resultant wake loss.

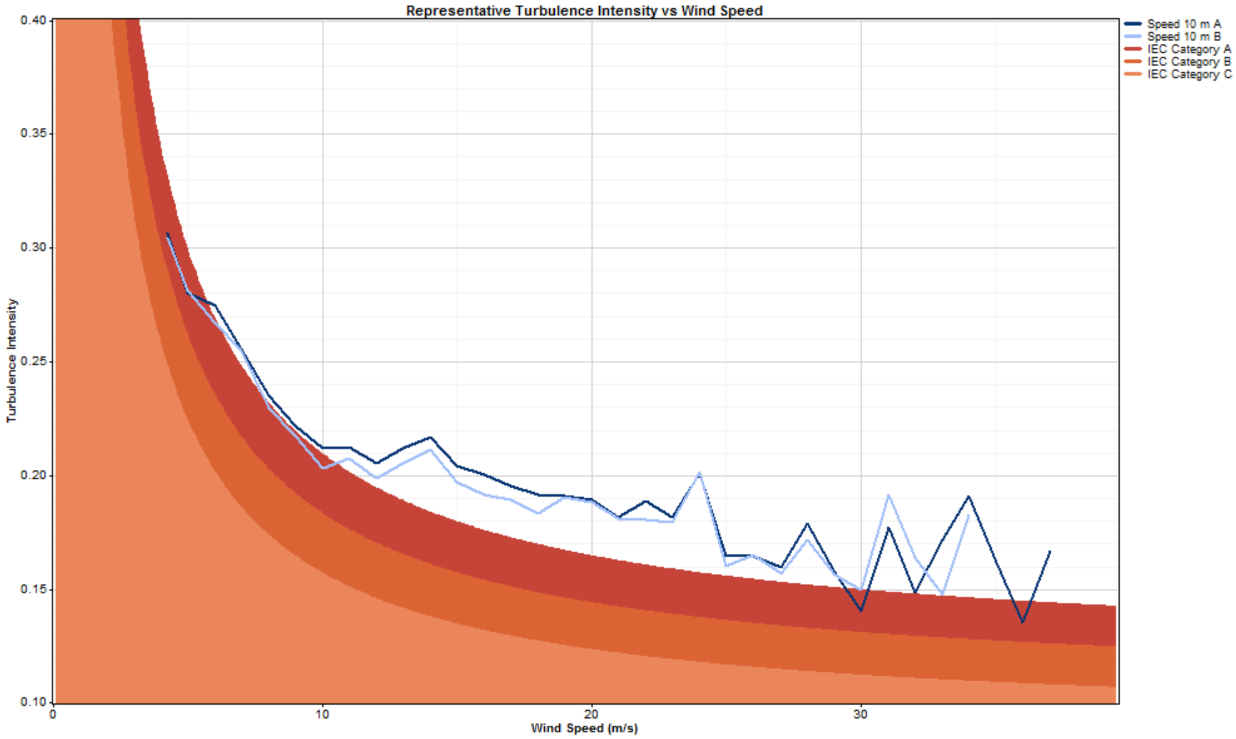
Site Summit met tower wind rose



Turbulence

The turbulence intensity (TI) at the Site Summit met tower site at 10 meters above ground level is very high with a mean turbulence intensity of 0.144 and a representative turbulence intensity of 0.204 at 15 m/s wind speed, indicating rough air for wind turbine operations. This exceeds International Electrotechnical Commission (IEC) 61400-1, 3rd Edition (2005) turbulence category A (Category A is most turbulent; C is least). Note however the low sensor height of only 10 meters and the presence of nearby infrastructure nearly directly upwind. It is very likely that actual turbulence in a more open location and/or a higher elevation above ground level would be much lower and hence more suitable for wind power operations.

Turbulence intensity, all direction sectors



WAsP Wind Flow Model

Wind flow modeling was accomplished with WAsP (Wind Atlas Analysis and Application Program), a Danish PC-based software for predicting wind climates, wind resources and power production from wind turbines and wind farms and can be used to predict wind turbine performance. WAsP is the most widely used wind power analysis software in the world. Modelling begins with a digital elevation map (DEM) of the wind farm site and surrounding area and conversion of coordinates to Universal Transverse Mercator (UTM).[6]

