MEMORANDUM TO COUNCIL

To: Mayor and City Council Members
From: Steve Tompkins, Director of Public Utilities
Bob Cummings, City Engineer
Through: Chris Hladick, Interim City Manager
Date: November 10, 2022
Re: V3 Energy Wind Power Development Update

SUMMARY: Engineer Doug Vaught of V3 Energy will present the Wind Resource Assessment Report dated February 18, 2022, update Council on current efforts under the current Alaska Energy Authority (AEA) Grant, and highlight some additional AEA grant funding opportunities and production credits available under the Inflation Reduction Act of 2022.

PREVIOUS COUNCIL ACTION: Previous Council actions related to Wind Power Integration are outlined below.

In FY2003, Unalaska City Council approved the Wind Integration Assessment Project through Ordinance 2003-11.

In FY2018, Council funded the Wind Power Development and Integration Assessment Project (EL18C) through Capital Budget Ordinance 2017-07.

In FY2018, Council entered into an agreement with V3 Energy, LLC to perform the Wind Power Development & Integration Assessment Phase II – IV Project in the amount of $48,481 via resolution 2017-63, moving forward with Phase II work.

Budget Amendment Ordinance 2018-12, passed and adopted October 23, 2018, added $220,000 to the Engineering Services line item of the Project budget to begin Phase III work.

Budget Amendment Ordinance 2019-17, passed and adopted on January 14, 2020, provided an additional $75,000 for Phase III.

Budget Amendment Ordinance 2021-16, passed and adopted on December 14, 2021, accepted $139,000 from Alaska Energy Authority and appropriated $139,000 in the Wind Power Development Project. This work is on-going.

BACKGROUND: The Wind Energy Assessment project is comprised of four phases:

Phase I: Past Assessments is complete

Phase II: Pre-design and Site Selection is complete

Phase III: Data Collection and Analysis is complete

Phase IV: Feasibility and Design. The feasibility study is currently in progress and is funded through an AEA grant.

From 2003 to 2005, a Phase I analysis of the feasibility for wind energy in Unalaska was conducted by Northern Power Systems, however, Phase II of that project was never realized. Local interest in renewable energy and the availability of new technology led the City of Unalaska Department of Public Utilities to issue a Request for Qualifications for Phase II – IV of the Wind Power Development and Integration Assessment Project, with the work awarded to V3 Energy, LLC.

MET towers were set up at four locations around Unalaska and engineer Doug Vaught of V3 Energy analyzed the data and generated the *City of Unalaska Wind Power Development and Integration Assessment Project, Wind Resource Assessment Report* dated February 18, 2022. Doug will present a brief overview of this report, highlight some grant opportunities, and be available to answer questions.

DISCUSSION: Staff feel there will soon be sufficient data to make an informed decision on the future of wind power generation in Unalaska, both with and without the context of geothermal power. There are some interesting funding opportunities, some of which are time sensitive, and some of which are green energy production credits that are favorable to the installed cost per kWh for wind energy. With a bright future for increasing our electrical load demands, it may be that some wind generation would provide a baseload that will increase the City's overall installed capacity, without requiring additional permitting for increasing diesel generation. Additionally, wind power could probably be deployed quicker than either additional diesel units or geothermal, offering bridge baseload power until one of these options are on-line.

Staff requests Council provide direction on pursuing grant opportunities to help fund future of wind power development in Unalaska.

ALTERNATIVES: Either Staff can work with V3 Energy to prepare an AEA grant application to help fund future wind development in Unalaska or Staff could wait until after the feasibility study is complete, present this information to Council, and seek direction from Council at this time. If the second option is chosen, the current AEA grant opportunity will no longer be available, but perhaps other funding opportunities would be.

FINANCIAL IMPLICATIONS: At this point there are no financial implications. Only after the outcome of the grant application, if submitted, is known (after FY24 State of Alaska Budget is passed by the State Legislature) and the feasibility study and cost estimate are complete will the City have a clear indication of the economics of installing wind power generation capacity in Unalaska. Early indications are that wind power is roughly comparable with other options (i.e. diesel or geothermal) on an installed cost per kilowatt basis.

LEGAL: Not applicable.

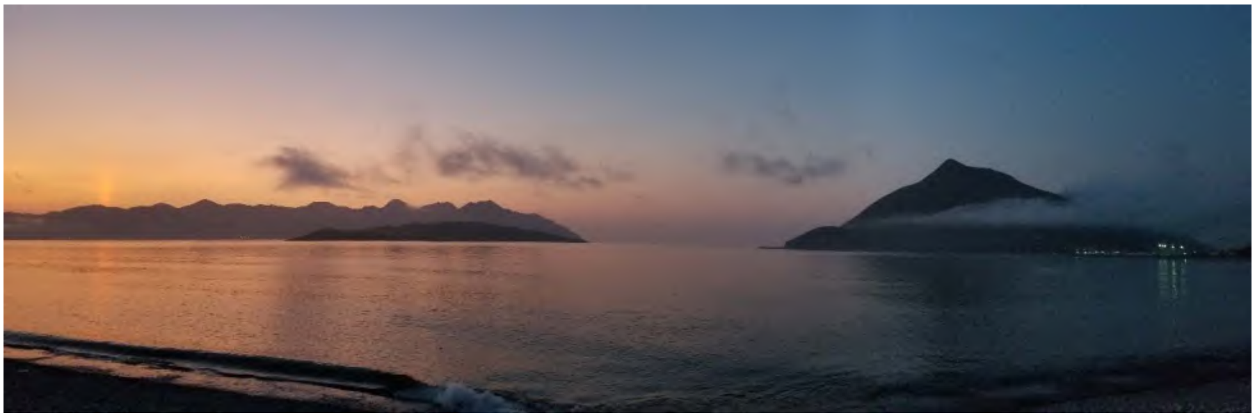
STAFF RECOMMENDATION: Staff is looking for guidance only.

PROPOSED MOTION: If Council wishes to proceed with the AEA Grant now: "I move to direct the City Manager to work with V3 Energy to prepare an AEA grant application to help fund future wind development in Unalaska."

CITY MANAGER COMMENTS:

ATTACHMENTS: Wind Power Development and Integration Assessment Project, Wind Resource Assessment Report

City of Unalaska Wind Power Development and Integration Assessment Project, Wind Resource Assessment Report



Douglas Vaught photo

February 18, 2022

Douglas Vaught, P.E.
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Anchorage, Alaska

V3 Energy LLC
Anchorage, Alaska 907.350.5047

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Introduction

With frequent high winds, Unalaska Island, home of City of Unalaska and Dutch Harbor, has long been considered an optimal location for wind energy. The August 2017 *Request for Proposals, Analysis of the City of Unalaska Wind Power Development and Integration Assessment Project* was broken into three phases, starting with Phase II (Phase I, a survey-level assessment of wind power potential for Unalaska, was completed in draft form in 2005). Phase II of the project, "Develop a Data Collection Plan," was completed by V3 Energy LLC with a Phase II report dated August 6, 2018.

Phase III of the project, "Implement Data Collection Plan," was initiated shortly following completion of Phase II with obtaining landowner permission, permits, ordering equipment, etc. over the following year. As described herein, three met towers were installed in October 2018 and the fourth in August 2019. In August 2021 the last of the four met towers was decommissioned, signifying the end of the data collection aspect of Phase III. This report presents and discusses the data collected through that nearly three-year period.

In a slight change to the 2017 plan as described in the *Requests for Proposals*, the Phase IV ("Pre-development Plan") effort will be accomplished via a State of Alaska Renewable Energy Fund Round 13 grant award with a project entitled *City of Unalaska Wind Power Feasibility.*

Site Selection

There were several criteria to consider for wind prospecting in Unalaska (completed under Phase II of the wind project), that commenced with an assessment of the regional wind climate (refer to pages 13 through 20 of the Phase II report). In short, developable locations for wind power in rural Alaska, including Unalaska, are those with the following criteria:

- Wind resource: high (but not too high) mean wind speed, normal or near normal Weibull distribution, low-to-moderate turbulence (steady wind flow), acceptable extreme winds, and unimodal or bimodal wind direction distribution.
- Power distribution infrastructure: proximity to existing (or near-term planned) distribution lines with sufficient amperage capacity to accept input from planned wind farm capacity, including expansion potential.
- Roads/access: proximity to existing roads, or reasonable cost to develop or improve access.
- Site area: large enough to host a wind turbine array that meets project wind power capacity goals.
- Land use: available for development (ownership, easement restrictions, lease rates, etc.).
- Airspace: no insurmountable FAA restrictions for airport flight operations.
- Terrestrial wildlife and avian species: no or minimal impacts to critical habitat, flyways, etc.
- Wetlands, parks, and other high-value environments: no insurmountable restrictions and/or acceptable mitigation requirements are possible.
- Noise, shadow flicker, and aesthetics: no or minimal impact to residents.
- Rime icing environment and/or ice throw risk: no or minimal risk and/or acceptable mitigating measures possible.

With these considerations, four locations were chosen for installation of meteorological (met) towers for wind resource evaluation (see Figure 1):

1. Pyramid (Lower Pyramid Valley)
2. Hog Island
3. Icy Creek Reservoir
4. Bunker Hill (referenced in the Phase II report as Little South America)

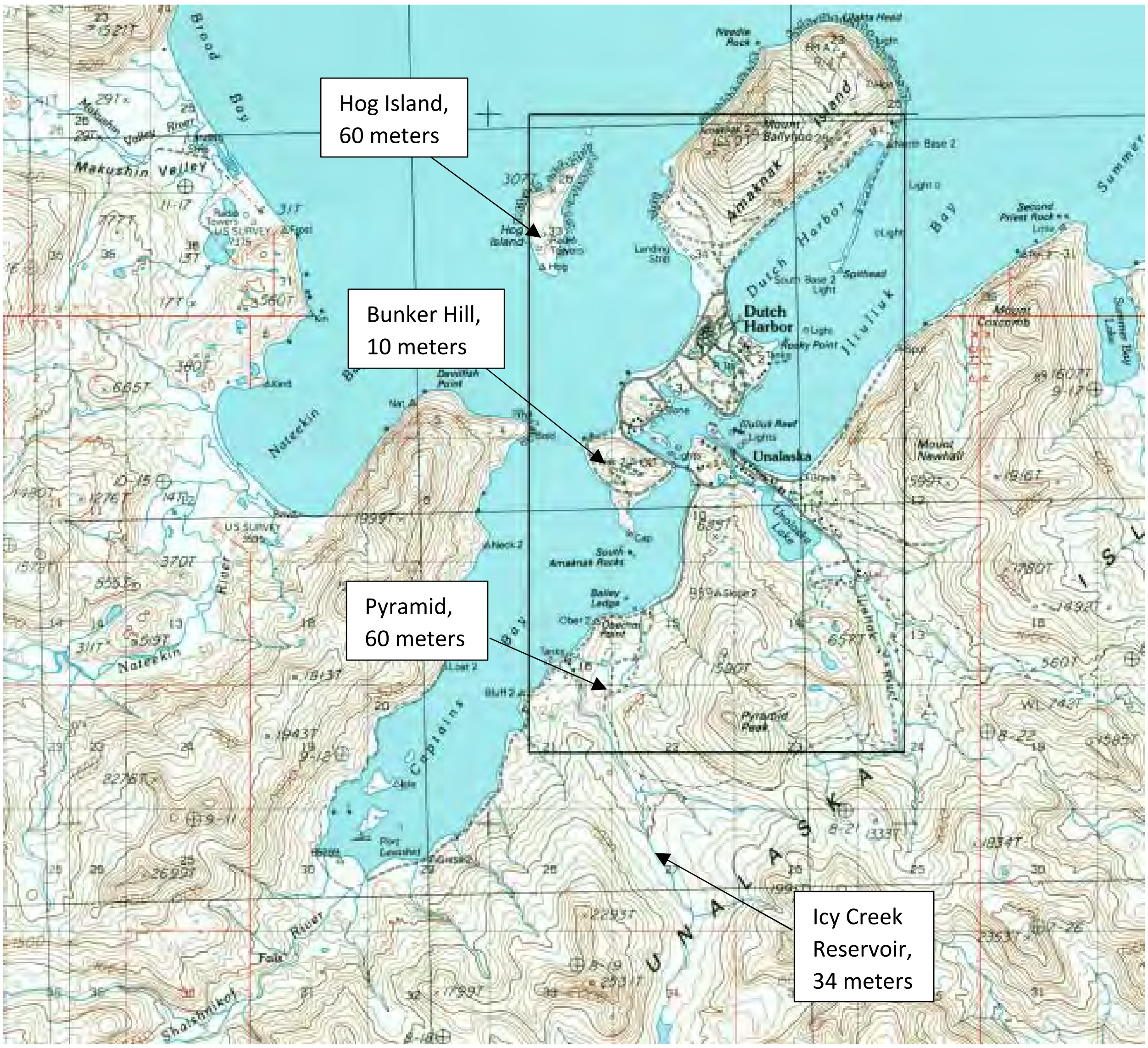

Figure 1: Met tower locations and heights (map from Topozone.com)

There are two primary uses of wind data for wind power development. First is classification of site(s) to determine suitable turbine models. Wind turbine manufacturers require International Electrotechnical Commission (IEC)[1] classification of a site to ensure that the proposed turbine model is appropriate and

[1] See IEC Classification discussion in Appendix A

warranty coverage valid. Financial institutions and/or partners require proper classification to ensure the wind turbine investment will perform as predicted throughout planned service life and that a warranty can be offered.

The second use of wind data is calculation of annual energy production (AEP) for wind turbines of interest with reasonable deductions for wake, electrical, O&M, soiling, and other losses. Net AEP data is used to model economic benefit of a wind power project.

Pyramid (lower Pyramid Valley)

Pyramid Valley, source of Unalaska's water supply, was considered at project outset to be the most promising location in Unalaska for a wind power project. The plateau area that comprises the lower valley is large enough to host several megawatts of wind power capacity; a wide, well-maintained gravel road provides access; the area is devoid of housing and other community-use development other than the water plant; and of considerable importance, the valley is served by an underground high capacity, three-phase power distribution line (3 phase power routes to the water plant with single phase continuing to Icy Creek Reservoir) that is minimally loaded at present. Additionally, Pyramid Valley is relatively distant from Dutch Harbor Airport and displaced from established landing patterns and normal air traffic routing.

Figure 2: Pyramid 60-meter met tower (Andy Dietrich aerial photo)

Pyramid Site and Met Tower Information

A 60-meter height (197 ft.) NRG Systems, Inc. tubular, guyed met tower was installed[2] in mid-October 2018 on City of Unalaska land just south of Veronica Lake (see Figure 2 and Figure 3) and was decommissioned by Department of Public Works personnel in August 2021. Refer to Table 1 for summary information of the met tower and data collected from it.

[2] Met tower installation accomplished by V3 Energy LLC with contracted assistance from Bering Straits Development Company and Solstice Alaska Consulting. The considerable support provided by City of Unalaska Dept. of Public Works personnel is much appreciated.

Table 1: Pyramid met tower summary information

Data dates	10/16/2018 to 8/12/2021 (34 months)
Datalogger information	NRG Symphonie PRO, 26 channel, site no. 3550
Site coordinates	53.8496 North, 166.5625 West (WGS 84 datum)
Site elevation	103 meters (334 ft.)
Wind speed, mean annual, 60 m level	6.84 m/s corrected to Dutch Harbor Airport long-term weather station data; 6.39 m/s as measured
Wind power density, mean annual, 60 m	548 W/m^2 when corrected to Dutch Harbor Airport long-term weather station data; 446 W/m^2 as measured
Wind power class	5 (excellent), when corrected to Dutch Harbor Airport long-term weather station data) of 7 defined classifications; 4 (good) as measured
Maximum 10-min. avg wind speed	37.5 m/s (83.9 mph)
Maximum 3-sec. gust wind speed	51.4 m/s (115.0 mph)
Wind shear power law exponent	0.100 (low; 0.140 considered nominal)
Calm wind frequency (winds < 4 m/s)	Approx. 33%
Extreme wind probability (50-year period)	41.3 to 47.6 m/s
Turbulence intensity, 60 m level	0.120
IEC 61400-1 3rd ed. classification	Class IIB

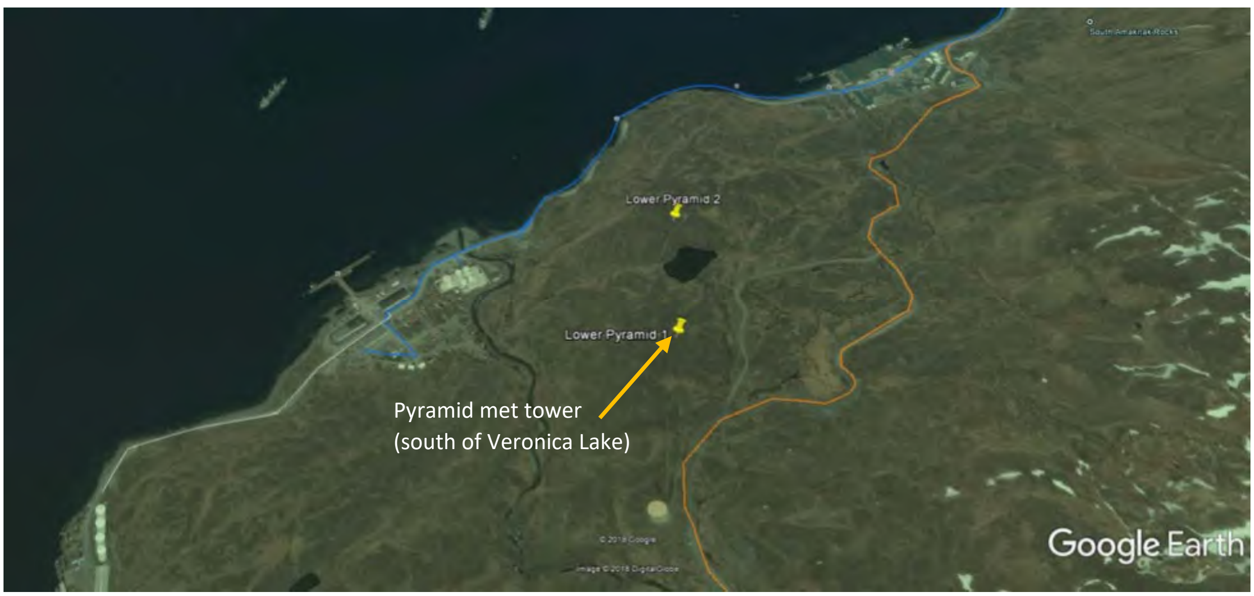

Figure 3: Pyramid met tower location (orange line shows underground power distribution routing, 3 phase to the water house/tank, continuing at single phase to Icy Creek Reservoir), view north; Google Earth image

Before installing the met tower, a Federal Aviation Administration (FAA) obstruction evaluation was requested. FAA issued Aeronautical Study No. (ASN) 2018-WTW-5350-OE in July 2018 with a determination of no hazard to air navigation. Obstruction lighting was not required although FAA requested alternating bands of aviation orange and white paint on the met tower and that orange high-visibility marker balls be attached near the top of the outer guy wires to improve tower visibility to aviators. Both requirements were accomplished.

The Pyramid met tower was equipped with two anemometers each at 60 meters, 50 meters and 40 meters; one wind vane each at 60 meters and 50 meters; a vertical wind propeller anemometer at 55 meters; and temperature and relative humidity sensors at the tower base (refer to Table 2). Refer to Appendix B for detailed sensor technical information and to Appendix F for documentation photographs.

