Elim, Alaska
Wind-Diesel Analysis

Google Earth image of Elim

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Introduction

Alaska Village Electric Cooperative (AVEC) is the electric utility for the Native village of Elim, Alaska. AVEC was awarded a grant from the Alaska Energy Authority (AEA) to complete resource assessment and feasibility work for installation of wind turbines in the community of Elim.

Executive Summary

Depending on the project site – the met tower location or possibly the hill west of the airport – Elim has a low to moderate wind resource for wind power development, but the new Northern Power Systems NPS100C-24 wind turbine is expressly designed for lower wind class environments and modeling results predict the potential for surprisingly good energy production. Site options for wind turbines are limited in Elim and given the poor wind resource at the met tower site, the hill west of the airport is the only truly viable option, but development of the hill site likely would require another met tower study, FAA permitting, and consideration of project capital costs.

Village of Elim

Elim is located on the northwest shore of Norton Bay on the Seward Peninsula, 96 miles east of Nome. It lies 460 miles northwest of Anchorage. Elim falls within the transitional climate zone, characterized by tundra interspersed with boreal forests, and weather patterns of long, cold winters and shorter, warm summers. Norton Sound is ice-free generally between mid-June and mid-November. Summers are cool and rainy; winters are cold and dry.

This settlement was formerly the Malemiut Inupiat Eskimo village of Nuviakchak. The Native culture was well-developed and well-adapted to the environment. Each tribe possessed a well-defined subsistence harvest territory. The area became a federal reindeer reserve in 1911. In 1914, Rev. L.E. Ost founded a Covenant mission and school, called Elim Mission Roadhouse. The city was incorporated in 1970. When the Alaska Native Claims Settlement Act (ANCSA) was passed in 1971, Elim decided not to participate and instead opted for title to the 298,000 acres of land in the former Elim Reserve. The Iditarod Sled Dog Race passes through Elim each year.

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Topographic map of Elim and vicinity

Google Earth image of Elim (view north)

Wind Resource

A 34 meter NRG Systems, Inc. tubular-type meteorological (met) tower was installed in Elim in an open area of city land immediately northeast of the community and just east of the road to Moses Point. The met tower was operational for nineteen months, from late January 2014 to mid-September 2015.

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The wind resource measured at the Elim met tower site is marginal with a mean annual wind speed of 5.12 m/s and a wind power density of 191 W/m^2 at 34 meters above ground level. This confirms the AWS Truepower wind resource map which predicts wind power Class 2 winds at this location. The wind resource is summarized below, and described in detail in the Appendix of this report. Higher winds are predicted on the high terrain surrounding Elim, including the hills immediately west and north of the airport.

Elim met tower data synopsis

Data dates	1/30/2014 to 9/14/2015 (19 months)
Wind speed mean, 34 m, annual	5.12 m/s (11.5 mph)
Wind power density mean, 34 m	191 W/m^2
Max. 10-min wind speed	17.5 m/s (39.1 mph)
Maximum 2-sec. wind gust	25.5 m/s (57.0 mph)
Weibull distribution parameters	k = 1.71, c = 5.54 m/s
Wind shear power law exponent	0.247 (low)
Surface roughness	0.74 meters (urban)
IEC 61400-1, 3rd ed. classification	Class IIIA
Turbulence intensity, mean (at 34 m)	0.145 (at 15 m/s)
Calm wind frequency (at 34 m)	41% (< 4 m/s) (19 mo. measurement period)

Measured Wind Speeds

During the measurement period, winds at the test site measured 5.12 m/s (annualized), which can be considered fair for wind power development, provided a wind turbine optimized for lower wind speeds is selected.