A wind data (or wind atlas) reference point is added to the digital elevation map, wind turbine locations identified, and a wind turbine selected to perform annual energy production calculations. WAsP considers the orographic (terrain) effects on the wind, plus surface roughness and obstacles, and calculates wind velocity increase or decrease at all nodes of the map. The mathematical model has several limitations, including the assumption that the overall wind regime of the turbine site is same as the met tower reference site, prevailing weather conditions are stable over time, and surrounding

[6] 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 zone (60 longitudinal zones are further subdivided by 20 latitude bands) for the easting coordinate, and distance from the equator for the northing coordinate. Units are meters.

terrain at the wind data reference point and turbine sites is sufficiently gentle and smooth to ensure laminar, attached wind flow. The version of WAsP software used for this study is not capable of modelling non-laminar wind flow resulting from sharp terrain features such as mountain ridges, canyons and shear bluffs. For that, computational fluid dynamics, otherwise known as CFD, modeling would be required. For the model resultants presented below, higher confidence can be assigned to southeast-to-southwest upslope flow than high vertical relief downslope flow and/or downwind flow from sharp edge terrain features.

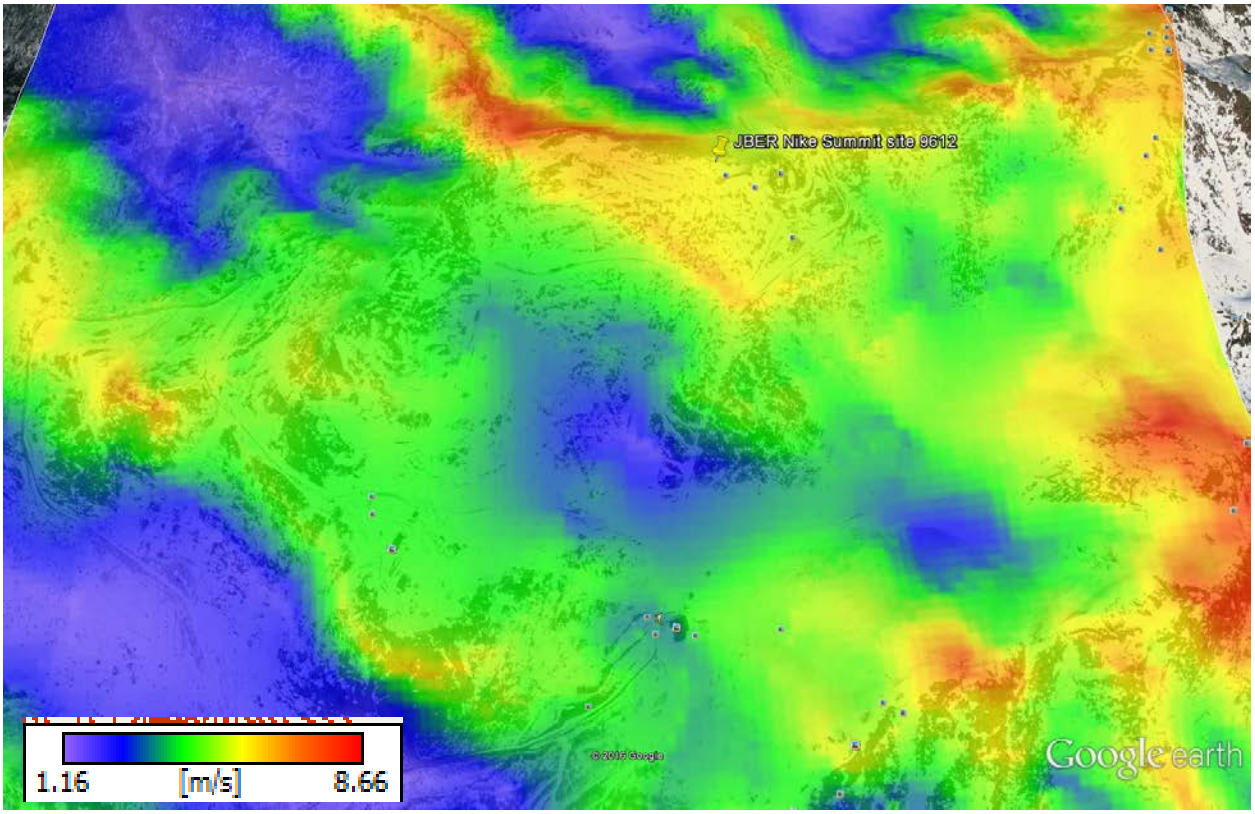
Site Summit Met Tower Reference

Windographer and WAsP software processed the Site Summit met tower 10m B anemometer data (note that the B anemometer returned a higher mean wind speed than the A anemometer, hence is used here) to reflect a 5.68 m/s mean annual wind speed[7], a 402 W/m^2 power density, and a Weibull k value of 1.27 for the WAsP wind flow model. Mentioned previously in this report, the prevailing wind measured at the met tower is SSW. Although this measured wind direction likely is an artifact of specific site issues and may not representative of the area-wide prevailing wind, it was not adjusted for the WAsP model using Site Summit met tower data as the wind atlas reference point for this WAsP analysis as there was no basis to do so, other than a qualitative comparison to a reference station.