Table 2: Pyramid met tower sensors

Ch	Sensor Type	Model	Name	Height (m)	Dir. (°T)
1	Anemometer	40C	60m E	59.7	094
2	Anemometer	40C	60m W	59.3	269
3	Anemometer	40C	50m E	50.2	094
4	Anemometer	40C	50m W	49.7	269
5	Anemometer	40C	40m E	38.9	094
6	Anemometer	40C	40m W	38.4	269
13	Vane	200M	60m	57.4	027
14	Vane	200M	50m	48.0	038
16	Temp	T60	Temp	3.0	000
19	Rel. Humidity	RH5X	RH	2.0	000
20	RM Young	27106T	Vert Spd	55.3	311

Pyramid Data Quality Control

The met tower sensor data was manually filtered to remove compromised records. This included startup sequencing, isolated periods of power supply problems, icing events, tower shading[3], and poorly functioning sensors. As indicated in Figure 4, anemometer data recovery from the Pyramid met tower was outstanding initially but as the sensors aged, they began to fail. In 2020 the channel 1, channel 4, and channel 6 anemometers began "dragging", or behaving abnormally compared to their companion anemometers. From the ground, a damaged anemometer appears to function normally, but close observation – both visual and via the data record – indicates that it spins more slowly than its companion and stops rotating at slightly higher wind speeds. On a positive note, infrequent icing events[4] have been detected, indicating minimal concern for atmospheric icing that can negatively impact wind turbine operations.

Note in Figure 4 periods of loss of function of the wind vanes and temperature sensor early in the project. This was due to a power supply problem that was corrected in February 2019. At that time, a relative humidity (RH) sensor was installed to aid in the detection and inference of wintertime icing events. Table 3 presents *data recovery rate* for each Pyramid sensor.

[3] Tower shading results from airflow distortion by the met tower. Air decelerates slightly upwind of the tower, accelerates as it goes around the tower (Bernoulli principle), and decelerates markedly in the lee of the tower where a flow separation bubble may occur, resulting in disturbed airflow downwind (source: Windographer help menu). Because of that, anemometers in a 30-degree arc downwind are filtered from the dataset. Anemometers are paired opposite each other and perpendicular to the prevailing winds to minimize the tower shading effects.

[4] Icing is inferred in the dataset by observing stationary anemometers and/or wind vanes combined with temperature near freezing or below and relative humidity at or near 100%, indicating the likelihood of snow or freezing rain.

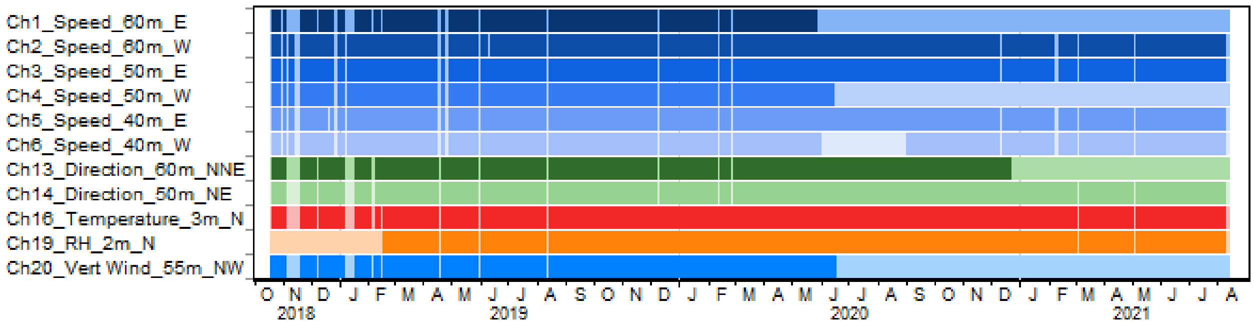

Figure 4: Pyramid met tower data recovery rate graphic (tower shading filtering excluded)

Table 3: Pyramid met tower data recovery rate table (tower shading filtering excluded)

Data Channel	Height	DRR (%)
Ch1_Speed_60m_E	59.7 m	54.9
Ch2_Speed_60m_W	59.3 m	98.9
Ch3_Speed_50m_E	50.2 m	98.9
Ch4_Speed_50m_W	49.7 m	58.3
Ch5_Speed_40m_E	38.9 m	98.8
Ch6_Speed_40m_W	38.4 m	90.3
Ch13_Direction_60m_NNE	57.3 m	75.3
Ch14_Direction_50m_NE	48.0 m	97.6
Ch16_Temperature_3m_N	3 m	97.8
Ch19_RH_2m_N	2 m	88.0
Ch20_Vert Wind_55m_NW	55.2 m	57.3

Pyramid Environmental Measurements

Unalaska experiences a cool, damp maritime climate, with a relatively narrow range of temperatures and typically high relative humidity, especially compared to northern and interior Alaska. From the perspective of wind turbine operations, cool damp air is beneficial as it yields higher air density than equivalent elevation in warmer climates. Figure 5 shows boxplot summaries of measured temperature, relative humidity, and calculated air density at Pyramid for the data collection period but presented as *mean of monthly means* where repeating months are averaged.

Note that although standard air density[5] at 103 meters (334 ft.) elevation is 1.213 kg/m^3, the measured air density at Pyramid was 1.248 kg/m^3, 2.9% higher than standard density at 103 meters elevation and 1.9% higher than standard sea level conditions. This is important as higher density proportionally increases the lift force imparted to the rotor blade, increasing turbine power output.

[5] Standard air density at sea level is 1.225 kg/m^3 (at 15° C)

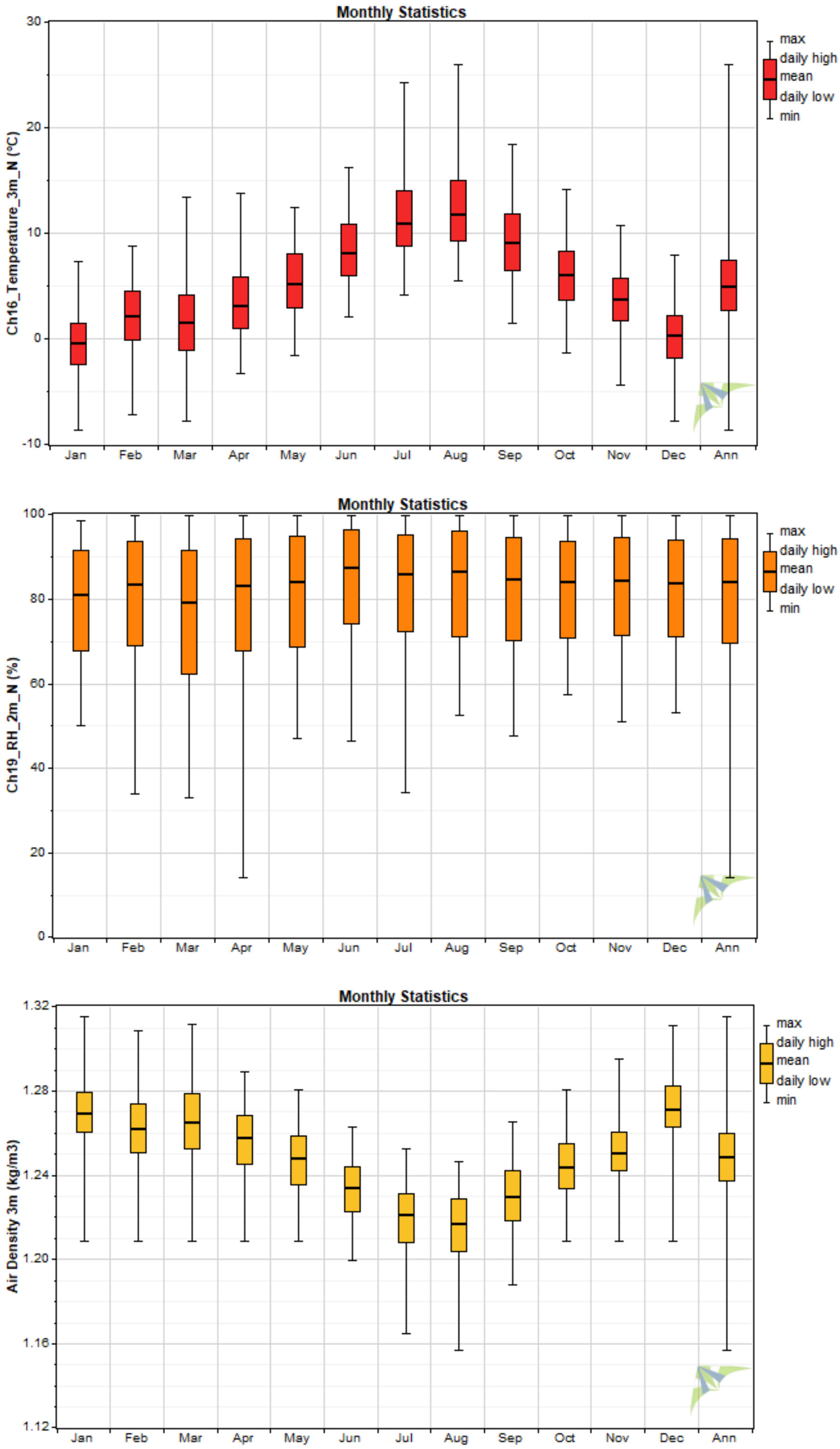

Figure 5: Pyramid met tower temperature, relative humidity, and air density boxplots

Pyramid Wind Speed and Anemometer Combination

Filtered wind speed data, as described in Data Quality Control, yields more representative information than raw data. But the NRG 40C anemometer, as used on the Pyramid met tower, responds more quickly to gusts than falling wind speeds. In moderate-to-higher turbulence conditions, as was measured at Pyramid, this can yield high-bias wind speed data compared to that obtained from high precision anemometers.[6] A net correction of approximately -1% was applied to the anemometer data set using Equation 1. Note that this correction is applied to each 10-minute time step.

Equation 1: NRG 40C anemometer wind speed measurement adjustment for turbulence

$$Uadjusted = \frac{Uobserved}{(0.095 \times TI) + 0.992}$$

With filtering and adjusting anemometer response for turbulence with Equation 1, an anemometer data summary is presented in Table 4.

Table 4: Pyramid wind speeds, filtered and adjusted by Equation 1

Variable	Ch1_Speed_60m_E	Ch2_Speed_60m_W	Ch3_Speed_50m_E	Ch4_Speed_50m_W	Ch5_Speed_40m_E	Ch6_Speed_40m_W
Mean wind speed (m/s)	6.32	6.39	6.25	6.21	6.15	6.23
Mean wind speed (mph)	14.1	14.3	14.0	13.9	13.8	13.9
Max 10-min wind speed (m/s)	29.9	37.5	37.0	28.6	36.5	35.8
Max 10-min wind speed (mph)	66.8	83.9	82.8	63.9	81.6	80.1
Max gust wind speed (m/s)	41.0	51.4	51.4	49.7	49.7	41.3
Max gust wind speed (mph)	91.8	115.0	115.0	111.2	111.2	92.4
Mean power density (W/m²)	439	446	416	405	403	405
Frequency of calms (%)	33.3	33.9	34.8	34.2	35.5	33.6

Combined Anemometers

Although Table 4 represents wind speed data with necessary filtering, long periods of met tower operation with asymmetric data collection, especially from the 60-meter and 50-meter level anemometers, yields divergent wind speed data for paired anemometers. Two primary options can be used to correct this: synthesize missing data or mathematically combine the anemometers (or both). Both methods typically yield similar results, but anemometer combination is more conservative in that less change is introduced to the data set. Hence, only anemometer combination was used to create a more representative data set than that presented in Table 4.

Table 5: Pyramid combined anemometer data (DRR: data recovery rate)

Combined Sensor	Height (m)	First Anemometer		Second Anemometer		Combined Sensor	
		DRR (%)	Mean (m/s)	DRR (%)	Mean (m/s)	DRR (%)	Mean (m/s)
Speed 60m cmb	59.5	54.9	6.32	98.9	6.39	98.3	6.39
Speed 50m cmb	50.0	98.9	6.25	58.3	6.21	97.6	6.28
Speed 40m cmb	40.7	98.8	6.15	90.3	6.23	98.7	6.16

[6] Explanation and equation from Windographer software help menu

Seasonal and Diurnal Variation

Pyramid's monthly wind speed profile (see Figure 6) demonstrates a pronounced seasonal variation of wind speeds with higher winter winds and lower summer winds. This is a normal pattern and matches well with typical seasonal power demands in a community. Figure 7 indicates a normal, though somewhat muted, diurnal (daily) wind speed profile of higher afternoon winds compared to night and morning. This is also typical.

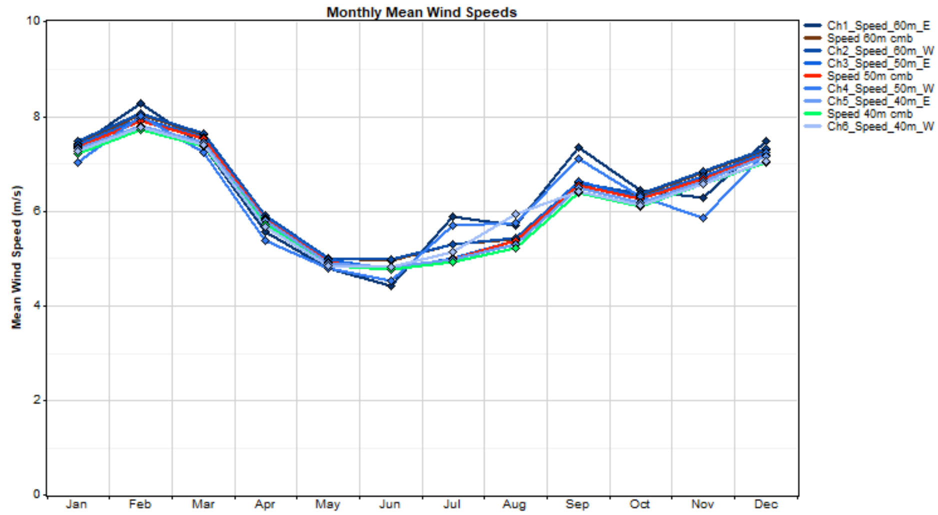

Figure 6: Pyramid mean (mean of monthly means) wind speeds, all anemometers

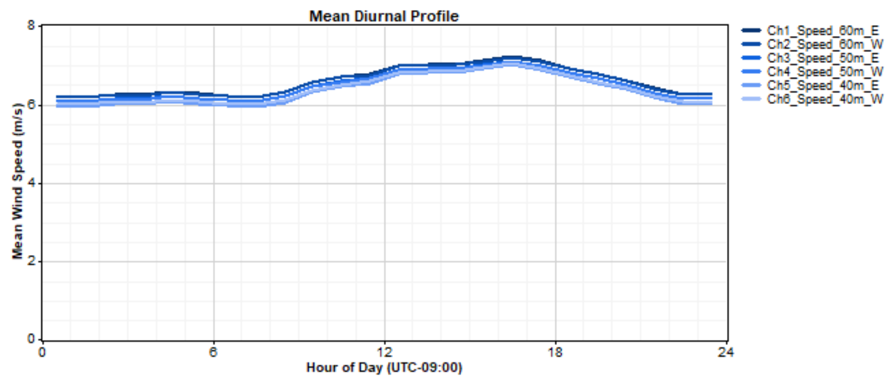

Figure 7: Pyramid diurnal wind speed profile

Pyramid Wind Speed Adjustment Against Airport Reference Data

The Pyramid met tower was operational for 34 months, which is relatively long for a wind resource assessment project but brief when considering long-term climatology. This presents a risk of site mischaracterization, which can be high or low as three years of met tower data may capture unusually windy or unusually calm winter season(s), skewing or biasing the results. At Pyramid, the measured and adjusted mean annual wind speed of 6.39 m/s at the 60-meter level (refer to Table 5) is 8% lower than the 6.95 m/s mean wind speed at Pyramid at the 60-meter level predicted by AWS Truepower Windnavigator wind modeling software, which raises a question of possible data skew or bias.[7]

[7] See Table 4 on page 30 of the Unalaska Wind Assessment Phase II project report

To assess data skew, Pyramid met tower data was adjusted by comparison to nearby Dutch Harbor Airport, located 5.6 km (3.5 miles) north-northeast of the met tower. Automated airport weather station data from January 1988 to July 2021 was obtained to provide 33.5 years of comparative wind speed data. With reference to Figure 8, the 33 complete months of Pyramid overlap – November 2018 to July 2021 – demonstrates that Dutch Harbor Airport had lower than average wind speeds from start of the Pyramid met tower project through October 2020. Beginning in November 2020, airport wind speeds were generally higher than their long term (33.5-year) average.

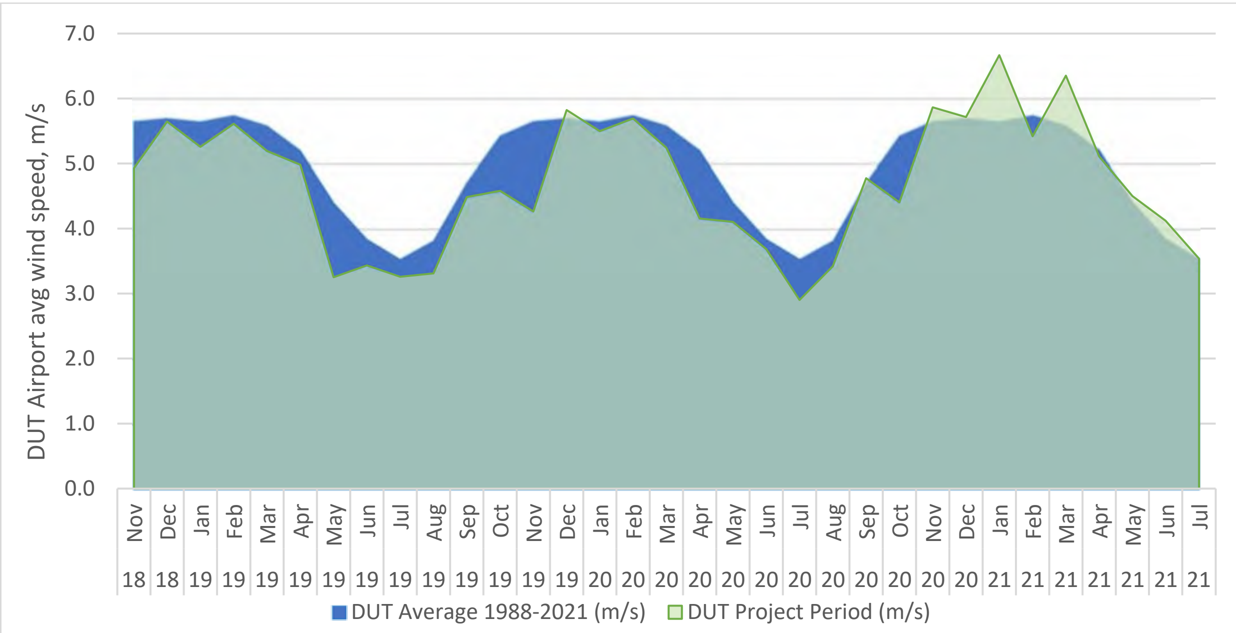

Figure 8: Dutch Harbor Airport wind speed comparison, Pyramid test period vs. 33.5-year average

The implication of lower-than-average wind speeds at the airport during the Pyramid study period is that mean wind speeds calculated from the Pyramid data set are likely biased low. An adjustment was made to the Pyramid data to correct that bias. Table 6 combines data from Table 5 and Figure 8 to adjust the 60-meter level combined anemometer against the long-term average. This yields an 8% increase in mean wind speed, from 6.39 m/s to 6.84 m/s, which is 98.4% of the 6.95 m/s AWS Truepower Windnavigator-predicted wind speed at the site.