### *Elim met tower wind speed graph*
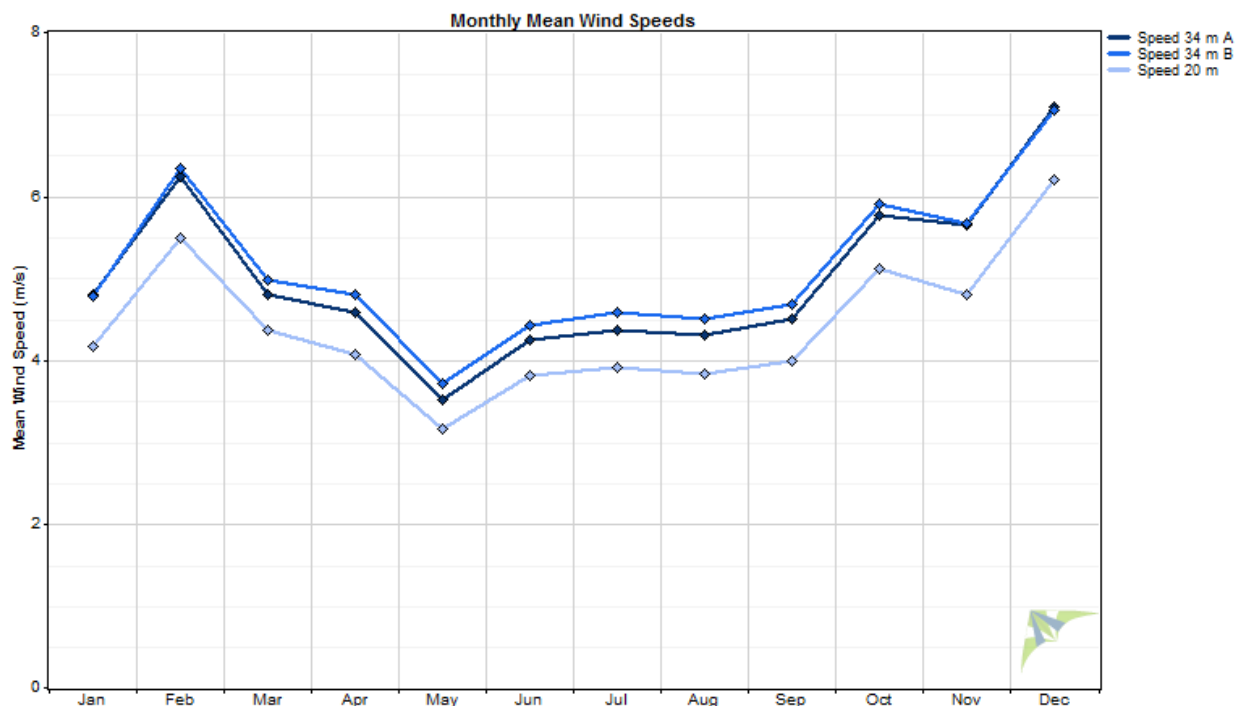
Wind Roses

Wind frequency rose data indicates that winds at the Elim met tower site are primarily bi-directional, with east-northeasterly and west-southwesterly winds predominating. The mean value rose (see Appendix A) indicates that ENE winds are of equal intensity as WSW winds, but with more frequent ENE winds, the dominant energy winds are from that direction.

Calm frequency, the percent of time that winds at the 34-meter level are less than 4 m/s, a typical cut-in speed of larger wind turbines, was 41 percent during the 19-month test period.
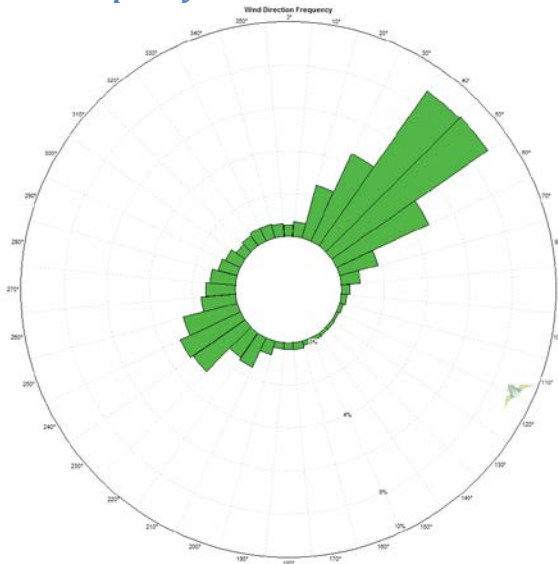
Wind Frequency Rose   *Wind Energy Rose*
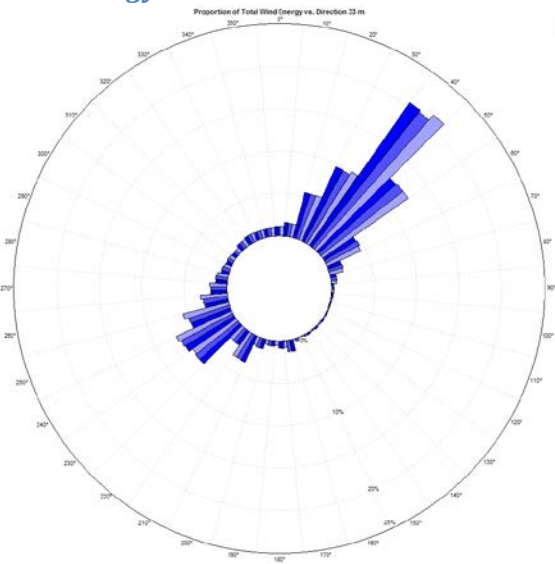
WAsP Wind Flow Model