As one can see below in the Site Summit met tower wind speed overlay graphic, WAsP software – noting again that it cannot model non-laminar wind flow, which almost certainly occurs at or near the Site Summit met tower due to the high topographic relief to the north – predicts relatively high winds (red and yellow) on the Site Summit area itself, the ridge extending northwest from the summit and nearby Rendezvous Peak to the southeast. Lower wind speeds (green) are predicted along the ridge to the west that connects the lower launch complex to Site Summit, and lowest winds (blue) are in the valleys, as one would expect.

[7] The WAsP wind speed algorithm relies on a Weibull calculation that resulted in a non-coincident mean wind speed average compared to the measured annual mean.

Site Summit met tower, 10 m, wind speed overlay on Google Earth image, view north

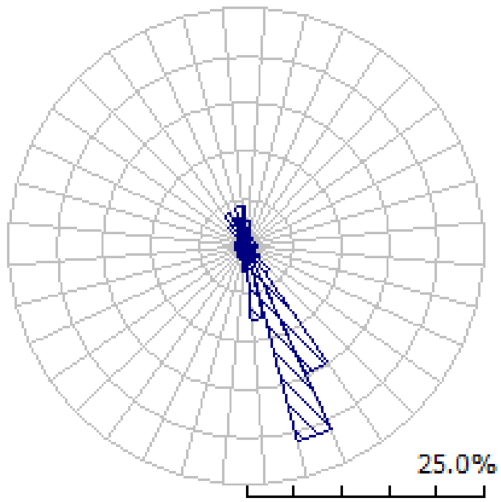


Arctic Valley Mesonet Weather Station Reference

Data from the Arctic Valley mesonet weather station, located on the mountain ridge immediately south of the Site Summit ridge, was used to create a wind data atlas for a WAsP wind flow model. This weather station, with an anemometer at approximately 5 meters above ground level, is similar to the Site Summit met tower site in that it is located directly on top of a ridge with the attendant limitations of high topographic relief, possible non-laminar airflow in the vicinity, and unknowable shear behavior.