Table 6: Pyramid 60 m level wind speed adjustment to Dutch Harbor Airport

Month	Pyramid 60 m cmb Speed (m/s)	Wind Speed Correction (%)	60 m Adjusted Wind Speed (m/s)
Jan	7.45	98%	7.32
Feb	8.05	103%	8.30
Mar	7.63	101%	7.68
Apr	5.92	111%	6.55
May	5.01	114%	5.69

Month	Pyramid 60 m cmb Speed (m/s)	Wind Speed Correction (%)	60 m Adjusted Wind Speed (m/s)
Jun	4.96	103%	5.13
Jul	5.31	110%	5.85
Aug	5.41	114%	6.14
Sep	6.61	102%	6.73
Oct	6.35	121%	7.68
Nov	6.83	114%	7.82
Dec	7.29	99%	7.25
Annual	6.39	108%	6.84

Adjusting met tower data to a long-term average has important implications for wind turbine energy production potential as the power of the wind is a function of the velocity cubed, as noted in Equation 2.

Equation 2: Wind power density equation (P=power, A= rotor swept area, ρ=air density, V=wind speed; units Watts/m²)

$$\frac{P}{A} = \frac{1}{2} * \rho * V^3$$

So, although the long-term average predicted wind speed of 6.84 m/s is 7% higher than the 6.39 m/s measured win speed at Pyramid during the study period, the cubic relationship of wind speed vs. power (or energy) yields a 23% higher power density (6.84^3 divided by 6.39^3). This adjustment boosts the wind power class of the Pyramid site from Class 4 (good) to low Class 5 (excellent).

Pyramid Wind Direction

The prevailing wind directions at Pyramid are broadly northerly, southeasterly, and southwesterly, with southeasterly and southwesterly winds strongest (see Figure 9). The represents winds flowing across Unalaska Bay from the north, Pyramind Valley from the southeast, and Shaishnikof Creek and Captains Bay from the southwest. The practical interpretation of Figure 9 is that power-generating winds are generally southerly and northerly. Hence, for the most part, Pyramid's winds are bimodal, which is advantageous in that a multi-turbine array layout can be relatively easily designed to minimize rotor wake interference.

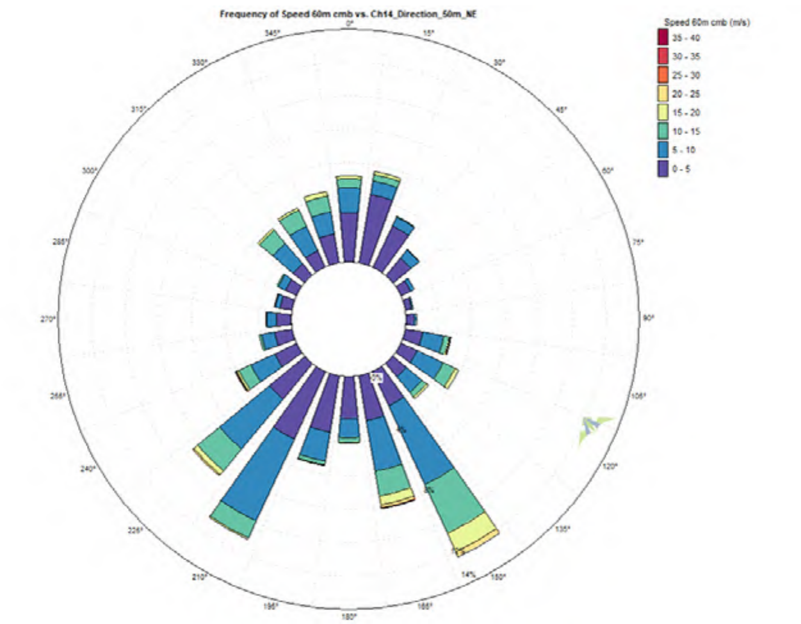

Figure 9: Pyramid wind energy rose, 50-meter level combined anemometers and 50-meter wind vane

Pyramid Vertical Wind Flow

A RM Young propeller vane anemometer was installed at the 55-meter (180 ft.) level to enable calculation of wind flow angle, an important engineering consideration with wind turbines that affects main rotor shaft bearing loading. Relatively high wind up-flow angle from westerly winds (see Figure 10) may pose some concern and should be discussed in detail with wind turbine manufacturers.

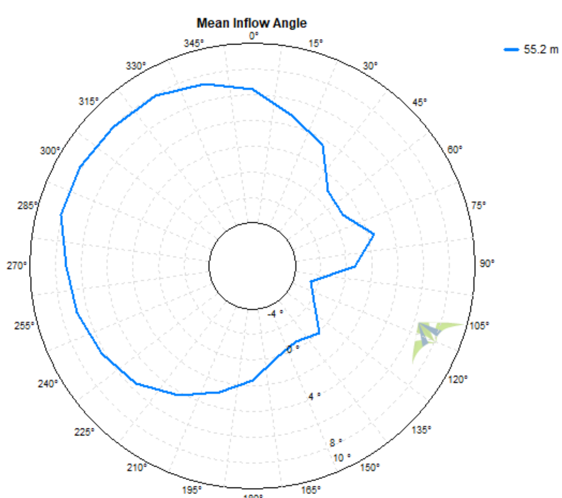

Figure 10: Pyramid vertical wind flow rose, combined 60-meter anemometers

Pyramid Wind Distribution, Weibull

The probability distribution function, or histogram, of the Pyramid met tower 60-meter combined anemometer wind speed data indicates a shape curve dominated by low-to-moderate wind speeds with a somewhat high percentage of calm winds (see Figure 11).

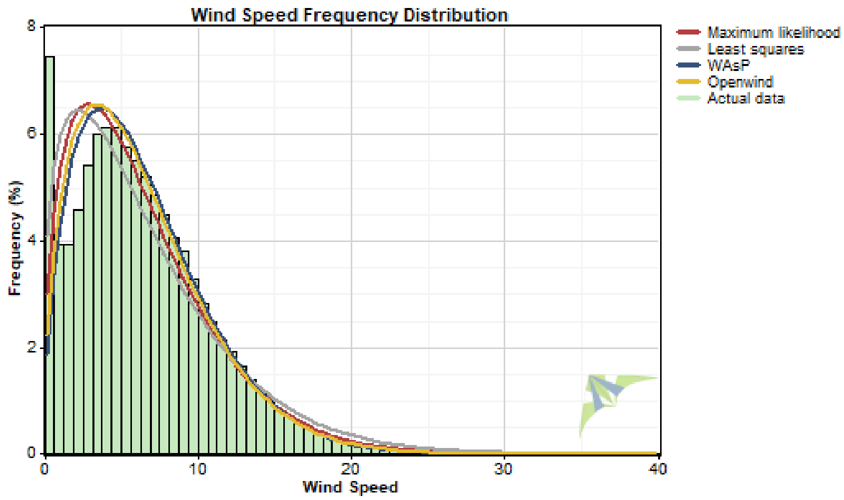

Figure 11: Pyramid wind speed probability distribution histogram

With reference to Figure 11, Table 7 includes the statistical information of the fitted shape curves for the measured wind speed distribution. Note that a Weibull k for all four estimation models is lower than 2.0; the latter which represents a "normal" shape curve in the wind power industry known as the Rayleigh curve. This demonstrates a predominance of lower wind speeds in the data set.

Table 7: Pyramid wind speed distribution table

Algorithm	Weibull k (-)	Weibull A (m/s)	Mean (m/s)	Proportion Above 6.421 m/s	Power Density (W/m2)	R Squared (-)
Maximum likelihood	1.40	7.00	6.38	0.413	481	0.902
Least squares	1.28	7.14	6.62	0.419	627	0.906
WAsP	1.55	7.24	6.52	0.438	440	0.893
Openwind	1.49	7.09	6.41	0.424	440	0.897
Actual data			6.41	0.438	440	

Pyramid Wind Shear and Roughness

Wind shear is defined as the change in wind velocity (wind and direction vector) with height above ground level. Low wind shear is desirable as the marginal increase in power output at higher heights is minimal, leading to the possibility of lower height wind turbine towers to significantly reduce project costs.

Pyramid wind shear is low by wind industry standards with a mean calculated power law exponent of 0.100 from the combined anemometers and all wind direction sectors (see Figure 12). A view by wind direction though (see Figure 13) shows higher wind shear with prevailing southeasterly and southwesterly winds. The calculated surface roughness of 0.00022 meters is equivlant to that of a very smooth surface, such as a calm sea.

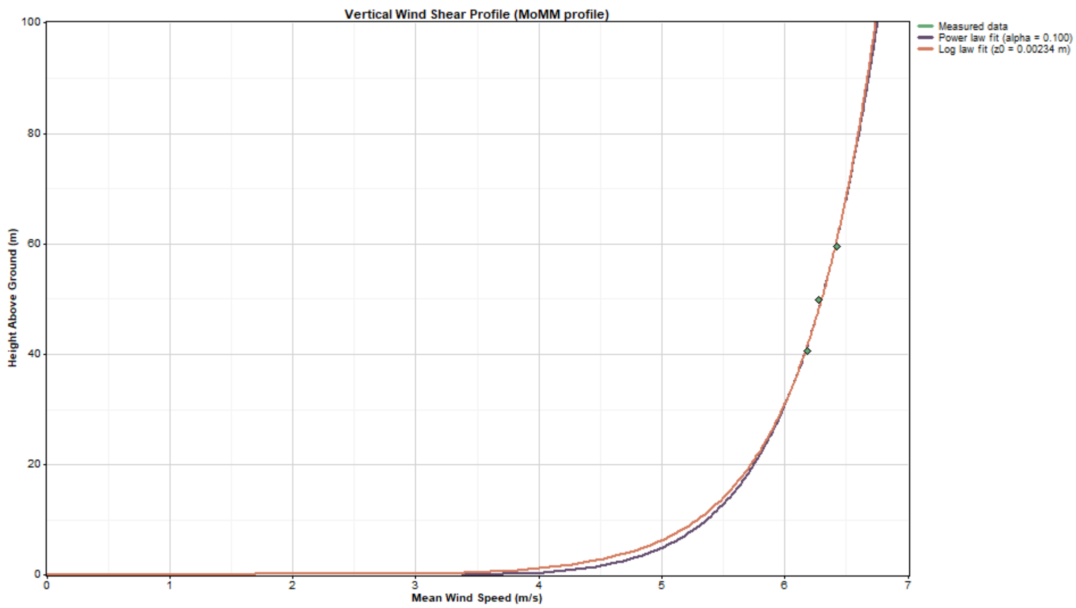

Figure 12: Pyramid vertical wind shear profile (calculated 0.100 power law exponent)

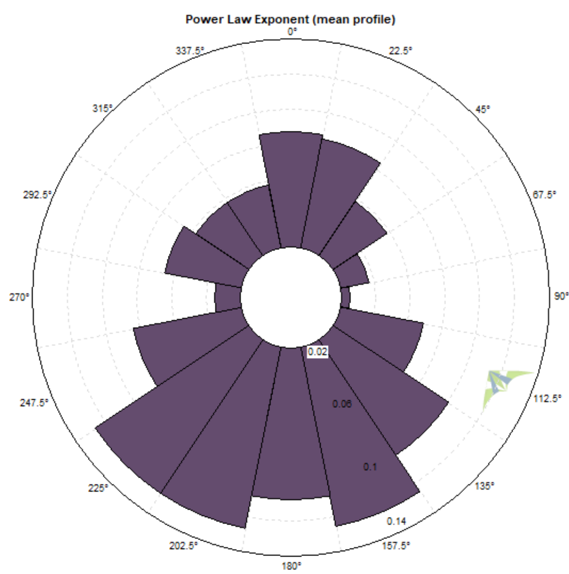

Figure 13: Pyramid vertical wind shear rose (0.14 power law exponent, outer ring)

Pyramid Extreme Wind Behavior

Extreme wind is described by Vref, or reference velocity, in a 50-year return period (see Table 21 in Appendix A) as defined by IEC 61400-1, 3rd edition (2005) standards. Reference velocity is the highest 10-minute average wind speed predicted to occur once every 50 years. Because very few wind studies for wind power development approach 50 years duration, a Gumbel distribution analysis estimates the 50-year extreme wind probability using collected met tower data.[8] Three estimation methods for wind

[8] In probability theory and statistics, the Gumbel distribution models the distribution of the maximum or minimum of several samples of various distributions; see https://en.wikipedia.org/wiki/Gumbel_distribution for further explanation.

power are commonly used: periodic maxima, method of independent storms, and European Wind Turbine Standards II, with results shown in Table 8. Note that one very strong wind event, which suprisingly occurred during the summer, on August 31, 2020, significantly influenced Pyramid's 50-year extreme wind probability.

Periodic Maxima

The first method to estimate Vref is a Gumbel distribution analysis modified for monthly maximum winds versus annual maximum winds, which are typically used for this type calculation. Thirty-four months of wind data are acceptable for this analysis, using the 60-meter combined anemometer. With filtered and preconditioned (by Weibull k) data, the predicted Vref by this method is 42.6 m/s. With reference to Appendix A, this result just exceeds IEC Class II criteria, the middle-defined category of extreme wind probability.

Method of Independent Storms

A second extreme wind estimation method, method of independent storms, yields a Vref estimate of 47.6 m/s, which is significantly higher than that predicted by the periodic maxima method and would classify the site as IEC 61400-1 Class I.

European Wind Turbine Standards II (EWTS II)

The third estimation technique, EWTS II, ignores measured peak wind speeds and calculates Vref from the Weibull k factor. There are three variants of this method – Exact, Gumbel, and Davenport – which yield a Vref between 41.3 and 44.6 m/s at Pyramid. These results are like that of the periodic maxima method and classify the site as IEC Class I or II.

Table 8: Extreme Wind Vref (50-year return period), Pyramid 60m combined anemometer

Method	Vref (50 yr) (m/s)
Periodic Maxima	42.6
Method of Independent Storms	47.6
EWTS II (Exact)	41.3
EWTS II (Gumbel)	41.8
EWTS II (Davenport)	44.6

Turbulence

Turbulence at the Pyramid met tower site is moderate with a mean turbulence intensity of 0.12 at 15 m/s (refer to Appendix A for further explanation). Considering the reputation of the Aleutian Islands for extremely rough and turbulent wind conditions, this is a desirable outcome. Note in Figure 14 moderate turbulence for wind speeds up to approximately 24 m/s, at which point turbulence increases, though curiously, decreases at about 27 m/s. This is somewhat a moot point however as most wind turbines are designed to secure operating at 25 m/s sustained wind speed.

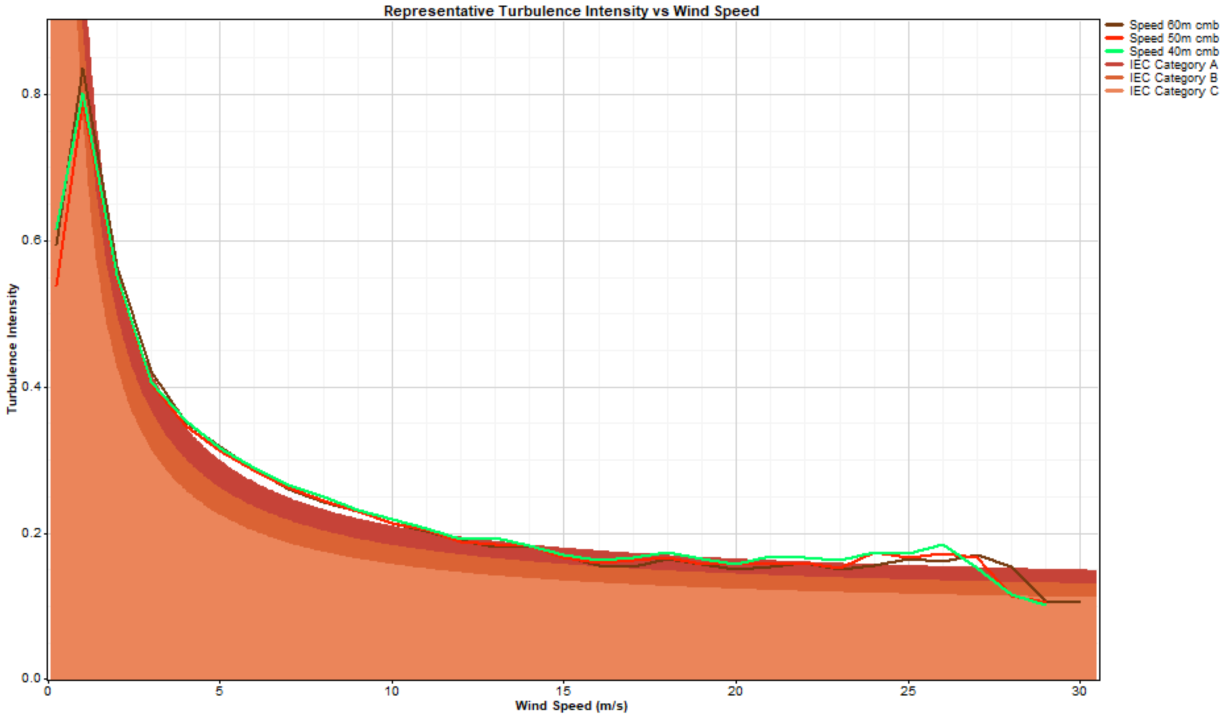

Figure 14: Pyramid turbulence intensity vs. wind speed

There is, however, a caveat as turbulence with easterly winds (coming from Pyramid Mtn) and westerly winds (coming from the ridgeline north of Captains Bay) is very high (see Figure 15), possibly presenting an operational limitation. Note however in Figure 9 that easterly and westerly winds at the Pyramid site are uncommon and hence the operational limitation would be minimal.

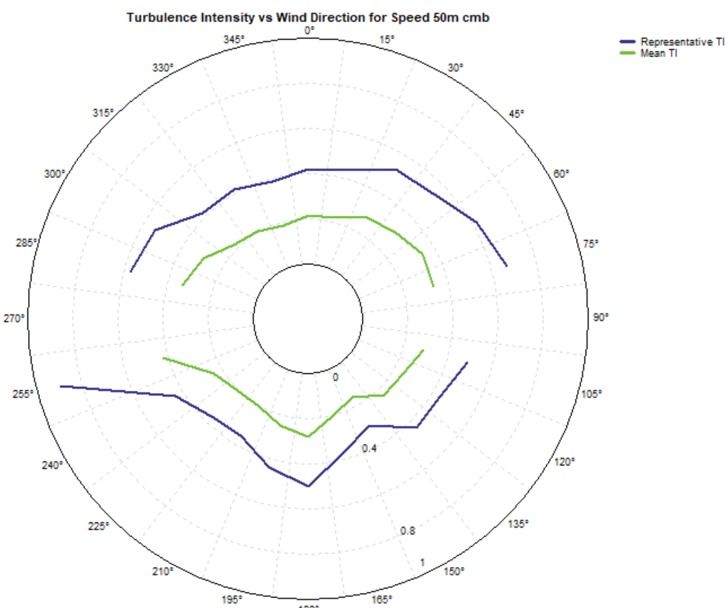

Figure 15: Pyramid turbulence intensity by wind direction

For IEC classification, a category is assigned for turbulence intensity at 15 m/s. With winds from all sectors, Table 9 indicates moderate turbulence at the three wind speed measurement heights. Note again however with reference to Figure 15 that turbulence from easterly and westerly winds is high.

Table 9: Pyramid turbulence intensity table and IEC categories

		15 m/s Speed Bin				
Wind Speed Sensor	Height (m)	Data Points	Mean TI	Standard Deviation of TI	Represen-tative TI	IEC 3 ed. Turbulence Category
Speed 60m cmb	59.5	73,431	0.120	0.038	0.168	C
Speed 50m cmb	50.0	73,431	0.122	0.036	0.168	B
Speed 40m cmb	40.7	73,431	0.126	0.034	0.170	B

Pyramid IEC Classification

As noted in previous sections and discussed in greater detail in Appendix A, for the purposes of wind turbine design and selection, IEC 61400-1, 3rd edition (2005) standards classify a site by its extreme wind and turbulence behavior. The Pyramid extreme wind probability indicates a high Class II environment and calculated TI demonstrates Category B turbulence, hence a Class IIB site classification.