WAsP (Wind Atlas Analysis and Application Program) is a PC-based software designed to estimate wind resource and power production for individual wind turbines and/or wind turbine farms. WAsP was used to predict wind turbine performance at selected locations in Elim.

Orographic Modeling

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

A met tower reference point is added to the digital elevation map, wind turbine locations identified, and a wind turbine(s) selected to perform the calculations. WAsP considers the orographic (terrain) effects on the wind, plus surface roughness variability and obstacles if added, and calculates wind flow increase or decrease at each node of the DEM grid. The mathematical model, although robust, has a number of

limitations, including an assumption that the wind regime at the turbine site is the same as at the met tower reference site, prevailing weather conditions are stable over time, and the surrounding terrain at both sites is sufficiently gentle and smooth to ensure laminar, attached wind flow. The version of WAsP software used for this analysis is not capable of modeling turbulent wind flow resulting from sharp terrain features such as mountain ridges, canyons, shear bluffs, etc.

Given the hilly terrain of Elim and surrounding area, orographic modeling with the met tower station as the reference point indicates higher winds may be found on the hill west of the airport, the prominent treeless knob immediately north of Elim (along the road to Moses Point), and other higher terrain further from the community. This confirms the AWS Truepower mesoscale wind model which predicts wind power class 2 winds at the met tower site and up to wind power class 4 winds on the hill west of the airport. WAsP predicts a wide range of wind speeds on the hill west of the airport, but for evaluation 6.0 m/s is chosen as representative of a location on the northeast slope of the hill, between the forest margin and the high point.

WAsP wind modeling of Elim
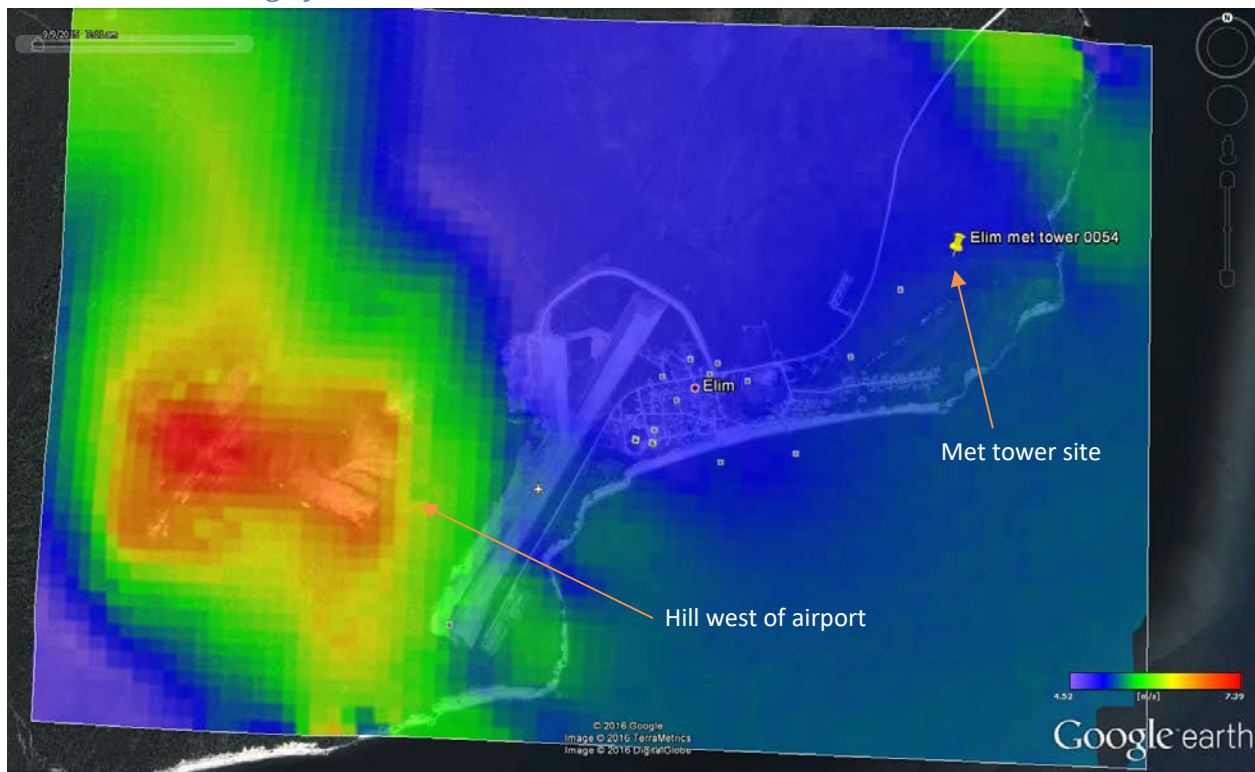
Wind Turbine Project Site Options