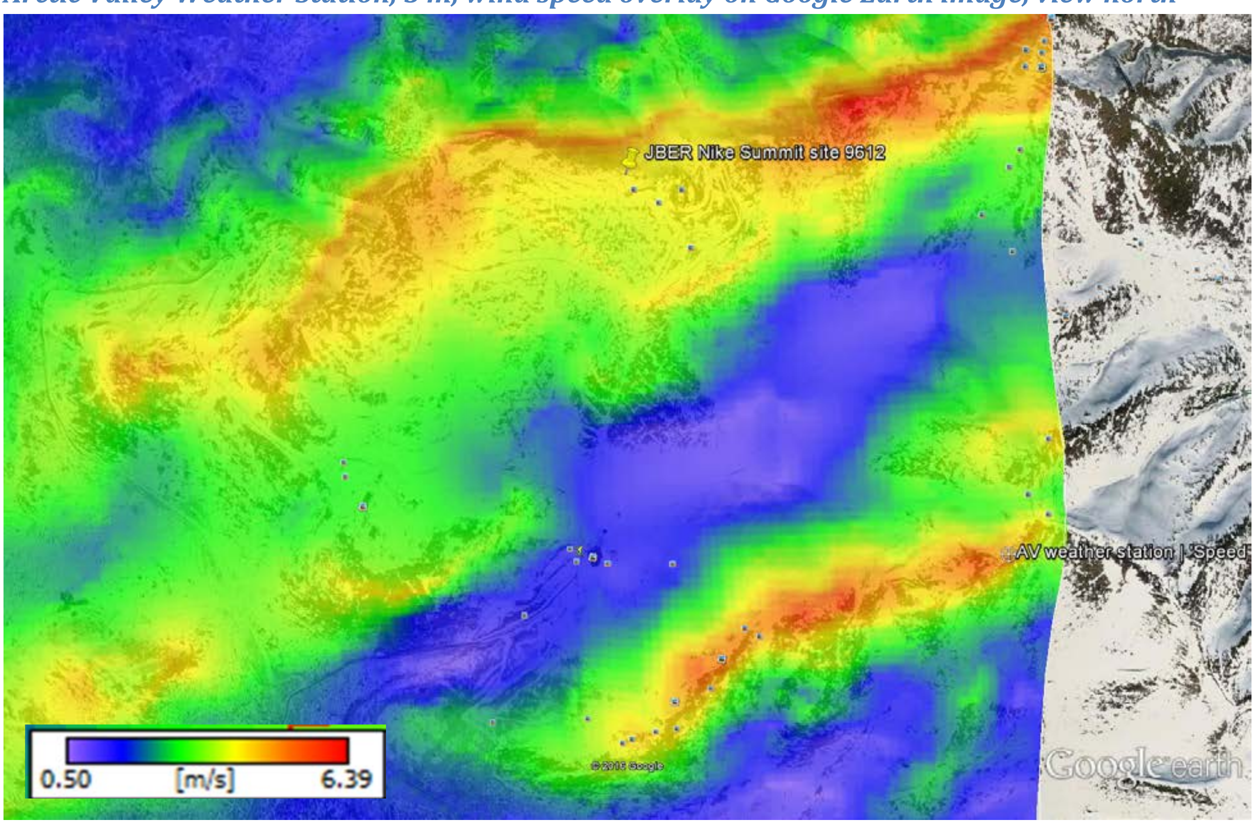
One year of hourly data was analyzed for this model, from July 1, 2013 to July 1, 2014. During this period, WAsP software processed the data to reflect a 4.71 m/s mean annual wind speed, a 172 W/m^2 power density, and a Weibull k value of 1.48. This is a lesser wind resource than measured on Site Summit, which is somewhat unexpected given nearly identical site elevations. One possible explanation, besides different reporting periods, is that the Arctic Valley mesonet station is in a more open location on a ridge and not constrained by surrounding terrain as was the Site Summit met tower, which may have led to wind channeling. The prevailing wind measured at the Arctic Valley weather station is SSE, which is intuitively accurate as nearby and upwind Ship Creek and South Fork Eagle River valleys, through which the winds funnel, are aligned SSE-to-NNW.

Arctic Valley mesonet weather station wind rose



As one can see below in the Arctic Valley weather station wind speed overlay graphic, WAsP software – noting again that it cannot model non-laminar wind flow, predicts relatively high winds (red and yellow) on the Site Summit area itself, but with a SSE prevailing wind orientation, also on the ridge which trends to the west that connects the lower launch complex to Site Summit. Lower winds speed (green and blue) are lower slopes and valley areas.

Arctic Valley Weather Station, 5 m, wind speed overlay on Google Earth image, view north



Chugach Electric Association Met Tower Reference

Chugach Electric Association (CEA) operated a 40-meter met tower on a promontory along Site Summit access road for approximately one year in 1998 and 1999. Unfortunately, the original data files have been lost but a summary of data results are documented in a January 2000 report by John Wade, a Portland, Oregon-based meteorologist, entitled, "*Chugach Electric Wind Resource Assessment Data Analysis Final Report*". In Table 7 of the report, an annual mean wind speed of 6.8 m/s at the 40-meter level, corrected for icing and annual variation, is documented. The report does not contain wind rose information but an Excel spreadsheet of summary data, obtained from Mr. Wade, indicates prevailing southeasterly winds, which validates other sources except for the Site Summit met tower.

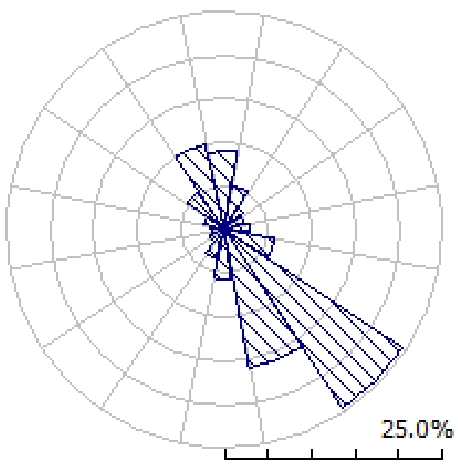
CEA met tower location, 1998-99, Google Earth image, view north

AWS Truepower Data Reference

Recognizing the neither the Site Summit met tower or Arctic Valley mesonet weather station data sources are ideal reference points for wind turbine modeling with WAsP software – the former due to an apparent wind rose discrepancy, the latter due to distance from the area of interest, and both due to low anemometer height and lack of shear information – AWS Truepower virtual met mast (VMM) wind data for a hub height (above ground level) elevation was obtained for a location near the Site Summit met tower. The location, noted in internal communication as "Nike 2", is not on the ridgeline itself, is about one kilometer west-southwest of the Site Summit met tower location and is within the footprint of a prospective wind turbine array on Site Summit ridge.