Hog Island

The August 2017 *Request for Proposals, Analysis of the City of Unalaska Wind Power Development and Integration Assessment Project Phases II to IV* that initiated the wind resource study envisioned up to five primary sites to be instrumented with met towers. Unalaska's topography is complex and wind power site options are limited, however, as discussed in the Phase II report. Initially, only lower Pyramid Valley was considered a primary site and recommended for a large, 60-meter met tower. The 34-meter Icy Creek Reservoir met tower was intended as an auxiliary to the larger Pyramid met tower to both assess upper valley winds and to serve as a reference point for wind flow modeling. The 10-meter Bunker Hill met tower was installed as a higher elevation reference to validate climatology data derived from Cold Bay upper air monitoring data.

With that, a second primary site was desired as an alternative should the Lower Pyramid Valley wind resource prove insufficient or unsuitable. With due consideration of the options, it was felt that only Hog Island readily possessed the development characteristics necessary to host several wind turbines and hence was added to the project. Unfortunately, meso-scale wind resource models such as UL's AWS Truepower Windnavigator (discussed in the Phase II report) do not include Hog Island and hence its anticipated wind resource was uncertain. It was hoped that Hog Island's relative distance from high elevation, shadowing terrain would prove beneficial, but there was concern that its low elevation may prove disadvantageous with respect to wind speeds.

Figure 16: Hog Island met tower (D. Vaught photo)

Hog Island is only accessible by boat or helicopter and has no existing power distribution. Steep topography on the northern half of Hog Island and instrument approach area boundaries for Dutch Harbor Airport Runway 13 likely restrict future wind power development to only the southern half of the island. But according to City of Unalaska Public Works personnel, Hog Island may be less expensive to develop than the Ptarmigan Road site area in Iliuliuk Valley (refer to the Phase II report for site information and discussion). This reflects the nature of power distribution supplying Iliuliuk Valley compared to a relatively straight-forward requirement to route approximately 1.25 miles of power distribution across Unalaska Bay from an electrical substation near the airport.

Hog Island Site and Met Tower Information

A 60-meter (197 ft.) NRG Systems, Inc. tubular, guyed met tower was installed in mid-August 2019 on Ounalashka Corporation land on Hog Island and was decommissioned in April 2021 (see Figure 16).[9] Refer to Table 10 for summary information of the met tower and data collected from it.

Table 10: Hog Island met tower summary information

Data dates	8/17/2019 to 4/22/2021 (20 months)
Datalogger information	NRG Symphonie PRO, 26 channel, site no. 3550
Site coordinates	53.9029 North, 166.5755 West (WGS 84 datum)
Site elevation	30 meters (98 ft.)
Wind speed, mean annual, 60 m level	6.0 m/s
Wind power density, mean annual, 60 m	293 W/m^2
Wind power class	3 (fair) of 7 defined classifications
Maximum 10-min. avg wind speed	32.8 m/s
Maximum 3-sec. gust wind speed	40.7 m/s (91 mph)
Wind shear power law exponent	0.225

[9] Met tower installation accomplished by V3 Energy LLC with contracted assistance from Bering Straits Development Company and Solstice Alaska Consulting, and with the generous material and personnel support of City of Unalaska Department of Public Works.

Calm wind frequency (winds < 4 m/s)	34%
Extreme wind probability (50-year period)	Not calculated
Turbulence intensity, 60 m level	0.131
IEC 61400-1 3rd ed. classification	Not determined

Figure 17: Hog Island met tower location, view north; Google Earth image

Prior to installation of the met tower, a Federal Aviation Administration (FAA) obstruction evaluation was requested. FAA issued Aeronautical Study No. (ASN) 2018-WTW-5353-OE in September 2018 with a determination of no hazard to air navigation. Obstruction lighting was required in addition to alternating bands of aviation orange and white paint on the met tower and orange high-visibility marker balls near the top of the outer guy wires to improve visibility. Obstruction lighting was accomplished with a strobe light kit from NRG Systems, Inc. and a 24 Volt custom designed and constructed battery power system with a 3 kW wind turbine and 1,000 kW solar power capacity supplied by APRS World of Minnesota.

The Hog Island met tower was equipped with two anemometers each at 60 meters, 50 meters and 40 meters; wind vanes at 60 meters and 50 meters; and temperature, relative humidity, and barometric pressure sensors at the tower base (see Table 11). Refer to Appendix C for detailed sensor technical information and to Appendix F for documentation photographs of the met tower installation.

Table 11: Hog Island met tower sensors

Ch	Sensor Type	Model	Name	Height (m)	Dir. (°T)
1	Anemometer	40C	60m E	59.7	098
2	Anemometer	40C	60m W	59.3	269
3	Anemometer	40C	50m E	50.3	098
4	Anemometer	40C	50m W	49.8	269
5	Anemometer	40C	40m E	40.9	098
6	Anemometer	40C	40m W	40.4	269
13	Vane	200M	60m	57.4	148
14	Vane	200M	50m	47.7	220
16	Temp	T60	Temp	3.0	000
17	Barom. Press.	BP20	BP	2.0	270
18	Rel. Humidity	RH5X	RH	2.0	270

Hog Island Data Quality Control

As with data collected from the Pyramid met tower, Hog Island met tower data was manually filtered to remove compromised records. This included startup sequencing, isolated periods of power supply problems, icing events, tower shading, and poorly functioning sensors. Unlike the Pyramid met tower though where all sensors performed very well until later in the project, several Hog Island anemometers experienced “dragging” problems (see Pyramid data quality control discussion) and by May 2020 both wind vanes failed (see Figure 18). NRG Systems anemometers and wind vanes are exceptionally reliable, and this rate of failure is unprecedented. A possible explanation is the exceptionally high population of bald eagles in Unalaska, which is a distinguishing aspect of the community compared to scores of locations throughout Alaska with met towers over the past 20 years. During met tower installation and subsequent site visits, bald eagles were often observed perched on the sensor boom arms. It is probable that eagles occasionally attempted to land on the sensors themselves, damaging them.

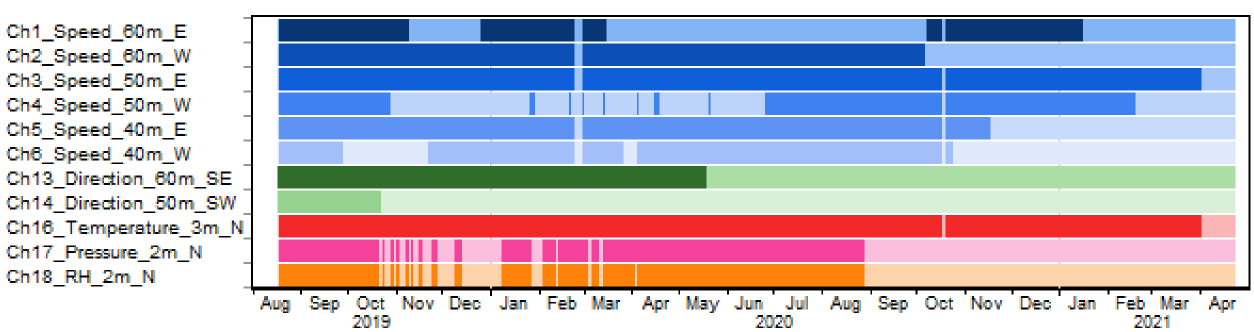

Figure 18: Hog Island met tower data recovery graphic (tower shading filtering excluded)

Hog Island Environmental Measurements

Environmental conditions at Hog Island do not differ substantially from those at Pyramid Valley, hence, one may reference the previous section for temperature, humidity, and density information. Unlike Pyramid though, Hog Island was equipped with a barometric pressure sensor (see Figure 19). The intent of this sensor was to record an extreme low-pressure event (960 mb or lower) to document possible accompanying extreme winds. Data recovery problems with the barometric pressure sensor compromised this analysis, but a trendline demonstrated decreasing wind gust speeds with higher atmospheric pressure (see Figure 20). Notably, highest wind gusts occurred with southwesterly to westerly winds during low pressure weather events.

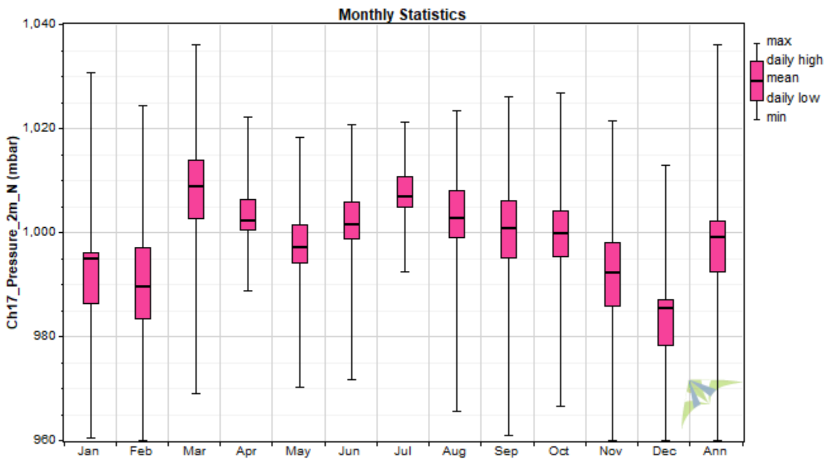

Figure 19: Hog Island barometric pressure boxplot

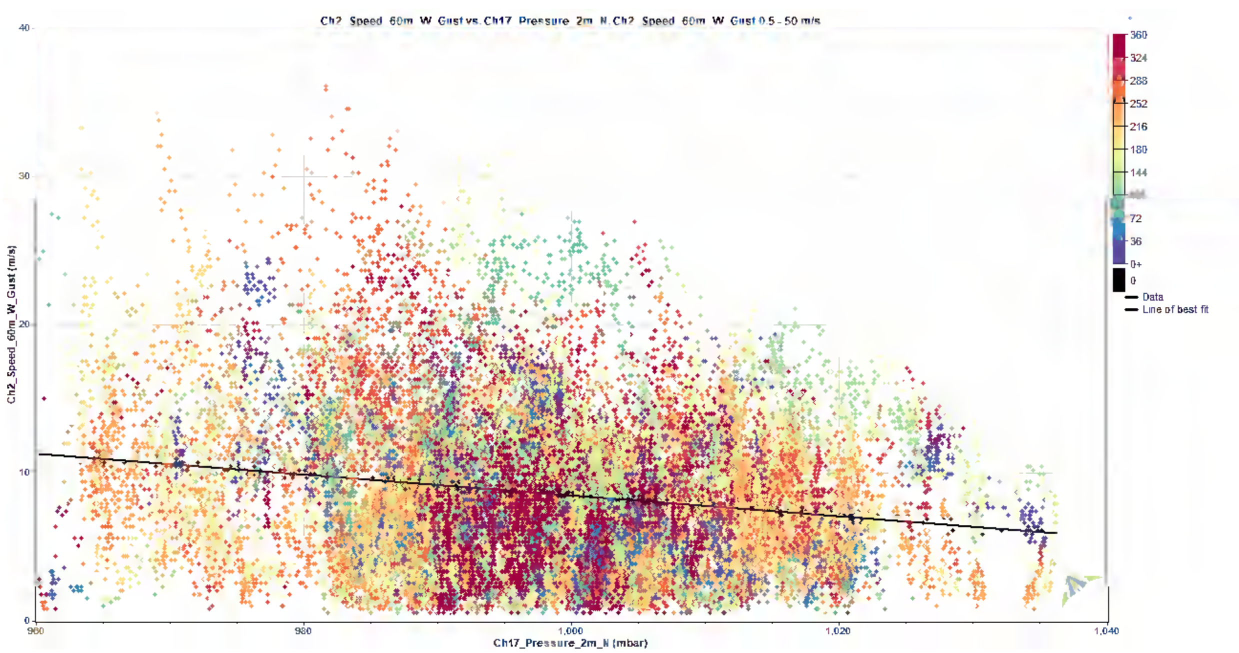

Figure 20: Scatterplot of Hog Island barometric pressure vs. 60 m level wind gust (color code indicates wind direction)

Hog Island Wind Speed and Anemometer Combination

For the three anemometers with higher data recovery rates (60m W, 50m E, and 40m E), mean wind speeds were low (see Table 12) at between approximately 5.1 and 5.9 m/s. Because comparison with Pyramid met tower (see succeeding discussion) demonstrates that Pyramid is the preferred wind power site of the two locations, wind speed adjustment for turbulence as employed with Pyramid data was not accomplished.

Table 12: Hog Island wind speeds, filtered

Variable	Ch1_Speed _60m_E	Ch2_Speed _60m_W	Ch3_Speed _50m_E	Ch4_Speed _50m_W	Ch5_Speed _40m_E	Ch6_Speed _40m_W
Mean wind speed (m/s)	6.87	5.80	5.91	6.19	5.12	4.96
Mean wind speed (mph)	15.4	13.0	13.2	13.8	11.5	11.1
Max 10-min wind speed (m/s)	26.3	32.2	31.7	30.8	31.7	30.2
Max wind speed (mph)	58.8	72.0	70.9	69.0	70.8	67.6
Max gust wind speed (m/s)	43.8	44.0	43.5	43.5	43.4	43.6
Max gust wind speed (mph)	98.0	98.4	97.3	97.3	97.1	97.5
Wind power density (W/m²)	495	319	336	410	264	247
Frequency of calms (%)	28.9	36.7	33.5	36.2	44.2	45.9

Combined Anemometers

Table 12 shows wind speed data with necessary filtering, but like Pyramid, long periods of met tower operation with asymmetric data collection yielded divergent wind speed data for paired anemometers. The two primary options can be used to correct this: synthesize missing data or mathematically combine the anemometers. Like with Pyramid, only anemometer combination was used to create a more representative data set (see Table 13).

Table 13: Hog Island combined anemometer data

Combined Sensor	Height (m)	First Anemometer		Second Anemometer		Combined Sensor	
		DRR (%)	Mean (m/s	DRR (%)	Mean (m/s)	DRR (%)	Mean (m/s)
Speed 60m cmb	59.5	40.7	6.85	65.6	5.81	83.2	6.11
Speed 50m cmb	50.1	94.4	6.19	50.5	6.11	95.9	6.15
Speed 40m cmb	40.7	72.5	5.14	57.9	4.96	73.1	5.11

Seasonal and Diurnal Variation

Hog Island's monthly wind speed profile (see Figure 21), like at Pyramid, demonstrates a pronounced seasonal variation of wind speeds with higher winter winds and lower summer winds. Figure 22 demonstrates a diurnal wind speed variation on Hog Island like that at Pyramid, but more pronounced with a greater difference between daytime and nighttime winds.

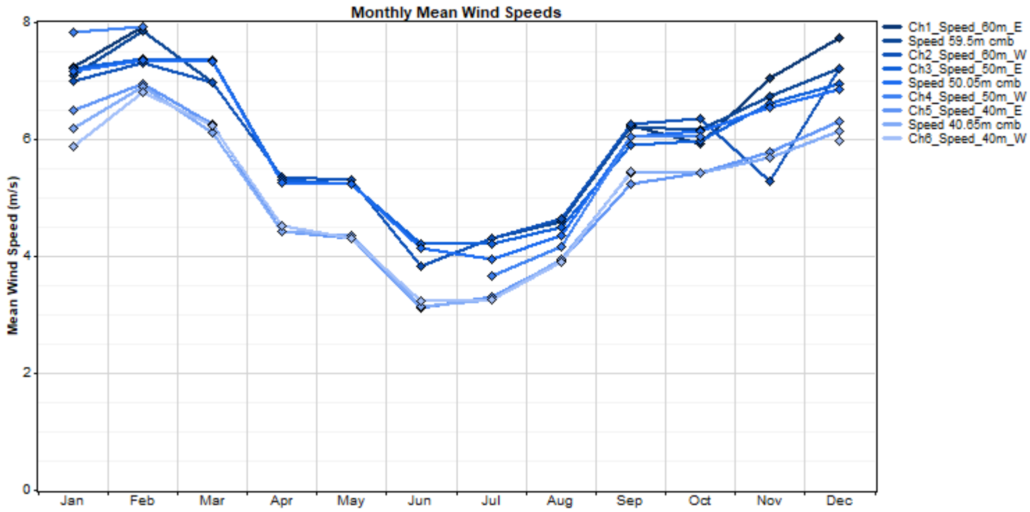

Figure 21: Hog Island monthly wind speeds, combined anemometers only

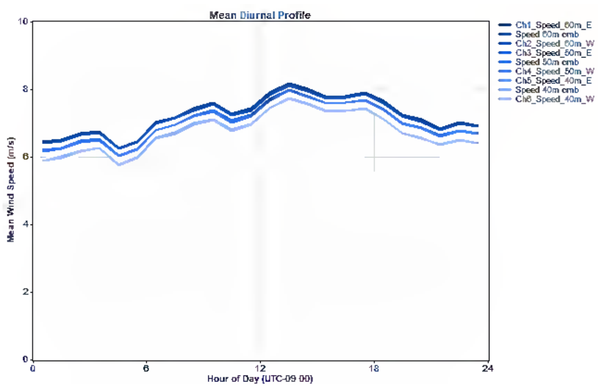

Figure 22: Hog Island diurnal wind speed profile

Hog Island Wind Distribution

The probability distribution function of the Hog Island met tower 60 meter combined anemometer wind speed data indicates a shape curve dominated by lower-to-moderate wind speeds (see Figure 23), but interestingly, with a lower percentage of calm winds (0 to 0.5 m/s) than measured at Pyramid (refer to Figure 11).

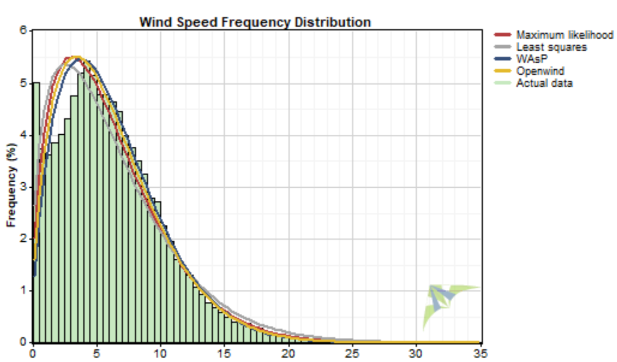

Figure 23: Hog Island wind speed probability distribution histogram

Hog Island Wind Shear and Roughness

Hog Island met tower site wind shear is moderate by wind industry standards with a mean power law exponent of 0.225 from all wind direction sectors (combined anemometers, 2019 only, see Figure 24). But, with reference to Figure 25, wind shear is extremely high with northwesterly to northerly winds. This reflects the topography of the met tower site area where a high hill lies to the north. This is an unavoidable constraint of Hog Island. The high terrain cannot be developed due to conflict with the Unalaska Airport Runway 13 instrument approach area, and the developable southwestern portion of the island is lower elevation and partially shadowed by higher terrain to the north.