The Elim met tower location is a site option for wind turbines, but the recently completed met tower study indicated that the wind resource in this location is poor suited for wind power and hence not an ideal choice. A second option is on the hill complex west of the airport, subject to successful approval of an FAA obstruction evaluation. Earlier discussions with FAA indicated that they objected to wind turbines at the high point of the hill but that lower elevations to the north side could possibly be

permitted. With that, a site on the northeast shoulder of the hill complex somewhat near the airport tarmac is another wind turbine site option in Elim.

Recommended Turbine Site

Although the Elim met tower site is modeled in this report, it is not recommended for wind power development due to insufficient wind resource and excessive turbulence. The hill west of the airport clearly has a better wind resource but turbulence is unknown at present, although likely less than the met tower site. The hill west of the airport is only recommended given the presumption of a better wind resource than at the met tower site, but land ownership, FAA permitting, and cost constraints are unknown at present.

Elim Power System

The Elim power system at present consists of three diesel generators without heat recovery and a three-phase power distribution network to serve the community.

Diesel Generators

The Elim power plant is equipped with three diesel generator models as described below. The power plant is not equipped with a recovered heat system because of its distance from other community facilities. Note also that the power plant is equipped with manual switchgear which would require upgrade to operate seamlessly with wind turbines.
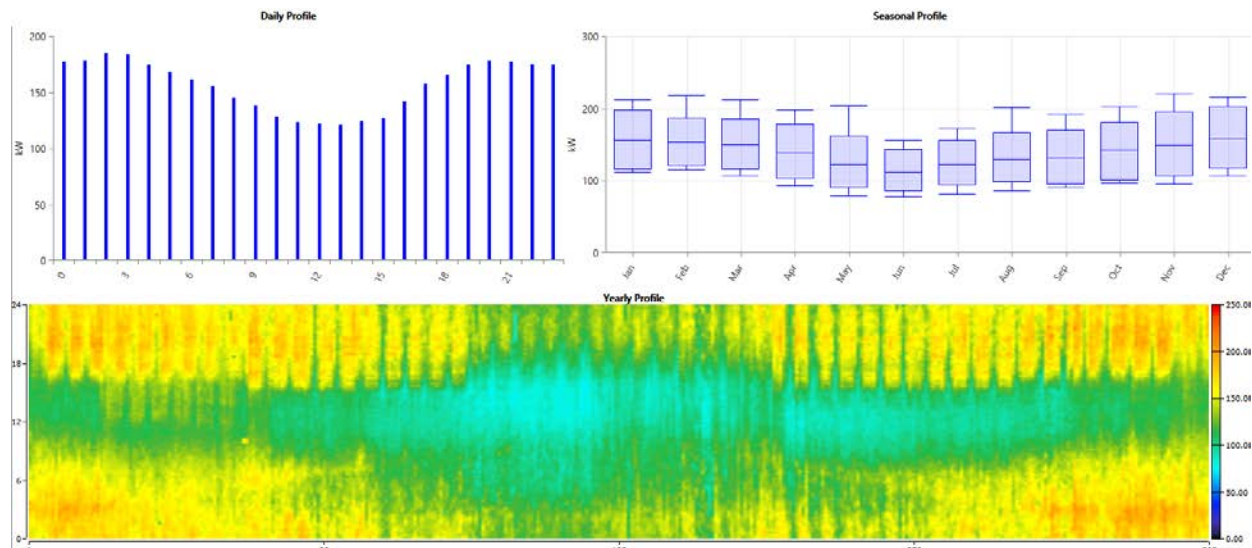
Elim power plant diesel generators