The Nike 2 VMM data is at the 80-meter (above ground) level, hence difficult to compare directly to Site Summit met tower data given the unknown vertical wind shear of the latter. WAsP software processed the Nike 2 VMM data to reflect an 8.05 m/s mean annual wind speed (at 80 meters), a 968 W/m^2 power density, and a Weibull k value of 1.40. Very importantly, the VMM data validates the wind rose measured by the Arctic Valley mesonet weather station which indicates prevailing SSE winds, although interestingly the VMM wind rose shows more variation with SE winds as strongest and appreciable NNW and northerly winds. Interestingly, the VMM data at 80 meters indicates much lower calm wind frequency – 29% vs. 43% – compared to the Site Summit met tower at 10 meters.

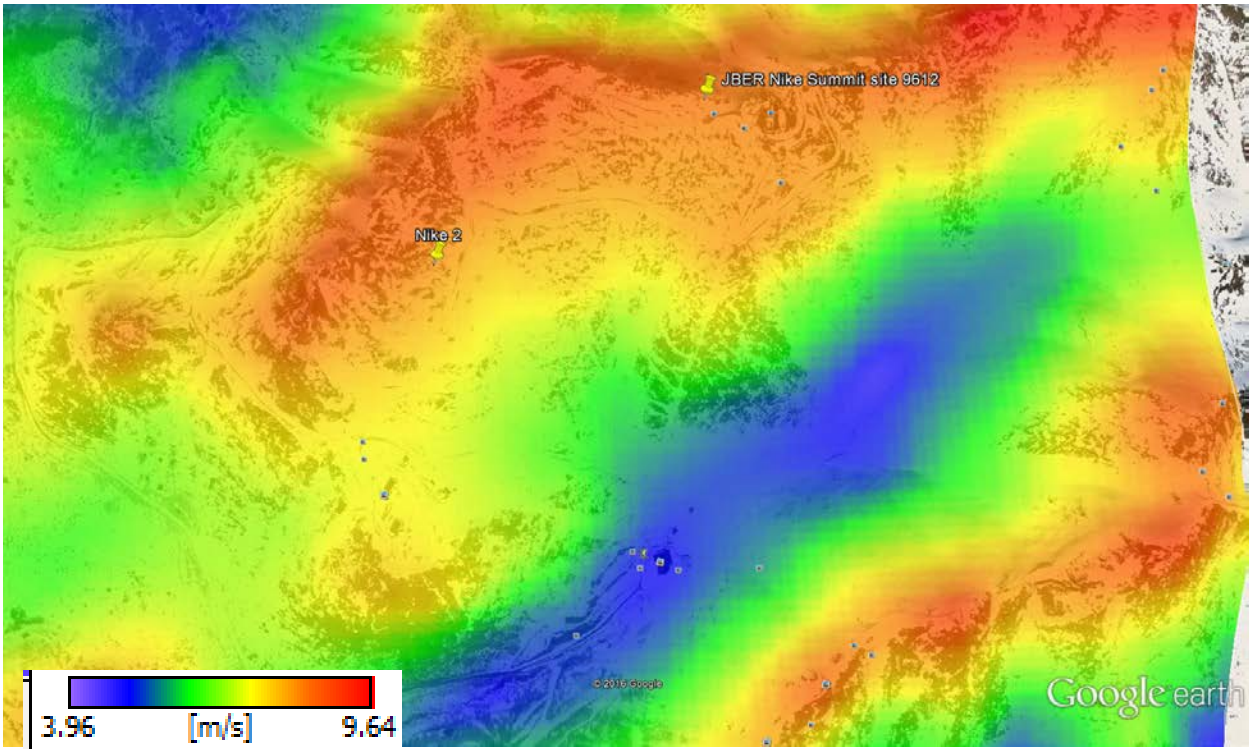
Nike 2 Virtual Met Mast (VMM) wind rose



Note with reference to https://www.awstruepower.com/products/maps-and-resource-data/, AWS Truepower modeling data, which is used to create VMM data sets, are derived from simulations of historical atmospheric conditions performed by a numerical weather prediction (NWP) model, which accounts for the local influences of terrain and surface conditions. AWS Truepower states that where appropriate the model output is fine-tuned using high-quality wind measurements, if available. Methods and validation of the AWS Truepower modeling methodology can be found at https://www.awstruepower.com/assets/Wind-Resource-Maps-and-Data-Methods-and-Validation1.pdf.