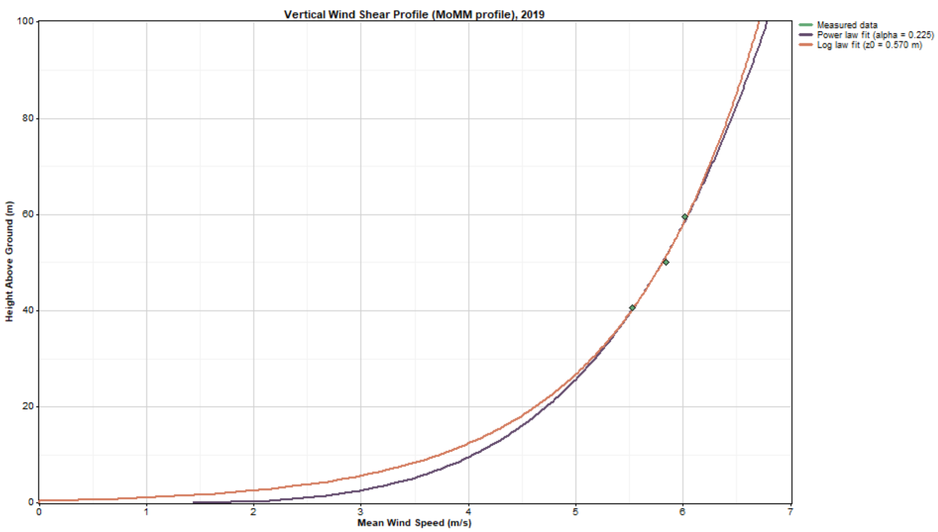

Figure 24: Hog Island vertical wind shear profile (calculated 0.225 power law exponent)

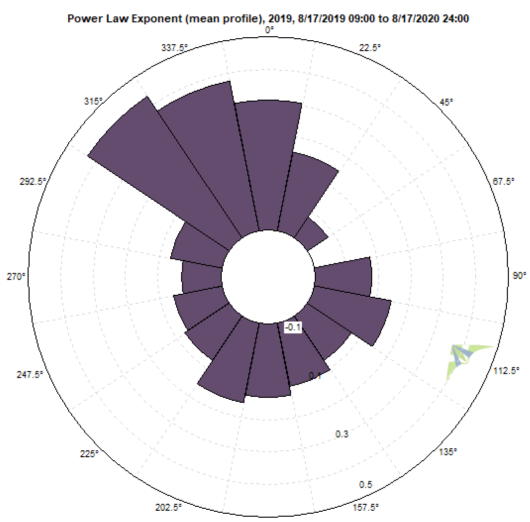

Figure 25: Hog Island vertical wind shear rose (0.50 power law exponent, outer ring)

Hog Island Turbulence

Turbulence at the Hog Island met tower site is moderate with a mean turbulence intensity (TI) of 0.13 at 15 m/s (refer to Appendix A for an explanation of turbulence calculation).

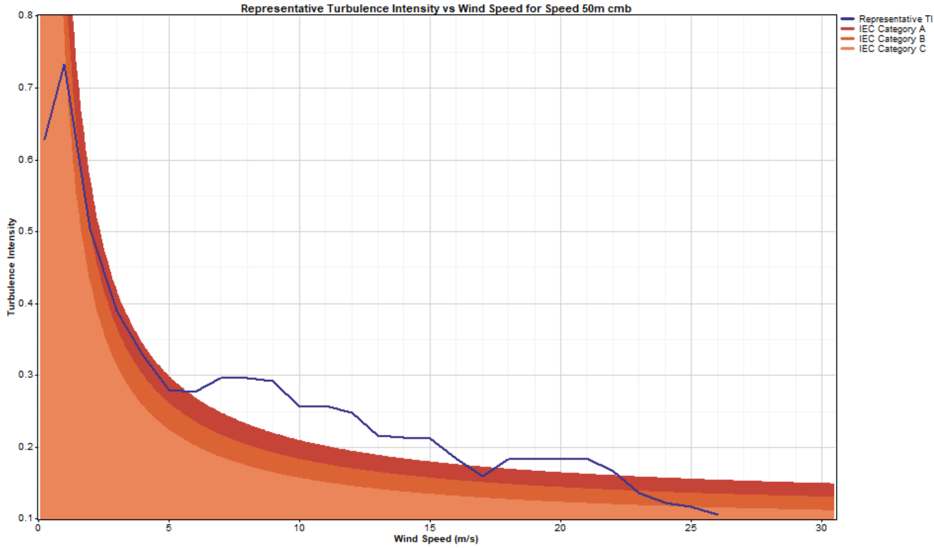

Figure 26: Hog Island turbulence intensity vs. wind speed

Hog Island Wind Direction

The prevailing wind directions at Hog Island are northeasterly and southeasterly to southwesterly, with the latter winds strongest (refer to Figure 27). This is largely consistent with wind directions measured at Pyramid.

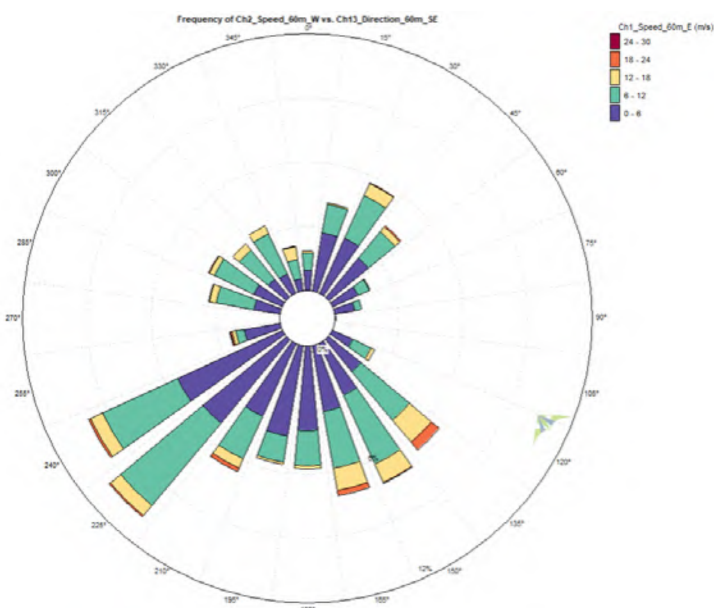

Figure 27: Hog Island wind energy rose, 60-meter west anemometer and 60-meter wind vane

Hog Island and Pyramid Comparison

A seminal objective of Unalaska's wind study was simultaneous collection of wind data from two or more primary sites. Primary sites were only lower Pyramid Valley and Hog Island, both equipped with 60-meter met towers. The 20 months of Hog Island met tower data overlapped completely with Pyramid data, which preceded and succeeded it.

With reference to Figure 28, for comparable anemometers (50-meter east-facing) the monthly mean wind speeds measured at Pyramid were consistently higher, or at least equivalent to, those measured at Hog Island. All other considerations aside, this is the definitive comparative assessment of the two site locations. For Hog Island to be the preferred location for City of Unalaska wind power development, it must be considerably windier than Pyramid, but clearly that was not observed.

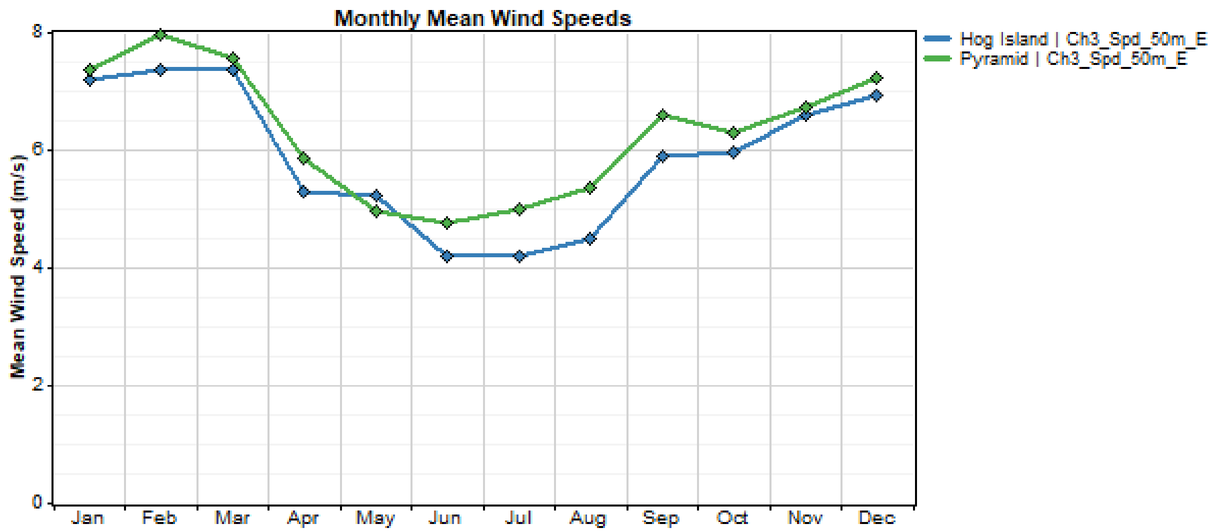

Figure 28: Hog Island vs. Pyramid wind speed comparison, 50 m anemometers

Icy Creek Reservoir (upper Pyramid Valley)

Upper Pyramid Valley, for the purposes of this analysis, comprises the area between Icy Creek Reservoir and Icy Lake at the top of the valley. Although of secondary interest given the wind power development advantages of the lower valley, upper valley was thought potentially promising should the lower valley wind resource prove less robust than desired and/or wind power development in the lower valley not be feasible for other reasons.

Figure 29: Icy Creek Reservoir 34-meter met tower (D. Vaught photo)

Given the lower likelihood of wind power development in the upper valley compared to lower valley, a 34-meter met tower was installed at a well-exposed location immediately west of Icy Creek Reservoir (see Figure 29). Besides providing wind data to lend insight into the upper valley wind resource, data from the Icy Creek Reservoir met tower was desired to serve as a reference point for a wind flow model using Pyramid met tower as the model's data set (see Figure 30).

Icy Creek Reservoir Site and Met Tower Information

The Icy Creek Reservoir met tower was installed in mid-October 2018 at the same time as the 60-meter Pyramid and 10-meter Bunker Hill met towers.[10] The tower was decommissioned and removed from the site by Department of Public Works personnel in October 2019 following failure of an outer guy wire that resulted in an unrepairable "crack-over" of the tower's top sections. Refer to Table 14 for summary information of the met tower and data collected from it.

Table 14: Icy Creek Reservoir met tower summary information

Data dates	10/16/2018 to 10/28/2019 (12 months)
Datalogger information	NRG Symphonie PRO, 16 channel, site no. 3551
Site coordinates	53.82946 North, 166.55130 West (WGS 84 datum)
Site elevation	168 meters (551 ft.)
Wind speed, mean annual, 34 m	5.46 m/s (12.2 mph)
Wind power density, mean annual, 34 m	318 W/m^2
Wind power class	3 (fair), of 7 defined classifications (possibly Class 4 with long-term climatology adjustment; see Pyramid met tower discussion)
Maximum 10-min. avg wind speed	28.9 m/s
Maximum 2-sec. gust wind speed	40.7 m/s (91.0 mph)
Wind shear power law exponent	0.0717 (very low; 0.14 considered nominal)
Calm wind frequency (winds < 4 m/s)	Approx. 44%
Extreme wind probability (50-year period)	Not calculated
Turbulence intensity, 34 m	0.122 (moderately high)
IEC 61400-1 3rd ed. classification	Not determined

[10] Met tower installation accomplished by V3 Energy LLC with contracted assistance from Bering Straits Development Company and Solstice Alaska Consulting.

Figure 30: Icy Creek Reservoir met tower location, view north, Google Earth image

Prior to installation of the met tower, a Federal Aviation Administration (FAA) obstruction evaluation was requested. FAA issued Aeronautical Study No. (ASN) 2018-WTW-5349-OE in July 2018 with a determination of no hazard to air navigation. Obstruction lighting was not required although FAA requested alternating bands of aviation orange and white paint on the met tower and orange high-visibility marker balls be attached near the top of the outer guy wires to improve visibility of the tower for aviators. Both requirements were accomplished.

The Icy Creek Reservoir met tower was equipped with two anemometers at 34 meters and one anemometer at 20 meters; one wind vane each 33 meters; and temperature and relative humidity sensors at the tower base (refer to Table 15). Refer to Appendix D for detailed sensor technical information and to Appendix F for documentation photographs of the met tower installation.

Table 15: Icy Creek Reservoir met tower sensors

Ch	Sensor Type	Model	Name	Height (m)	Dir. (°T)
1	Anemometer	40C	34m ESE	34.0	121
2	Anemometer	40C	34m WSW	34.0	262
3	Anemometer	40C	20m ESE	20.5	124
13	Vane	200M	Direction	33.0	281
16	Temp	T60	Temp	2.5	000
17	Rel. Humidity	RH5X	RH	2.0	000

Icy Creek Reservoir Data Quality Control

As with data collected from the Pyramid and Hog Island met towers, Icy Creek Reservoir met tower data was manually filtered to remove compromised records. This included startup sequencing, isolated periods of power supply problems, icing events, tower shading, and poorly functioning sensors. Figure 31 demonstrates mixed results regarding data recovery at Icy Creek. There was some minor data loss due to icing in but also periods of significant anemometer failure, possibly due to damage caused by eagles as discussed with Hog Island.

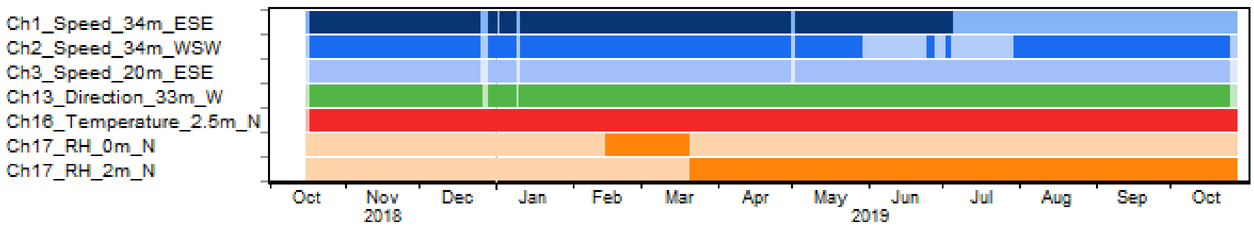

Figure 31: Icy Creek Reservoir met tower data recovery graphic (tower shading filtering not employed)

Icing Data

Considering the cool, wet climate of the Aleutian Islands, significant data loss due to icing was expected, especially at the higher elevation of Icy Creek Reservoir compared to lower Pyramid Valley. This concern proved unfounded however as icing loss was a very minimal 0.9 percent over the one-year data measurement period.

Icy Creek Reservoir Wind Speed and Data Synthesis

Given the data recovery problems with both 34-meter level anemometers, data reconstruction or gap-filling was employed to yield a more accurate dataset for analysis than raw or filtered data alone would provide.

With reference to reconstructed data, mean wind speeds at the 34-meter level were measured at approximately 5.44 m/s with a mean wind power density of 318 Watts/m^2 (see Table 16). This classifies lower Pyramid Valley as a Class 3 (description: fair) wind resource.

Table 16: Icy Creek Reservoir wind speeds with reconstructed (gap-filled) data

Variable	Ch1_Speed_ 34m_ESE	Ch2_Speed_ 34m_WSW	Ch3_Speed_ 20m_ESE
Mean wind speed (m/s)	5.37	5.44	5.18
Mean wind speed (mph)	12.0	12.2	11.6
Max 10-min wind speed (m/s)	28.7	28.9	27.7
Max 10-min wind speed (mph)	64.2	64.6	61.9
Max gust wind speed (m/s)	40.0	40.7	40.6
Max gust wind speed (mph)	89.5	91.0	90.8
Mean power density (W/m^2)	313	318	276
Frequency of calms (%)	44.9	43.9	46.7

Icy Creek Reservoir Wind Direction

The prevailing winds at the Icy Creek Reservoir site were measured as strongly northwesterly and southeasterly, which reflects the confining nature – due to enclosure by high mountains to the east and west – of upper Pyramid valley (see Figure 32).

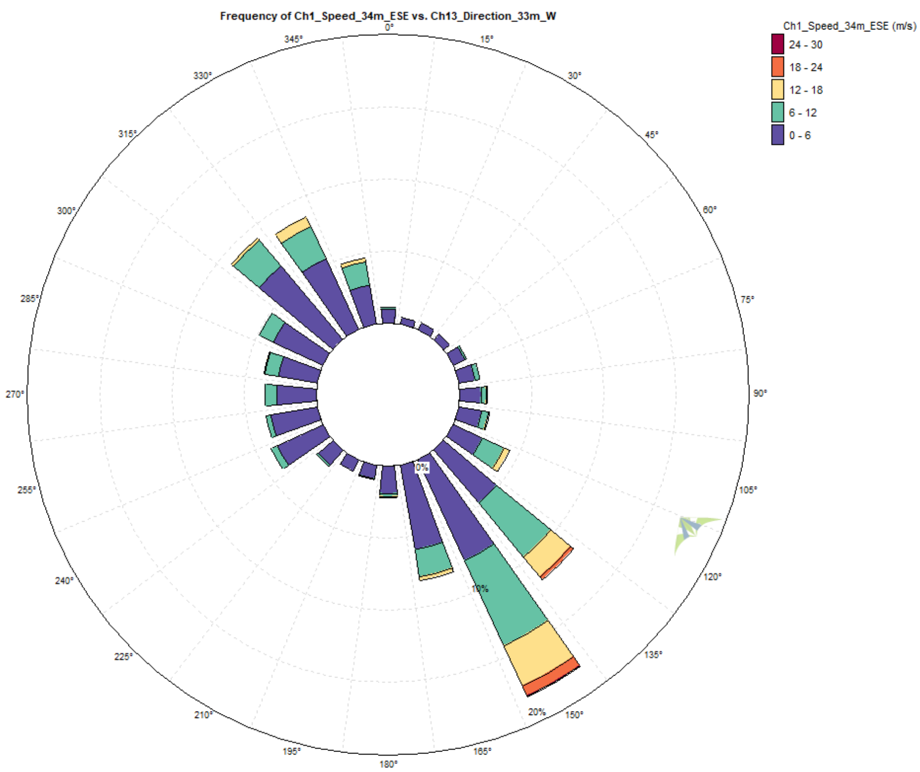

Figure 32: Icy Creek Reservoir wind energy rose

Icy Creek Reservoir and Pyramid Comparison

As noted earlier, one purpose of the Icy Creek Reservoir was to explore the wind potential of upper Pyramid Valley to determine possible suitability as a wind turbine location compared to lower valley. It was recognized during planning that the upper valley is geographically constrained compared to lower valley, which could prove disadvantageous.

With reference to measured wind shear at the Pyramid met tower (see Figure 12), a virtual 34-meter anemometer on the Pyramid tower was synthesized to enable direct comparison with the Icy Creek Reservoir wind speed data. Figure 33 shows the comparative monthly mean wind speeds, with Icy Creek clearly lower for all months except June 2018 and January 2019 when they were equal. As a result, the wind power class of Icy Creek Reservoir is less than at Pyramid (referring to lower Pyramid valley).

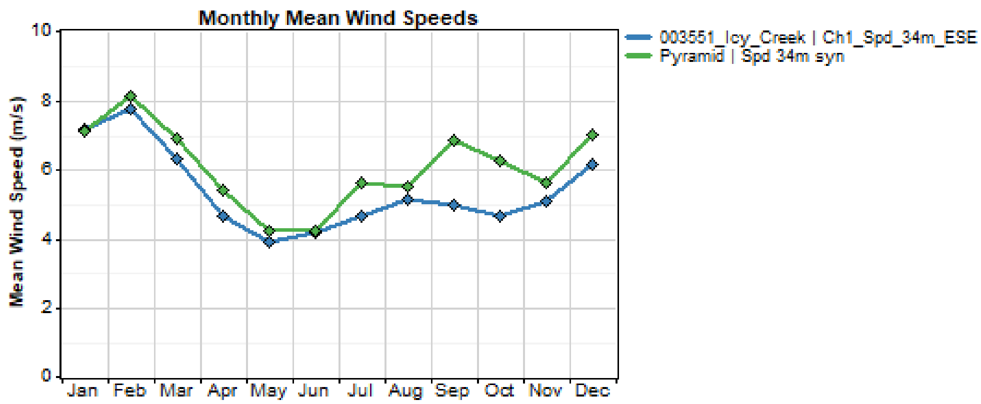

Figure 33: Icy Creek Reservoir vs. Pyramid wind speed comparison, overlap period

Although detailed month-by-month wind speed and wind direction data could provide additional insight, comparing the wind roses (overlap period, Figure 34) of the two sites clearly indicates Pyramid benefits from southwesterly winds along the reach of Captain's Bay while Icy Creek Reservoir does not due to high blocking terrain that comprises the eastern boundary of the upper valley.