Generator	Electrical Rating	Diesel Engine	Generator
1	363 kW	Detroit Diesel S60K4 1800 rpm	MAR 5M4027
2	236 kW	Detroit Diesel S60K4 1200 rpm	Newage
3	506 kW	MTU 8V2000	MAR 5M4030

Electric Load

Elim electric load was obtained from AVEC via its automated logging which requires energy delivered every 15 minutes. The file used for this analysis contained data from December 21, 2012 to March 5, 2016. Energy was converted to power, the 15-minute time periods were average to obtain a representative year logs, and the resulting file uploaded to HOMER software for analysis. AVEC data indicates an average load in Elim of 139 kW with a typical (15 minute) peak load of 220 KW which can occur in the coldest winter months of November through March. Total annual electric energy demand is 1,220 MWh.

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Elim electric load

Thermal Load

Jacket water heat from the Elim powerplant diesel engines is ejected to the atmosphere via the system radiators and hence is not used to offset thermal load demand in the larger structures of the community, such as the school. With that, to use excess energy from wind turbines, a remote node boiler must be installed in the school, water plant, or other location with significant thermal demand.

Wind-Diesel Hybrid System Design and Equipment

Wind-diesel power systems are categorized based on their average penetration levels, or the overall proportion of wind-generated electricity compared to the total amount of electrical energy generated. Commonly used categories of wind-diesel penetration levels are very low, low, medium, and high penetration. The wind penetration level is roughly equivalent to the amount of diesel fuel displaced by wind power. Note however that the higher the level of wind penetration, the more complex and expensive a control system and demand-management strategy is required.

Categories of wind-diesel penetration levels

Penetration Category	Wind Penetration Level		Operating Characteristics and System Requirements
	Instantaneous	Average	
Very Low	<60%	<8%	• Diesel generator(s) runs full time • Wind power reduces net load on diesel • All wind energy serves primary load • No supervisory control system
Low	60 to 120%	8 to 20%	• Diesel generator(s) runs full time • At high wind power levels, secondary loads are dispatched to insure sufficient diesel loading, or wind generation is curtailed • Relatively simple control system
Medium	120 to 300%	20 to 50%	• Diesel generator(s) runs full time

| Penetration Category	Wind Penetration Level		Operating Characteristics and System Requirements
	Instantaneous	Average	
			• At medium to high wind power levels, secondary loads are dispatched to insure sufficient diesel loading • At high wind power levels, complex secondary load control system is needed to ensure heat loads do not become saturated • Sophisticated control system
High (Diesels-off Capable)	300+%	50 to 150%	• At high wind power levels, diesel generator(s) may be shut down for diesels-off capability • Auxiliary components required to regulate voltage and frequency • Sophisticated control system

Medium penetration is a reasonable compromise between fuel use offset and relatively minimal system complexity and is AVEC's preferred system configuration. Installation of wind turbines in Elim would likely be configured at the medium penetration level.

Proposed Wind Turbine

The Northern Power Systems NPS 100C-24 wind turbine is proposed for Elim on the highest tower that can be permitted. This turbine is rated at 95 kW and is equipped with a permanent magnet, synchronous generator for direct drive (no gearbox) operation. The turbine has a 24.4-meter diameter rotor and is available with three tubular tower heights: 22, 29, and 37 meters. The NPS 100C-24 is specifically optimized for lower wind speed sites and is marketed as a IEC 61400-1, 3rd edition, Class III-C turbine.

The NPS 100C-24 is stall-regulated and for Elim would be equipped with an arctic package enabling operation at temperatures as low as -40° C. The NPS 100 is the most widely represented village-scale wind turbine in Alaska with a significant number of installations in the Yukon-Kuskokwim Delta and on St. Lawrence Island. The NPS 100 wind turbine is manufactured in Barre, Vermont, USA. More information can be found at http://www.northernpower.com/. The power output and coefficient of thrust (Ct) curves of the NPS 100C-24 are shown below.