As seen below in the Nike 2 VMM speed overlay graphic, WAsP software – noting that it cannot accurately model non-laminar wind flow – predicts relatively high winds (red and yellow color overlay) on the Site Summit area and along on the ridge west and southwest-trending ridge that connects to the lower launch complex. Lower winds speed (green and blue color overlay) are lower slopes and valley areas. In this respect, all three wind data sources – Site Summit met tower, Arctic Valley weather station, and AWS Truepower VMM data – agree.

Nike 2 AWS Truepower VMM, 80 m, wind speed overlay on Google Earth image, view north



Wind Turbine Energy Production Modeling

Note that specific turbine selection is a detailed process of customer and manufacturer consideration and hence appropriate to the detailed design phase of a project. For this exercise, a 2.5 MW General Electric 2.5-116 wind turbine generator was chosen as a suitable option based on presumed IEC classification of the site area and power capacity goals of a potential project.

For a representative wind turbine layout presented, an approximate turbine separation of 3.5 rotor diameters, or 400 meters, was used. This is near the short end of the three-to-five rotor diameter separation range generally recommended in the wind power industry for turbines oriented perpendicular to the prevailing wind. Given the strong SE to SSE prevailing wind predicted across the Site Summit site, this is a reasonable assumption at present.

For actual design of a wind farm, an optimization analysis of turbine separation distance would be accomplished. The optimization of turbine separation and placement recognizes the non-coincident relationship between turbine distance and wake loss. Increased inter-turbine distance decreases wake loss but increases project development costs. This is due to the need for longer access roads, larger land area purchase or lease, longer electrical transmission lines, etc. The opposite, naturally, is also true. There is no one correct answer, other than to reference standard industry practice and guidelines of approximately five percent aggregate wind farm wake loss as a suitable compromise with respect to site development costs.

GE2.5-116 Array, Site Summit Ridge

Site Summit ridge, extending east-to-west from Site Summit itself to near the lower launch complex, extends approximately 1,700 meters in somewhat of a hook shape. Given the large 116-meter rotor diameter wind turbine generator considered and a desire to maintain an approximate 3-to-4 rotor diameter separation distance, four turbines can reasonably be fit for a combined power generation capacity of 10 MW.

WAsP modeling of a prospective four-turbine array indicates a low turbine array wake loss of only 1.36 percent with a net annual energy production (AEP) of 41.9 GWh. This equates to a high wind farm net capacity factor of 47.8 percent. Note of course that this capacity factor represents only wake loss without consideration of other loss factors, such as maintenance, hysteresis, icing, electrical losses, etc. Note also that this model assumed a standard air density of 1.225 kg/m^3 and moderate turbulence intensity. The tables below present summary information of the wind farm model.

Wind Farm Model Summary results

Parameter	Total	Average[8]	Minimum	Maximum
Net AEP [GWh]	41.899	10.475	10.028	10.870
Gross AEP [GWh]	42.477	10.619	10.187	11.095
Wake loss [%]	1.36	-	-	-

Site results

Site	UTM Location [m]	Turbine	Elevation [m a.s.l.]	Height [m a.g.l.]	Net AEP [GWh]	Wake loss [%]
WTG1	(363247, 6793681)	GE 2.5-116	1,010.5	90	10.028	1.56
WTG2	(363450, 6794026)	GE 2.5-116	1,042.5	90	10.280	1.52
WTG3	(363794, 6794320)	GE 2.5-116	1,100.0	90	10.870	2.03
WTG4	(364176, 6794194)	GE 2.5-116	1,114.7	90	10.721	0.32