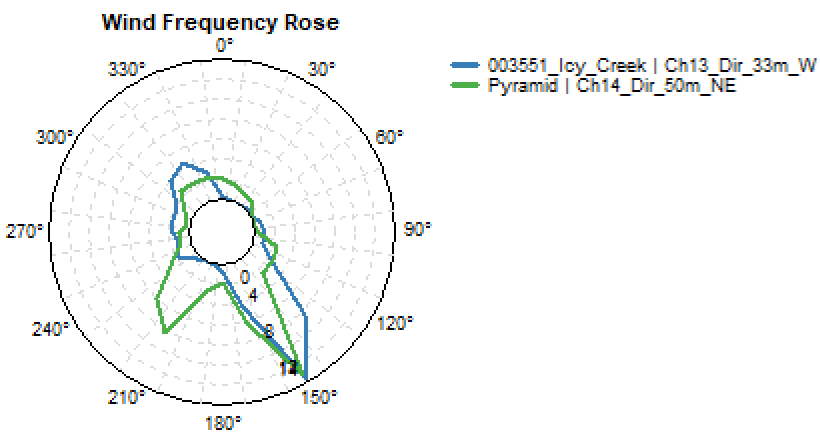

Figure 34: Icy Creek Reservoir vs. Pyramid wind direction comparison

Bunker Hill (aka Little South America)

Bunker Hill (also known locally as Little South America) was identified in the Phase II report as a suitable location to measure the wind resource – primarily wind directions – to validate meso-scale wind modeling of Cold Bay upper air data. There were two candidate sites – Bunker Hill and Ballyhoo (Amaknak Island) – for this purpose. In some respects, Ballyhoo may have been preferable to Bunker Hill as it is twice the elevation and hence better exposed, but the location of Bunker Hill between the main prospective met tower sites – Lower Pyramid Valley and Hog Island – made it the more suitable choice.

A short, 10-meter met tower was chosen for Bunker Hill as the location, though presumably with a comparable wind resource as lower Pyramid Valley, was not considered suitable for wind turbines. The summit area of Bunker Hill is small, and the existing road access would be expensive to improve. More importantly, with many WWII historical features, nearly the entire island and especially the Bunker Hill summit area is administered by the National Park Service as part of the Aleutian World War II National Historic Area.

Figure 35: Bunker Hill 10-meter met tower (K. Arduser photo)

Bunker Hill Site and Met Tower Information

The Bunker Hill met tower was installed in mid-October 2018 at the same time as the 60-meter Pyramid and 34-meter Icy Creek Reservoir met towers (see Figure 35).[11] Refer to Table 17 for summary information of the met tower and data collected from it.

Table 17: Bunker Hill met tower summary information

Data dates	10/18/2018 to 6/16/2020
Datalogger information	NRG Symphonie PRO, 16 channel, site no. 3547
Site coordinates	53.87568 North, 166.55820 West (WGS 84 datum)
Site elevation	110 meters (361 ft.)
Wind speed, mean annual, 10 m	6.14 m/s (13.7 mph)
Wind power density, mean annual, 10 m	400 W/m^2
Wind power class	4 (good) to 5 (excellent), of 7 defined classifications
Maximum 10-min. avg wind speed	30.9 m/s
Maximum 2-sec. gust wind speed	43.6 m/s (97.5 mph)
Wind shear power law exponent	Not calculated
Calm wind frequency (winds < 4 m/s)	Approx. 35%
Extreme wind probability (50-year period)	Not calculated
Turbulence intensity, 34 m	0.147 (high)
IEC 61400-1 3rd ed. classification	Not determined

[11] Met tower installation accomplished by V3 Energy LLC with contracted assistance from Bering Straits Development Company and Solstice Alaska Consulting.

Figure 36: Bunker Hill met tower location, view north, Google Earth image

Prior to installation of the met tower, a Federal Aviation Administration (FAA) obstruction evaluation was requested. FAA issued Aeronautical Study No. (ASN) 2018-WTW-5351-OE in September 2018 with a determination of no hazard to air navigation. Obstruction lighting was required in addition to alternating bands of aviation orange and white paint on the met tower and orange high-visibility marker balls near the top of the outer guy wires to improve visibility. Obstruction lighting was accomplished with an LED light from Unimar, Inc. and a 24 Volt battery power system with a 1 kW wind turbine supplied by Renewable Energy Systems of Alaska.

The met tower was purchased as a NOW configuration from NRG Systems, Inc. As such, it had a standard suite of instrumentation for a 10-meter met tower, including two anemometers, one wind vane, and one temperature sensor, plus a pyranometer (solar irradiance sensor) that was included as an additional sensor. In February 2019, a relative humidity sensor was added (refer to Table 18).

Table 18: Bunker Hill met tower sensors

Ch	Sensor Type	Model	Name	Height (m)	Dir. (°T)
1	Anemometer	40C	10m NE	10.0	054
2	Anemometer	40C	10m W	10.0	256
13	Vane	200M	10m	9.0	144
16	Temp	T60	Temp	3.0	000
17	Rel. Humidity	RH5X	RH	1.0	090
22	Pyranometer	Li-Cor	Pyra	2.0	180

Bunker Hill Data Quality Control

As with data collected from the other met towers, Bunker Hill met tower data was manually and automatically filtered to remove compromised records. This included startup sequencing, isolated periods of power supply problems, icing events, and poorly functioning sensors. Figure 37 demonstrates several problems including a faulty boom arm on the channel 1 anemometer in June 2019 that was not corrected until August 2019. Following, the direction sensor failed in October 2019 and was replaced in November 2019. The datalogger itself experienced unexplained and strange data loss from mid-March to mid-April 2020, which resolved on its own. A review of datalogger events was not revealing. On a positive note, data loss due to icing was extremely minimal.

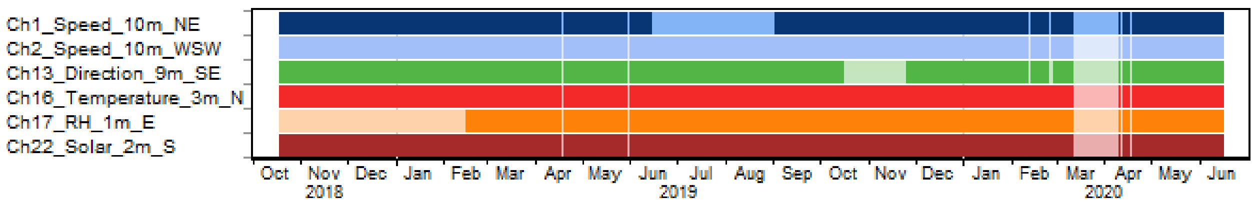

Figure 37: Bunker Hill met tower data recovery graphic

Bunker Hill Wind Speed and Data Synthesis

The Bunker Hill met tower was not installed with the intention of evaluating the wind resource at this location for wind power, but rather to lend insight into wind pattern differences between Pyramid Valley and Hog Island. As such, gap-filling reconstruction of filtered anemometer data was not employed, which explains the high measured wind speed variation between the two anemometers (see Table 19). Although a mean wind speed of 6.14 m/s at only 10 meters above ground level may seem extraordinary compared to the same mean wind speed measured at 40 meters on the Pyramid met tower, this is misleading. Although wind shear on Bunker Hill was not measured (a minimum of two levels of anemometers would be required), wind shear on exposed high hills is very nearly zero to even negative. With this, the measured wind speed at 10 meters on Bunker Hill is almost certainly representative of the wind speed much higher above ground level.

Table 19: Bunker Hill wind speeds with filtered data

Variable	Ch1_Speed_10m_NE	Ch2_Speed_10m_WSW
Mean wind speed (m/s)	6.14	5.85
Mean wind speed (mph)	13.7	13.1
Max 10-min wind speed (m/s)	30.9	29.8
Max 10-min wind speed (mph)	69.0	66.6
Max gust wind speed (m/s)	43.6	43.1
Max gust wind speed (mph)	97.5	96.4
Mean power density (W/m²)	400	353
Frequency of calms (%)	35.1	37.0

Bunker Hill Wind Direction

The primary purpose of the Bunker Hill met tower was to compare the site to mesoscale[12] winds from the Cold Bay upper air data to validate the selection of sites for installation of met towers (refer to pages 13 through 20 in the Phase II report). Figure 38 presents the measured wind rose on Bunker Hill and Figure 39 the Cold Bay upper air data wind rose. As one can see, they do not match well, possibly due to channeling of low elevation winds through the complex topography near Unalaska. Interestingly though, the Cold Bay wind rose better matches the Icy Creek Reservoir wind rose (see Figure 32) and to a lesser extent the Pyramid wind rose (see Figure 9).

In hindsight, installation of the Bunker Hill met tower was perhaps not strictly necessary as the options for readily developable wind power sites in Unalaska were few, limited to lower Pyramid Valley and Hog Island, and to a lesser extent upper Pyramid Valley, the Ptarmigan Road area of Iliuliak Valley, and on the periphery of possibility, Ballyhoo. Further, the measured wind roses of lower Pyramid valley (see Figure 9), Hog Island (see Figure 27) and Icy Creek Reservoir/Upper Pyramid Valley (see Figure 32) are explainable with their respective terrain exposures, without need to reference the upper air wind resource at Cold Bay, which lies far to the east.

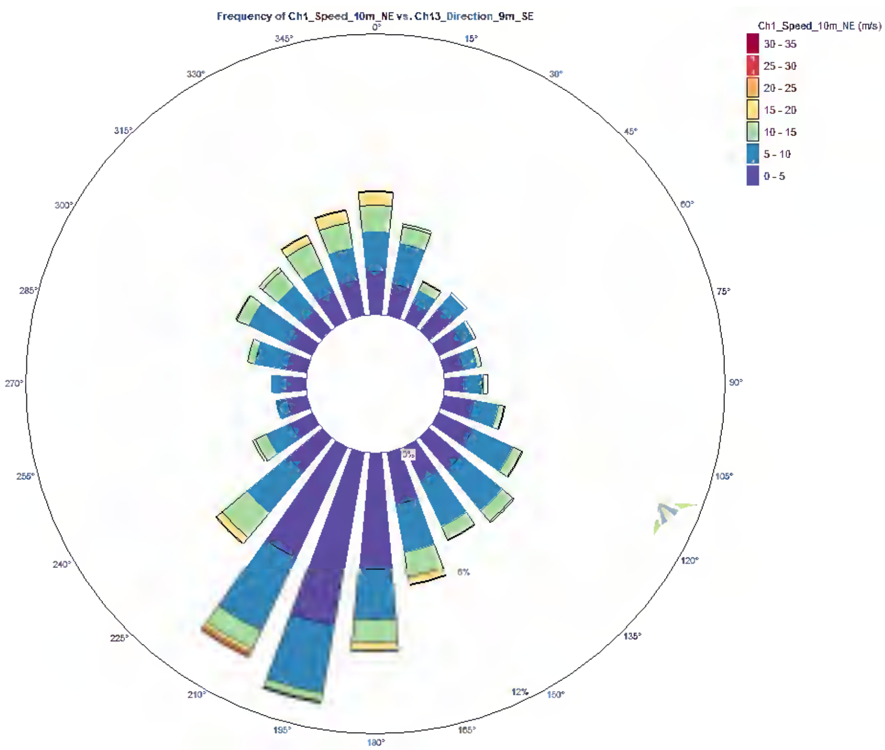

Figure 38: Bunker Hill wind energy rose, 10-meter NE anemometer

[12] Pertaining to meteorological phenomena, such as wind circulation and cloud patterns, that are about 1-to-100 km in horizontal extent (www.dictionary.com).

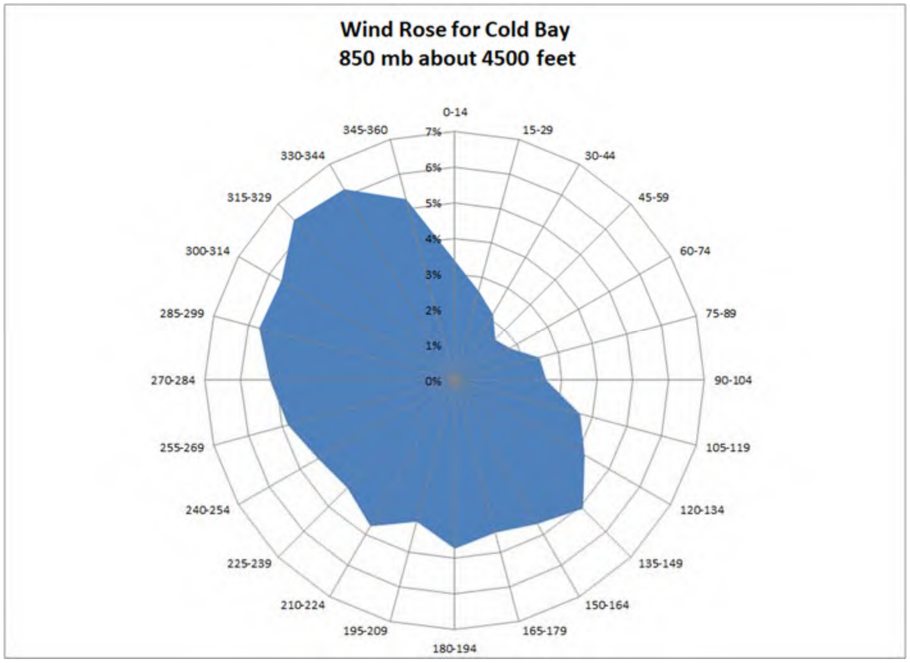

Figure 39: Cold Bay upper air (4500 ft. level) wind rose (from Phase II report)

Solar Irradiance

Bunker Hill was equipped with a pyranometer (solar irradiance sensor) to better understand Unalaska's solar power resource. Although not the focus of this report, solar power may be of interest to City of Unalaska and community residents. Figure 40 and Figure 41 lend insight into the potential, which will be explored further in a follow-on renewable energy feasibility study.

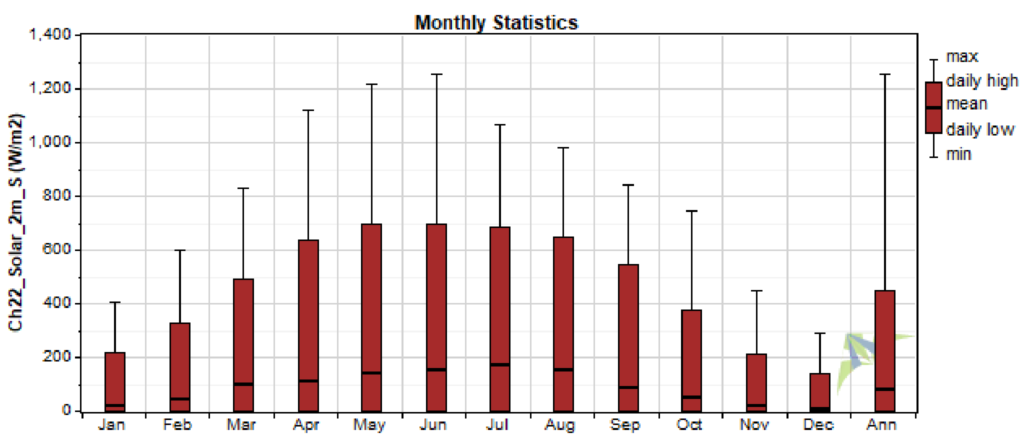

Figure 40: Bunker Hill solar irradiance boxplot, units of Watts/meter^2

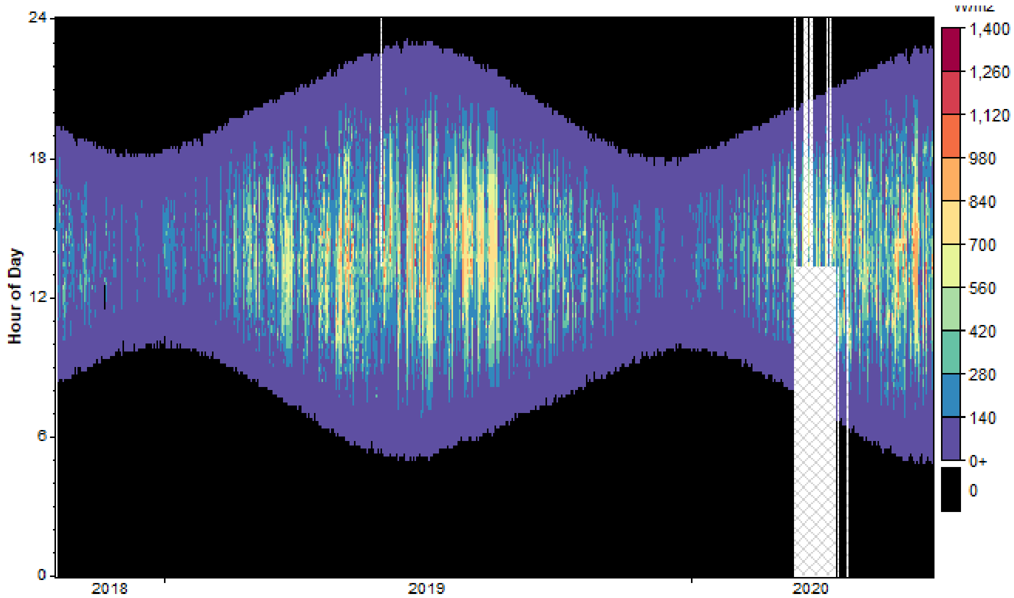

Figure 41: Bunker Hill solar irradiance Dmap, units of Watts/meter² on right-hand scale

Other Wind Power Site Options

During the Wind Power Development and Integration Assessment Project, Phase II site selection process, several site options other than upper and lower Pyramid Valley and Hog Island were considered (refer to pages 22 through 31 of the Phase II report). Most were rejected due to proximity to the airport, distance from existing power infrastructure, and other reasons. Two sites though – Ballyhoo (east summer area of Amaknak Island) and Ptarmigan Road (mid-elevation eastern flanks of Iliuliak Valley) – stand out as possible alternatives to lower Pyramid Valley and have high modeled wind speeds. Ballyhoo and Ptarmigan Road were considered for monitoring with met towers and ultimately rejected during the Phase II planning process in favor of focusing on Pyramid Valley and Hog Island.

Ballyhoo (east summit area of Amaknak Island)

AWS Windnavigator software predicts exceptionally strong winds on Ballyhoo (referring here to the formerly developed portion of Amaknak Island). At first glance this appears desirable, but Windnavigator modeling (discussed in the Phase II report) predicted winds that are too high for wind power development. Also, Ballyhoo is within the Aleutian World War II National Historic Area administered by the U.S. National Park Service, there is no existing power distribution serving the area, and perhaps most significantly, the access road is very steep with exceptionally tight switchback turns. These challenges aside, Ballyhoo presents significant wind power potential that may warrant wind resource measurement with a 10-meter met tower.