NPS 100C-24 power and thrust curves
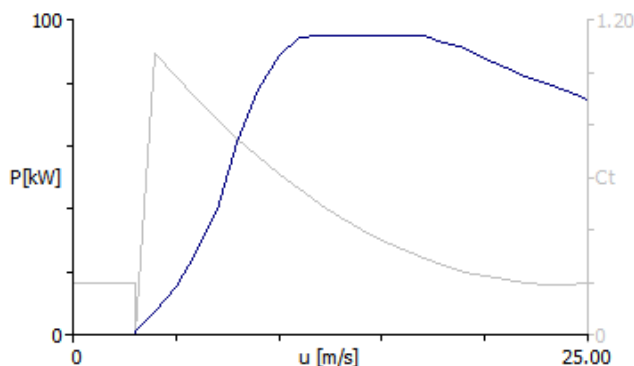
Northern Power Systems 100 (B model) wind turbines, Shaktoolik, Alaska

HOMER Modeling

HOMER energy modeling software was used to analyze the Elim power system. HOMER is a static energy balance and financial model designed to optimize hybrid power system designs that contain a mix of conventional and renewable energy sources, such as diesel generators, wind turbines, solar panels, batteries, etc. HOMER software is widely used in the State of Alaska to aid development of village wind-diesel power projects.

Modeling Assumptions

HOMER modeling assumptions are detailed in the table below. Many assumptions, such as project life, discount rate, operations and maintenance (O&M) costs, etc. are AEA default values. The base or comparison scenario is the existing Elim power plant with its present configuration of three diesel generators.

New NPS 100C-24 wind turbines constructed at the Elim site are assumed to operate in parallel with the diesel generators. Excess energy, if sufficient, will serve thermal loads via a remote node secondary load controller and electric boiler to serve thermal loads in the school, community water plant or other location. Installation cost of the wind turbines assumes road construction to either the met tower site or a site west of the airport.

HOMER and AEA modeling assumptions

Economic Assumptions	
Project life	20 years (2018 to 2037)
Discount rate	3% (reference: AEA *EvaluationModelREFR9Final* spreadsheet)
Operating Reserves	
Load in current time step	10%
Wind power output	50% (in event of loss of one wind turbine if two are operational)
Diesel Generators	

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O&M cost	$0.203/kWh (reference: AEA *EvaluationModelREFR9Final* spreadsheet)
Minimum load	15%
Schedule	Optimized; always diesels-on
Wind Turbines	
Net AEP	85% (net all losses: icing, wake, O&M, electrical, soiling, etc.)
O&M cost	1% of capex/year (reference: AEA *EvaluationModelREFR9Final* spreadsheet)
Wind speed	5.12 m/s at 34 m, measured at met tower; 6.0 m/s estimated by WAsP modeling on hill west of airport
Wind shear	0.187 power law exponent
Energy Loads	
Electric	3.34 MWh/day average Elim electric load
Thermal	Modeled as remote node and infinite

Model Results

HOMER energy modeling software was used to calculate wind turbine energy production and excess energy available (not demanded by the electrical load). Note that inclusion of wind turbines as a wind-diesel power system, even at lower penetration levels, can result in energy generation greater than electrical load demand. This is due to spinning reserve and minimum loading requirements of the diesel generators. Note that wind turbine energy production in these analyses is calculated at 85 percent of gross. HOMER software does not model system dynamic response. Possible system instability would be addressed during design.