Site wind climates

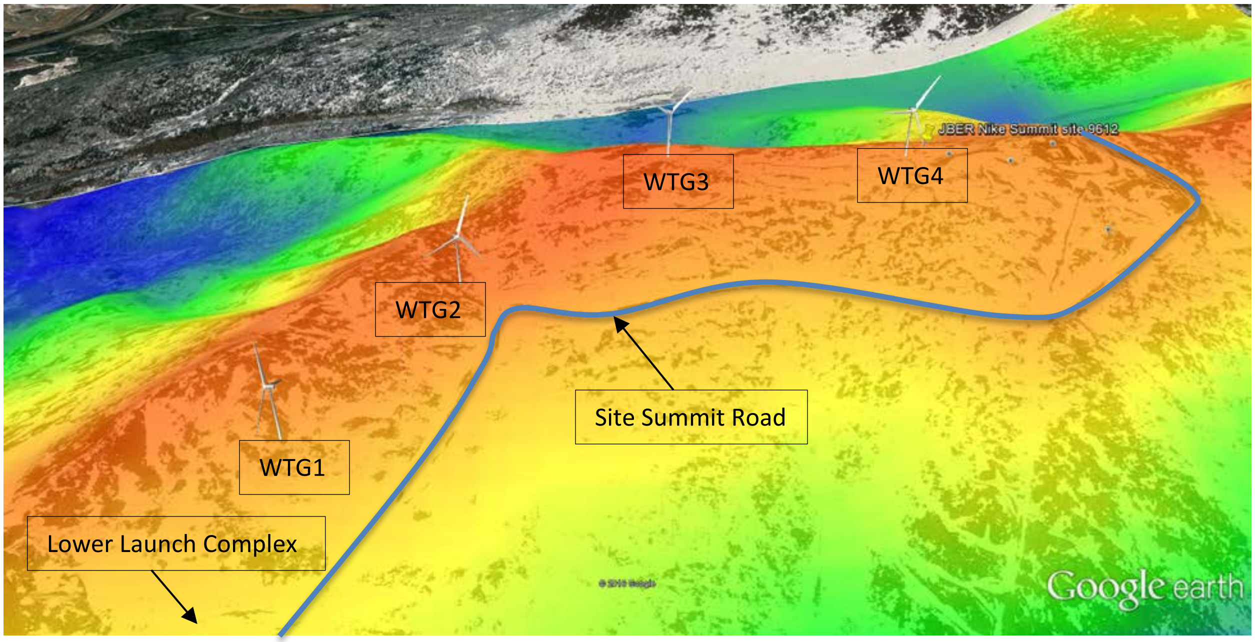
Site	UTM Location [m]	Hub Height [m a.g.l.]	Weibull A [m/s]	Weibull k (-)	Mean Wind Speed [m/s]	Mean Wind Energy [W/m²]	RIX[9] [%]
WTG1	(363247, 6793681)	90	9.1	1.42	8.23	1,007	22.9
WTG2	(363450, 6794026)	90	9.4	1.40	8.59	1,170	24.5
WTG3	(363794, 6794320)	90	9.7	1.51	8.73	1,094	27.8
WTG4	(364176, 6794194)	90	9.3	1.51	8.42	987	30.0

The following images demonstrate the locations and relative size of the wind turbines on the Site Summit and Arctic Valley landscapes.

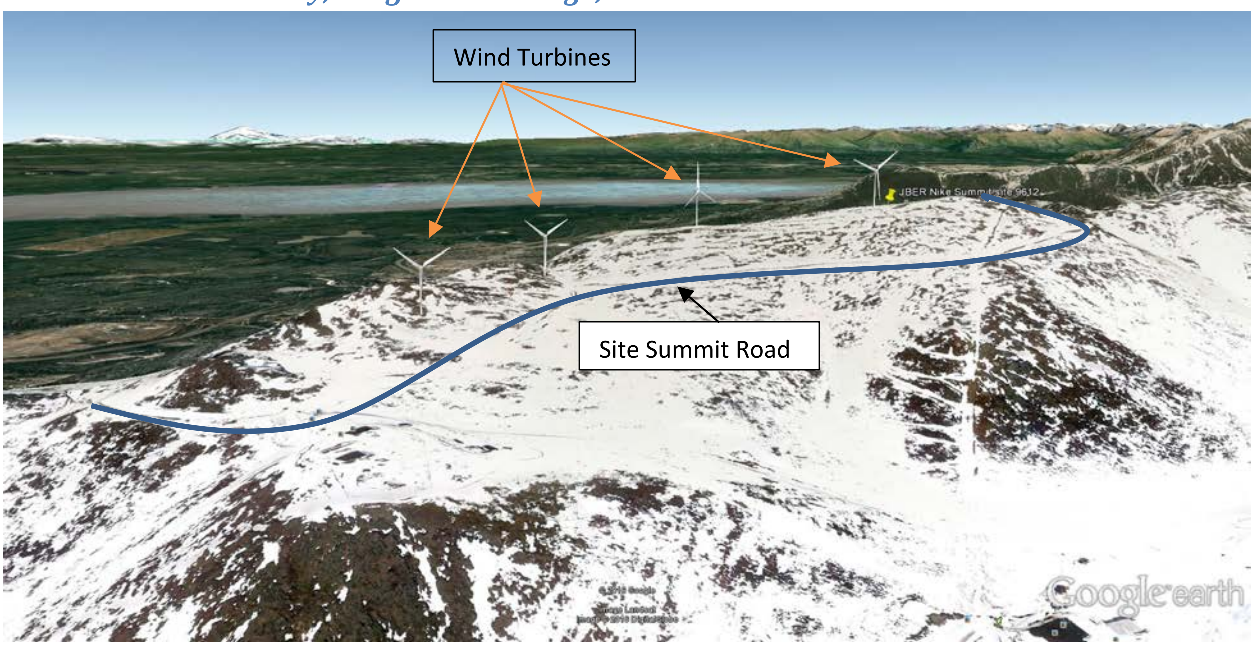
[8] Average, Minimum and Maximum are per turbine references.