Ptarmigan Road (eastern flank of Iliuliak Valley)

This site area is past the turnout of Upper Ptarmigan Road after it turns north and away from Ski Bowl Road. AWS Windnavigator software predicts an excellent wind resource in this area, mostly due to its higher elevation than lower Pyramid Valley. Ptarmigan Road consists of two possible sites, one near the end of the access road and the other downhill and beyond it.

Access to the site area is reasonably easy on a well-maintained road. Drawbacks however include lack of high voltage service in Iliuliuk Valley that would be expensive to upgrade per Department of Public Utilities personnel, location within the instrument approach area to Runway 31 (although this approach is not used and the restriction perhaps could be successfully challenged), and nearness to housing development with the potential for noise and shadow flicker complaints.

Comparison to Kodiak's Pillar Mountain

Comparison of Pyramid to Kodiak Island's Pillar Mountain wind power site was requested to better understand how the wind resource in Unalaska compares. With completion of data collection activities, Pyramid classifies as low wind power class 5 (description: excellent), of seven defined wind classes. With data collection from 2005 to 2007, Kodiak's Pillar Mountain was assessed as wind power class 7 (superb). Note however that comparatively few wind turbines worldwide operate in Class 7 winds.

Table 20: Pyramid-Kodiak Pillar Mountain comparison

Wind characteristic (60-meter level)	Unalaska Pyramid Valley	Kodiak Pillar Mountain
Site elevation	103 m (334 ft.)	390 m (1,280 ft.)
Mean wind speed	6.84 m/s (15.3 mph)	8.35 m/s (18.6 mph)
Wind power density	548 W/m^2 (class 5 of 7)	956 W/m^2 (class 7 of 7)
Max. 10-min. avg wind speed	37.5 m/s (83.9 mph)	39.9 m/s (89.2 mph)
Max. 2-second gust	51.4 m/s (115.0 mph)	49.7 m/s (111.2 mph)
Calm wind probability (winds <4 m/s)	~33%	~21%
Wind shear power law exponent	0.100 (low)	0.023 (extremely low)
Extreme wind probability (50-year period, 10-min avg. wind speed)	41.3 to 47.6 m/s, IEC Class II	46.0 m/s, IEC Class II
Turbulence intensity and category	0.120, Cat. B (moderate)	0.106, Cat. C (low)
IEC 61400-1, 3rd ed. classification[13]	Class II-B	Class II-C

As demonstrated in Table 20, Pillar Mountain's mean wind speed and associated wind power density are higher than at Pyramid, but gust winds and extreme wind probability are similar. From an IEC classification perspective, the wind turbines installed on Pillar Mountain are also suitable for Pyramid, but given Pyramid's lower mean wind speed, wind turbines there would have lower annual energy production than on Pillar Mountain.

[13] International Electrotechnical Commission design standard for Wind Energy Generation Systems

Appendix A – IEC Wind Classification

Six parameters comprise IEC 61400-1, 3rd edition, wind classification:

1. Extreme wind
2. Wind shear
3. Wake turbulence
4. Flow inclination
5. Wind distribution
6. Turbulence intensity

IEC's simplified wind classification is intended to apply to most sites and relies on two of the six parameters: extreme wind probability (Class I, II, III, or S) and turbulence intensity (Category A, B, or C).

Extreme Wind

The classification of extreme wind is by V_{ref}, the reference wind speed, which is the highest measured or probable 10-minute average wind speed in a 50-year return period. This is accomplished with a Gumbel distribution analysis[14] which can be used to model the probability of extreme wind events. It is categorized in Table 21. Note also in **Error! Reference source not found.**Table 21 reference to maximum (3-sec. duration) gust wind in a one-year return period for each IEC extreme wind classification.

Table 21: IEC 61400-1, 3rd edition, extreme wind classes

Wind Class	I	II	III	S
V_{ref} (m/s)	50.0	42.5	37.5	Designer spec.
V_{gust} (m/s)	70.0	59.5	52.5	

Wind Shear

A wind shear, or power law, exponent, α, calculated by Equation 3 where *V* = wind speed and *Z* = height above ground level, between 0 and 0.2. α=0 would indicate no wind shear and α=0.2 would indicate very high wind shear.

Equation 3: Wind shear and power law exponent

$$V(z) = V(hub) \times \left({}^{Z}/_{Zhub} \right)^{\alpha}$$

Wake Turbulence

For comparison with the normal turbulence model, the IEC suggests an effective turbulence intensity, which is an ideal turbulence independent on wind direction and expected to cause the same fatigue damage as variable turbulence in winds from all directions. The effective turbulence intensity includes added turbulence from wakes of neighbor turbines.[15]

Flow Inclination

A wind flow vector not exceeding 8 degrees from horizontal (plus or minus).

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[14] Gumbel distribution - Wikipedia
[15] The IEC 61400-1 turbine safety standard - WAsP

Wind Distribution

A wind speed, or histogram, where a Weibull function[16] yields a unitless shape factor (*k*) of 2.0 (known as a Rayleigh distribution) or less (see Figure 42).

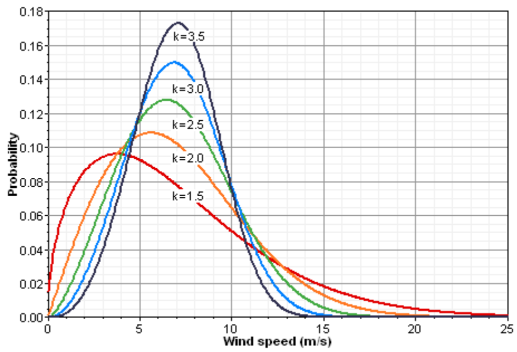


Figure 42: Weibull k shape curves

Turbulence Intensity

The turbulence intensity (*TI*) is a dimensionless number defined by the standard deviation (*σ*) of the wind speed within each time step (10 minutes for wind power analysis) divided by the mean wind speed (*V*) over that time step (see Equation 4).

Equation 4: Turbulence intensity

$$TI = {}^{\sigma i}/_{Vi}$$

IEC 61400-1, 3rd ed., defined turbulence categories based on mean turbulence intensity at a wind speed of 15 m/s (see Table 22).

Table 22: IEC 61400-1, 3rd edition, turbulence categories

Turb. Category	S	A	B	C
TI at 15 m/s	>0.16	0.14-0.16	0.12-0.14	<0.12

Simplified Wind Classification

Although there are six criteria to consider in IEC 61400-1 for wind turbine siting, the simplified evaluation considers just two of them: extreme wind probability and turbulence intensity. This yields the familiar wind turbine design classifications of, for example, Class IIA or Class IIIC (see Table 23).

Table 23: IEC 61400-1, 3rd edition, simplified wind classification

Wind Class	I	II	III	S
V_{ref} (m/s)	50.0	42.5	37.5	Values specified by the designer
A (TI_{ref})		0.16		
B (TI_{ref})		0.14		
C (TI_{ref})		0.12		

16 Weibull distribution - Wikipedia

Appendix B – Pyramid Valley detailed met tower information

Table 24: Pyramid met tower complete sensor installation information

Sensor Type	Model	Name	Height (m)	Dir. (°T)	Serial No.	Scale	Offset	Boom (m)	Mt Angle	Terminal	Logging mode
Anemometer	40C	60m E	59.7	094	311709	0.76770	0.3349	2.4		1	Stats and samples
Anemometer	40C	60m W	59.3	269	311713	0.76214	0.3485	2.4		2	Stats
Anemometer	40C	50m E	50.2	094	311722	0.75942	0.3471	2.4		3	Stats and samples
Anemometer	40C	50m W	49.7	269	311723	0.75805	0.3841	2.4		4	Stats
Anemometer	40C	40m E	38.9	094	311724	0.76344	0.3218	2.4		5	Stats
Anemometer	40C	40m W	38.4	269	311873	0.75806	0.3600	2.4		6	Stats
Vane	200M	60m	57.4	027	742	147.911	-1.4602	2.4	180	13	Stats and samples
Vane	200M	50m	48.0	038	807	147.911	-1.4602	2.4	180	14	Stats
Temp	T60	Temp	3.0	000	n/a	44.7436	-40.8555	none		16	Stats
Rel. Humidity	RH5X	RH	2.0	000	n/a	20	0	none		19	Stats
RM Young	27106T	Vert Spd	55.3	311	n/a	18	0	1.9		20	Stats and samples

Table 25: Pyramid met tower monthly combined anemometer data

		60m cmb				50m cmb			40m cmb		
		DRR	Mean	Max	Gust	Mean	Max	Gust	Mean	Max	Gust
Year	Month	(%)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)	(m/s)
2018	Oct	90.2	6.31	15.2	25.5	6.20	14.9	23.4	6.10	14.7	24.0
2018	Nov	95.3	5.85	17.1	31.1	5.73	17.0	34.0	5.66	17.0	34.2
2018	Dec	96.3	7.32	25.4	33.1	7.20	24.7	33.0	7.07	24.2	33.2
2019	Jan	100.0	7.50	29.8	36.9	7.36	28.8	36.5	7.24	28.5	36.2
2019	Feb	100.0	8.69	26.3	34.4	8.47	25.6	34.8	8.27	25.3	33.7
2019	Mar	100.0	7.21	25.8	31.3	7.11	25.1	30.7	6.97	24.7	29.8
2019	Apr	96.5	5.59	22.1	26.5	5.52	21.9	26.9	5.43	21.9	26.5
2019	May	99.3	4.37	12.8	21.4	4.34	12.3	20.1	4.28	12.0	19.7
2019	Jun	100.0	4.39	18.5	23.0	4.34	18.1	23.1	4.28	17.8	22.5
2019	Jul	100.0	5.77	17.4	21.2	5.70	17.1	21.4	5.66	16.8	20.7
2019	Aug	99.5	5.63	21.9	28.3	5.64	21.3	27.2	5.57	20.8	27.3
2019	Sep	100.0	7.22	22.2	27.5	7.12	21.6	28.4	6.96	21.2	27.6
2019	Oct	100.0	6.40	28.5	39.7	6.30	27.6	38.8	6.16	27.0	38.5
2019	Nov	100.0	6.11	18.1	27.3	5.97	17.6	26.2	5.86	17.4	26.5
2019	Dec	97.6	7.36	28.6	39.7	7.19	27.6	40.3	7.11	27.8	40.0
2020	Jan	100.0	6.69	23.8	29.6	6.56	23.2	29.2	6.52	22.9	29.6
2020	Feb	96.9	7.71	27.9	37.9	7.58	27.0	39.8	7.46	26.9	38.2
2020	Mar	100.0	7.39	26.3	34.6	7.29	25.5	36.0	7.19	25.0	35.4
2020	Apr	100.0	5.45	19.6	25.2	5.35	19.0	23.4	5.28	18.6	23.2
2020	May	99.4	5.33	26.0	33.1	5.21	25.4	32.8	5.17	25.0	31.6
2020	Jun	97.0	4.84	18.3	24.5	4.39	17.9	23.6	4.69	17.9	23.0
2020	Jul	96.2	4.38	15.6	18.6	3.57	15.3	17.8	4.45	15.8	18.6
2020	Aug	97.9	4.72	37.5	51.2	4.65	37.0	49.5	4.70	36.1	49.7
2020	Sep	97.9	5.99	19.1	25.2	5.99	19.5	24.9	5.83	19.4	25.5
2020	Oct	97.0	6.31	22.9	30.6	6.23	22.3	31.2	6.07	21.9	32.1
2020	Nov	98.8	8.49	25.4	38.2	8.40	25.5	39.6	8.16	25.2	41.5
2020	Dec	96.5	7.19	24.1	34.6	7.21	23.5	34.5	6.96	23.1	34.4
2021	Jan	100.0	8.15	25.4	36.2	8.15	25.0	34.3	7.92	24.8	37.2
2021	Feb	95.2	7.75	21.6	31.1	7.68	21.0	32.2	7.45	20.7	33.4
2021	Mar	97.3	8.30	23.7	37.9	8.25	23.1	38.3	7.99	22.8	38.5
2021	Apr	100.0	6.72	20.8	27.3	6.62	20.3	26.4	6.49	19.9	26.5
2021	May	100.0	5.31	17.8	23.2	5.27	17.2	23.4	5.10	16.7	22.2
2021	Jun	100.0	5.66	23.9	33.1	5.64	23.3	32.2	5.37	22.9	29.8
2021	Jul	100.0	5.74	15.6	20.4	5.67	15.4	19.8	4.69	14.8	19.9
2021	Aug	82.5	6.92	19.5	22.2	6.81	18.8	21.9	5.82	18.2	21.7
All Data		98.3	6.40	37.5	51.2	6.28	37.0	49.5	6.17	36.1	49.7
Mean of monthly means			6.39			6.28			6.16		

Appendix C – Hog Island detailed met tower information

Table 26: Hog Island met tower complete sensor installation information

Sensor Type	Model	Name	Height (m)	Dir. (°T)	Serial No.	Scale	Offset	Boom (m)	Mt Angle	Terminal	Logging mode
Anemometer	40C	60m E	59.7	098	315386	0.76311	0.318	2.4		1	Stats
Anemometer	40C	60m W	59.3	269	315376	0.76207	0.3316	2.4		2	Stats
Anemometer	40C	50m E	50.3	098	315397	0.76227	0.3393	2.4		3	Stats
Anemometer	40C	50m W	49.8	269	315394	0.76234	0.3279	2.4		4	Stats
Anemometer	40C	40m E	40.9	098	315393	0.76008	0.3338	2.4		5	Stats
Anemometer	40C	40m W	40.4	269	315375	0.76293	0.3252	2.4		6	Stats
Vane	200M	60m	57.4	148	1354	147.911	-1.4602	2.4	180	13	Stats
Vane	200M	50m	47.7	220	1346	147.911	-1.4602	2.4	180	14	Stats
Temp	T60	Temp	3.0	000	183	44.7436	-40.8555	none		16	Stats
Barom. Press.	BP20	BP	2.0	270	536670	217.9	106.3	none		17	Stats
Rel. Humidity	RH5X	RH	2.0	270	n/a	20	0	none		19	Stats
RM Young	27106T	Vert Spd	55.56	223	n/a	18	0	1.9		20	Stats

Appendix D – Icy Creek Reservoir detailed met tower information

Table 27: ICR met tower complete sensor installation information

Sensor Type	Model	Name	Height (m)	Dir. (°T)	Serial No.	Scale	Offset	Boom (m)	Mt Angle	Terminal	Logging mode
Anemometer	40C	34m ESE	34.0	121	311702	0.76336	0.3121	1.53		1	Stats
Anemometer	40C	34m WSW	34.0	262	311703	0.76077	0.3391	1.53		2	Stats
Anemometer	40C	20m ESE	20.5	124	311704	0.75933	0.3793	1.53		3	Stats
Vane	200M	Direction	33.0	281	794	147.911	-1.4602	1.53	180	13	Stats
Temp	T60	Temp	2.5	000	n/a	44.7436	-40.8555	none		16	Stats
Rel. Humidity	RH5X	RH	2.0	000	n/a	20	0.0000	none		17	Stats

Appendix E – Bunker Hill detailed met tower information

Table 28: Bunker Hill met tower complete sensor installation information

Sensor Type	Model	Name	Height (m)	Dir. (°T)	Serial No.	Scale	Offset	Boom (m)	Mt Angle	Terminal	Logging mode
Anemometer	40C	10m NE	10.0	054	311706	0.76026	0.338	1.53		1	Stats
Anemometer	40C	10m W	10.0	256	311707	0.76465	0.3163	1.53		2	Stats
Vane	200M	10m	9.0	144	804	147.911	-1.4602	1.53	180	13	Stats
Temp	T60	Temp	3.0	000	106	44.7436	-40.8555	none		16	Stats
Rel. Humidity	RH5X	RH	1.0	090	n/a	20	0	none		17	Stats
Pyranometer	Li-Cor	Pyra	2.0	180	105963	15.99	0.0000	none		22	Stats

Appendix F – Met tower documentation photographs


Pyramid 60 m met tower, view to north


Pyramid 60 m, water treatment plant and Icy Creek access road, south view from site area


Pyramid 60 m, north view


Pyramid 60 m, northeast view


Pyramid 60 m, east view


Pyramid 60 m, southeast view

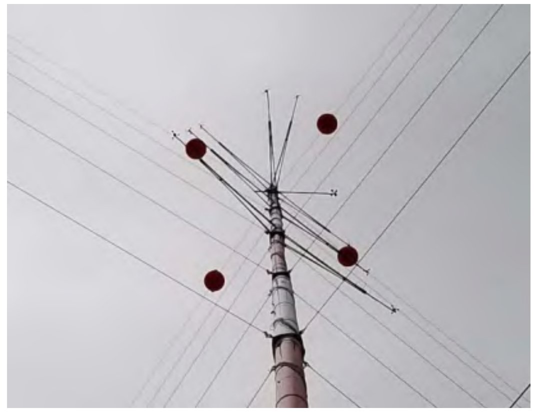

Pyramid 60 m, south view


Pyramid 60 m, southwest view

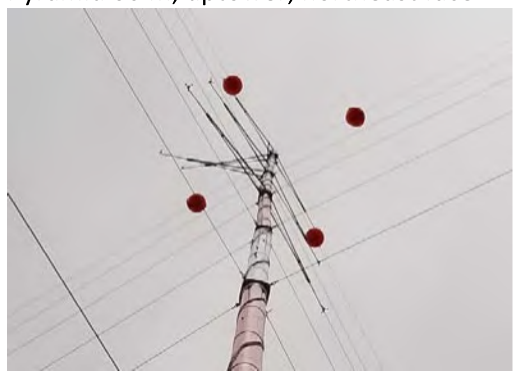

Pyramid 60 m, west view


Pyramid 60 m, northwest view

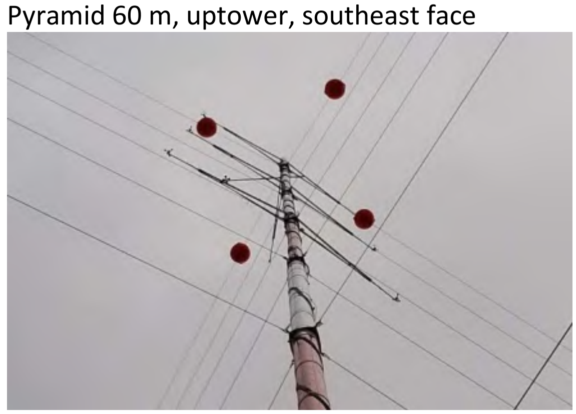

Pyramid 60 m, uptower, north face

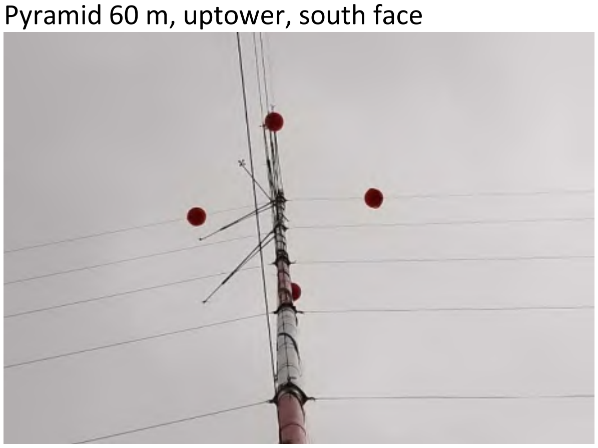

Pyramid 60 m, uptower, northeast face

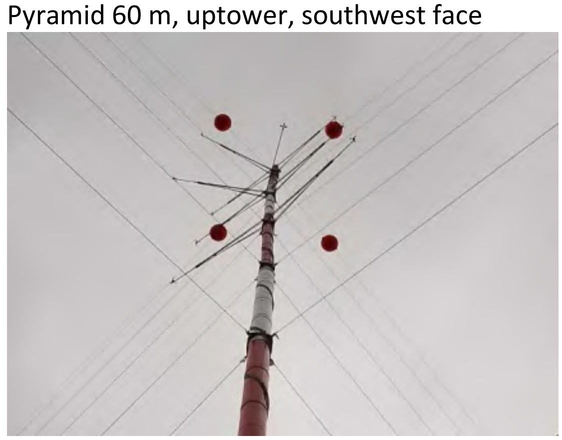

Pyramid 60 m, uptower, east face


Pyramid 60 m, uptower, southeast face


Pyramid 60 m, uptower, south face


Pyramid 60 m, uptower, southwest face


Pyramid 60 m, uptower, west face


Pyramid 60 m, uptower, northwest face


Pyramid 60 m, north side (view to south)