Met Tower Site, two NPS100C-24 turbines, 37 m hub height

This configuration is two Northern Power NPS100C-24 wind turbines on 37-meter towers at the existing met tower site. In this scenario, wind turbine penetration (percent electrical power production by wind) would be 26.1 percent. Excess energy is modeled as 35.8 MWh/year, or 2.9% of energy generated.
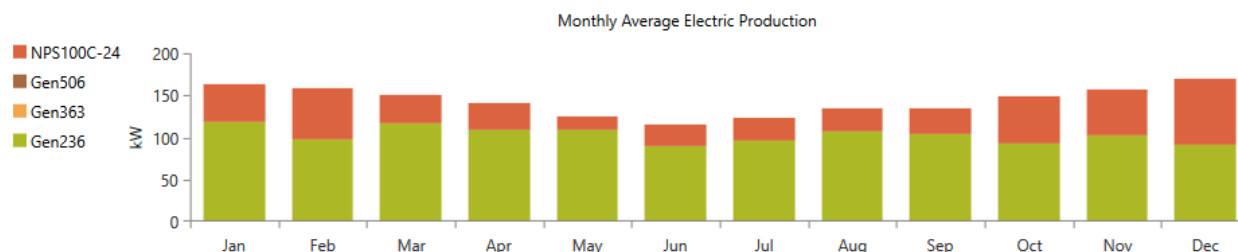
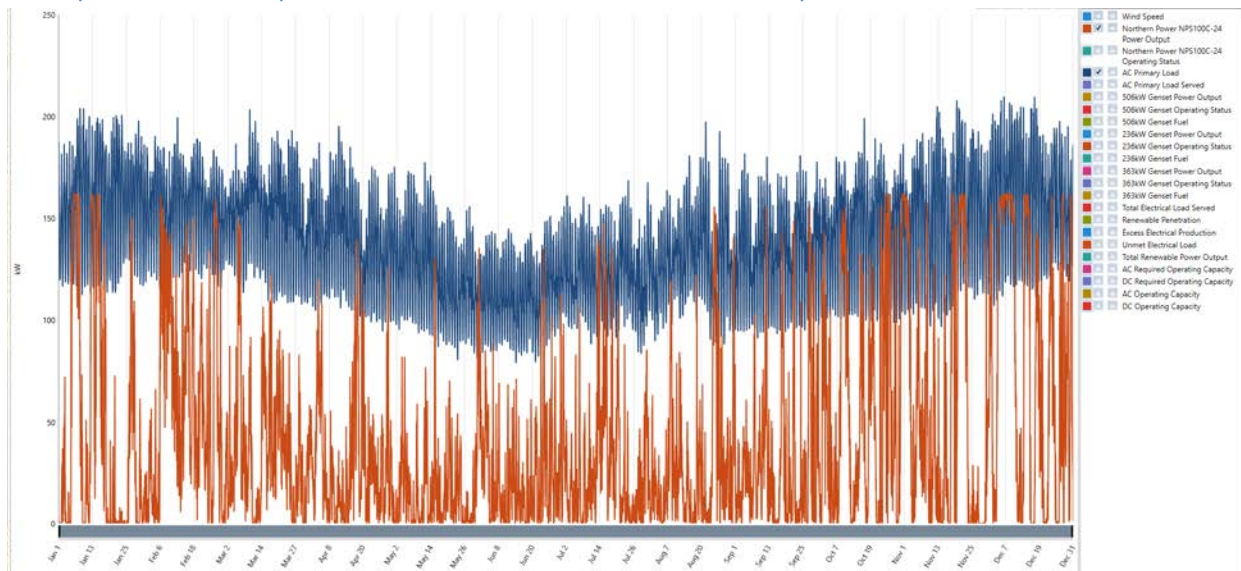### *Energy table, met tower site, two NPS 100C-24 turbines, 85% net AEP*

Production	kWh/yr	%
506kW Genset	0	0.00
236kW Genset	900,452	71.79
363kW Genset	0	0.00
Northern Power NPS100C-24	353,818	28.21
Total	1,254,270	100.00

Consumption	kWh/yr	%
AC Primary Load	1,218,409	100.00
DC Primary Load	0	0.00
Total	1,218,409	100.00

Quantity	kWh/yr	%
Excess Electricity	35,878.0	2.9
Unmet Electric Load	0.0	0.0
Capacity Shortage	0.0	0.0

Quantity	Value
Renewable Fraction	26.1
Max. Renew. Penetration	159.2

Monthly Average Electric Production

Chart, met tower site, electric load and two NPS 100 turbines, 85% net AEP

Airport Hill Site, two NPS100C-24 turbines, 37 m hub height

This configuration is two Northern Power NPS100C-24 wind turbines on 37-meter towers at a presently-undefined location on the hill west of the airport between the tree line and the hill summit. In this scenario, wind turbine penetration (percent electrical power production by wind) would be 34.2 percent. Excess energy is modeled as 68.8 MWh/year, or 5.6% of energy generated.