[9] RIX: ruggedness index, defined as percentage fraction of terrain steeper than a 30% critical slope. RIX for flat and slightly hilly 0%; for more complex hills <10%; for mountainous 10 to 50%; from WAsP help menu

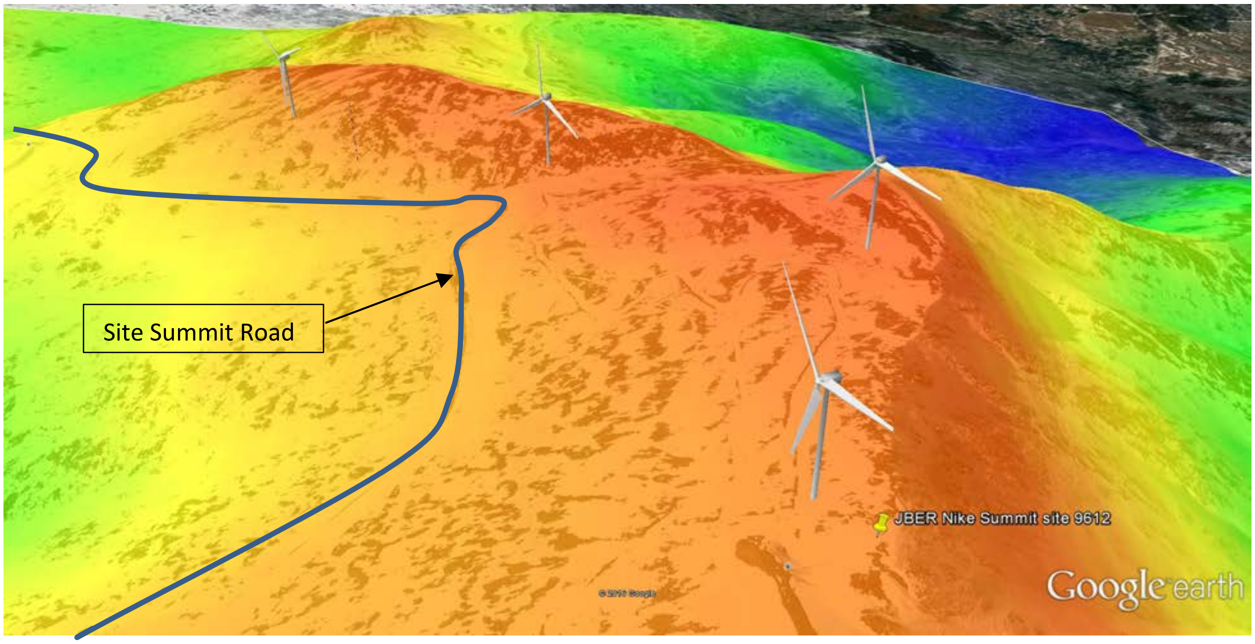
GE2.5-116 turbine array, wind speed overlay, Google Earth image, view north



GE2.5-116 turbine array, Google Earth image, view north



GE2.5-116 turbine array, wind speed overlay, Google Earth image, view west



GE2.5-116 turbine array, wind speed overlay, Google Earth image, view south