Pyramid 60 m, east side (view to west)

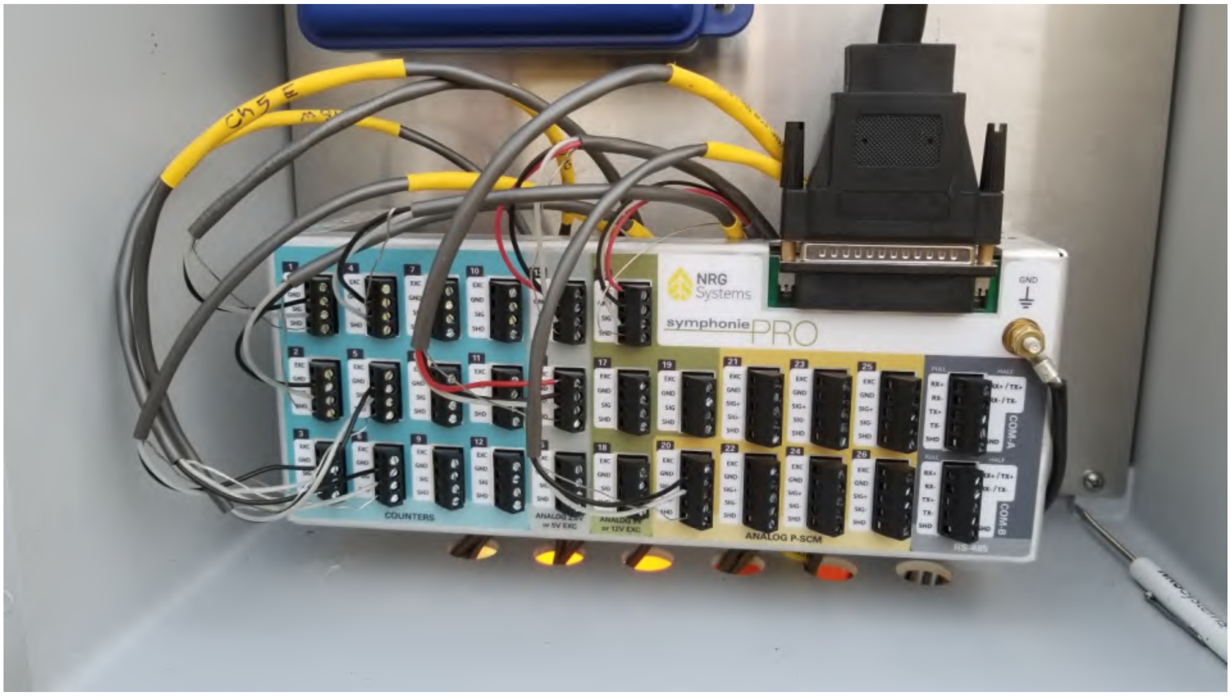

Pyramid 60 m, south side (view to north)


Pyramid 60 m, west side (view to east)

Pyramid 60 m, tower base


Pyramid 60 m, inside weather box

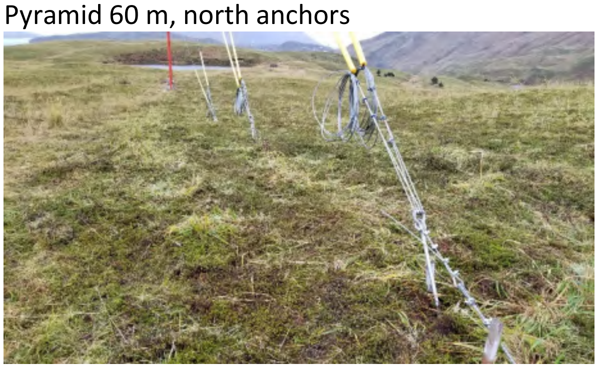
Pyramid 60 m, datalogger



Pyramid 60 m, datalogger wiring panel


Pyramid 60 m, north anchors


Pyramid 60 m, east anchors

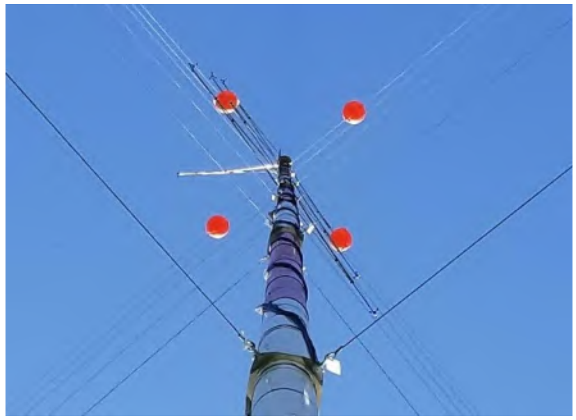

Pyramid 60 m, south anchors

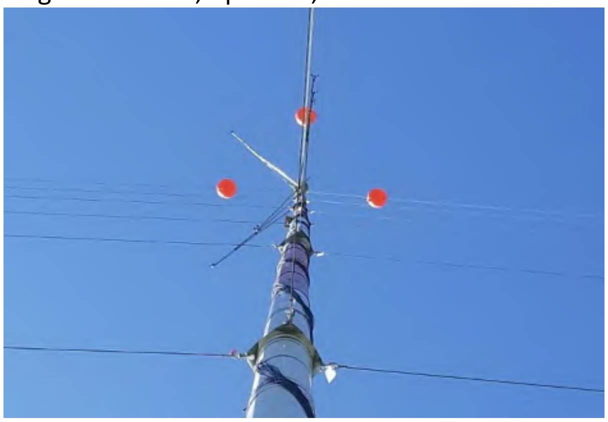

Pyramid 60 m, west anchors

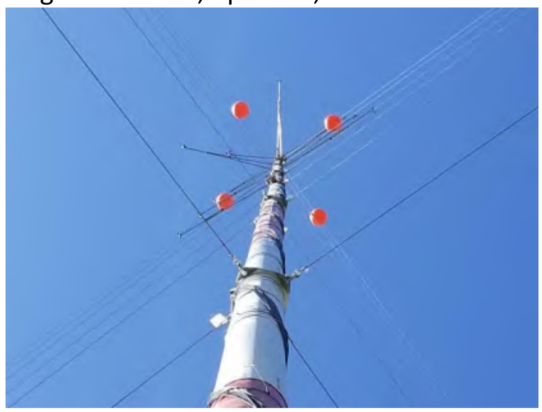

Hog Island 60 m met tower, view to north, Bob Cummings photo

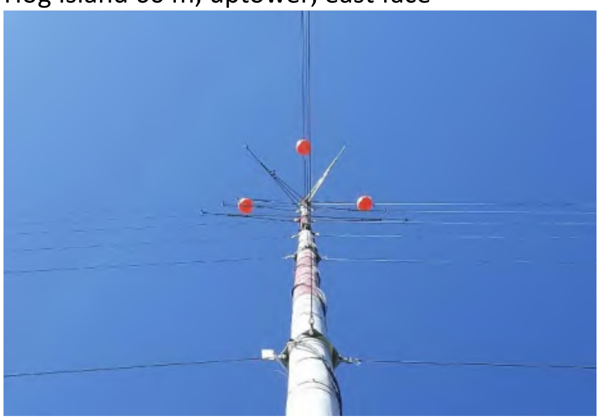
Hog Island tower during assembly, view south

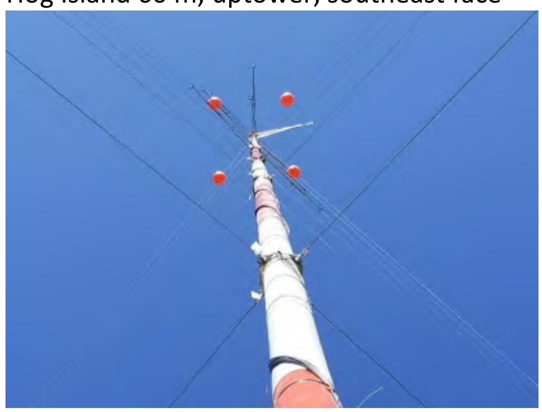

Hog Island 60 m, uptower, north face


Hog Island 60 m, uptower, northeast face


Hog Island 60 m, uptower, east face


Hog Island 60 m, uptower, southeast face


Hog Island 60 m, uptower, south face


Hog Island 60 m, uptower, southwest face


Hog Island 60 m, uptower, west face


Hog Island 60 m, uptower, northwest face

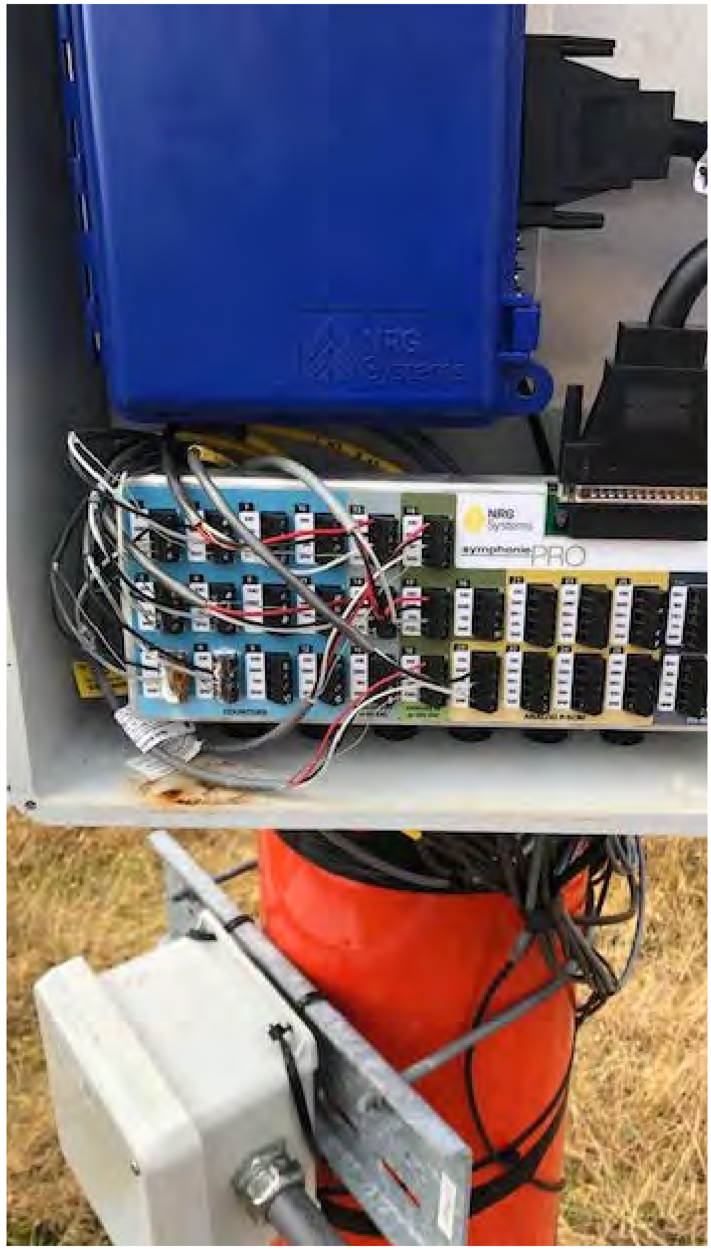
Hog Island 60 m, north side (view to south)

Hog Island 60 m, east side (view to west)


Hog Island 60 m, south side (view to north)


Hog island 60 m, west side (view to east)

Hog Island 60 m, tower base



Hog Island 60 m, inside weather box


Hog Island 60 m, power system for lights

Hog Island 60 m, inside lighting control weather box


ICR 34 m met tower, view to northwest

ICR 34 m met tower winter view, view to northwest (K. Arduser photo)


ICR 34 m site, north view

ICR 34 m site, northeast view

ICR 34 m site, east view

ICR 34 m site, southeast view (with K. Arduser)

ICR 34 m site, south view

ICR 34 m site, southwest view

ICR 34 m site, west view

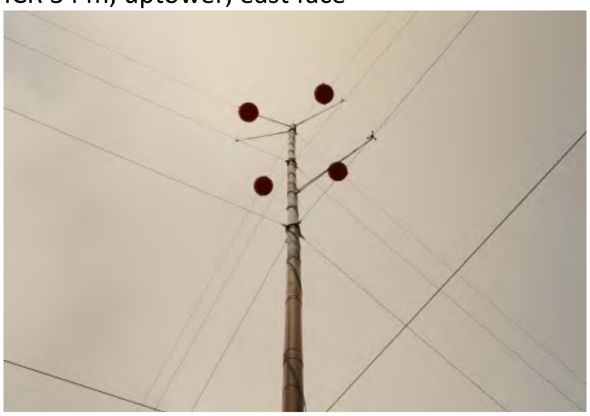
ICR 34 m site, northwest view


ICR 34 m, uptower, north face


ICR 34 m, uptower, northeast face

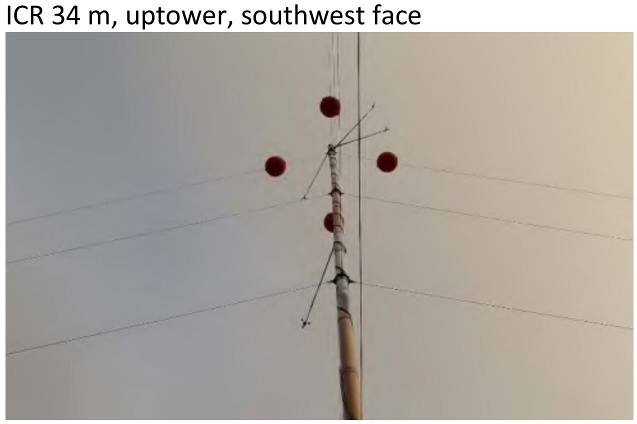

ICR 34 m, uptower, east face


ICR 34 m, uptower, southeast face

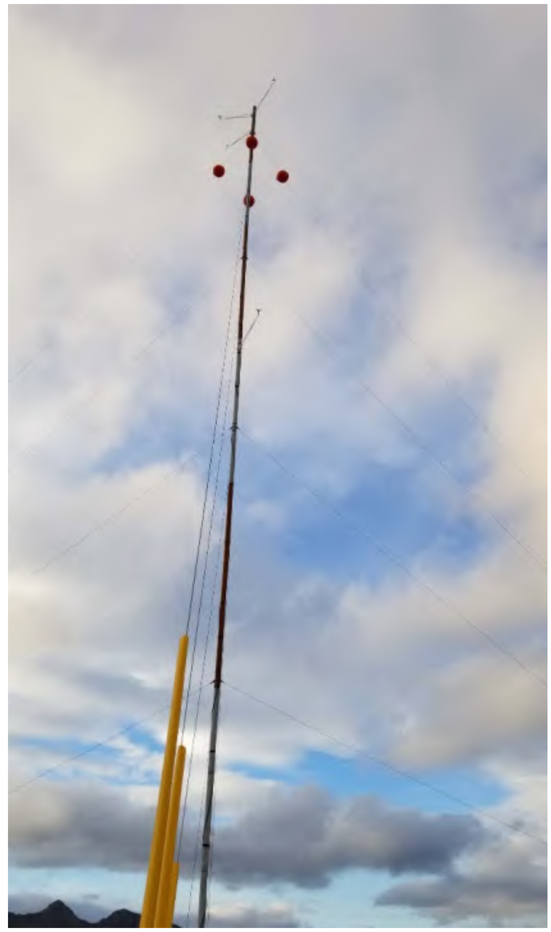

ICR 34 m, uptower, south face


ICR 34 m, uptower, southwest face


ICR 34 m, uptower, west face


ICR 34 m, uptower, northwest face

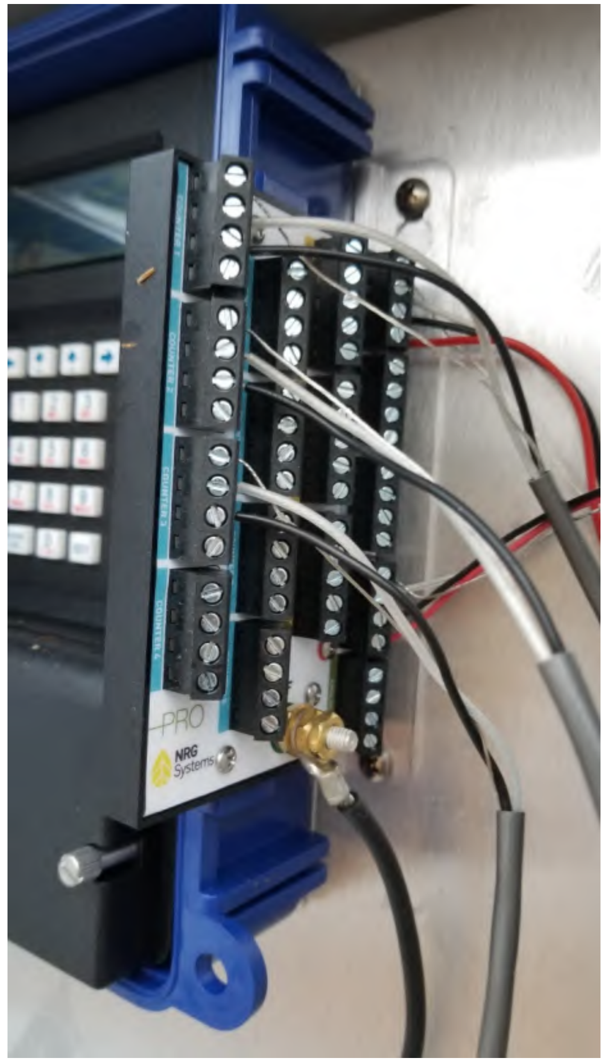

ICR 34 m, northeast side (view to southwest)


ICR 34 m, southeast side (view to northwest)


ICR 34 m, southwest side (view to northeast)


ICR 34 m, northwest side (view to southeast)

ICR 34 m, tower base



ICR 34 m, datalogger wiring panel

ICR 34 m, datalogger


ICR 34 m, northeast anchors


ICR 34 m, southeast anchors


ICR 34 m, southwest anchors


ICR 34 m, northwest anchors

Bunker Hill 10 m met tower, view to north

Bunker Hill 10 m met tower during installation


Bunker Hill 10 m site, north view


Bunker Hill 10 m site, northeast view


Bunker Hill 10 m site, east view


Bunker Hill 10 m site, southeast view


Bunker Hill 10 m site, south view


Bunker Hill 10 m site, southwest view


Bunker Hill 10 m site, west view


Bunker Hill 10 m site, northwest view

Bunker Hill 10 m, uptower, north face

Bunker Hill 10 m, uptower, east face

Bunker Hill 10 m, uptower, south face

Bunker Hill 10 m, uptower, west face

Bunker Hill 10 m, north side (view to south)

Bunker Hill 10 m, east side (view to west)

Bunker Hill 10 m, south side (view to north)

Bunker Hill 10 m, west side (view to east)

Bunker Hill 10 m, weather box

Bunker Hill 10 m, datalogger wiring panel

Bunker Hill 10 m, datalogger

Obstruction light batteries and turbine controller