Energy table, airport hill site, two NPS 100C-24 turbines, 85% net AEP

Production	kWh/yr	%
506kW Genset	0	0.00
236kW Genset	801,555	62.27
363kW Genset	0	0.00
Northern Power NPS100C-24	485,611	37.73
Total	1,287,167	100.00

Consumption	kWh/yr	%
AC Primary Load	1,218,409	100.00
DC Primary Load	0	0.00
Total	1,218,409	100.00

Quantity	kWh/yr	%
Excess Electricity	68,782.0	5.3
Unmet Electric Load	0.0	0.0
Capacity Shortage	0.0	0.0

Quantity	Value
Renewable Fraction	34.2
Max. Renew. Penetration	174.8

Monthly Average Electric Production
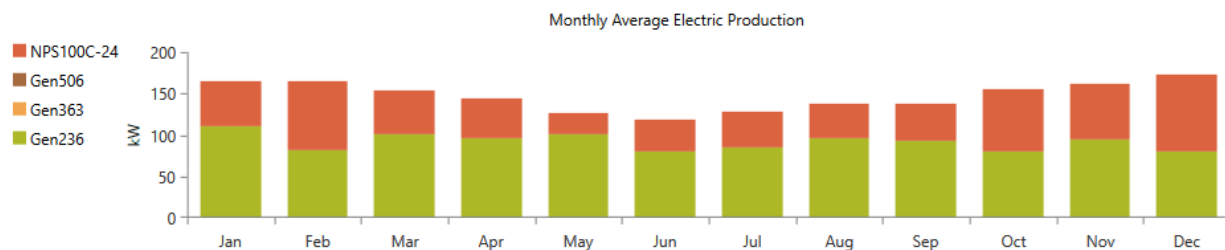
Chart, airport hill site, electric load and two NPS 100 turbines, 85% net AEP
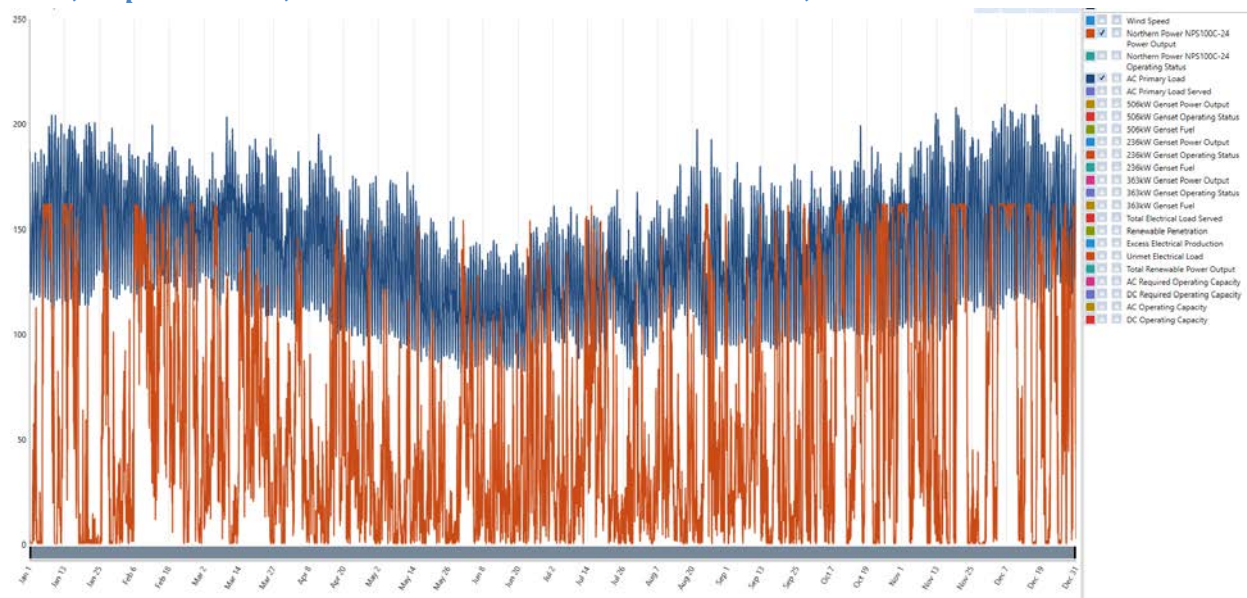
Economic Analysis

AEA's 2015 *EvaluationModelREFR9Final (1)* Excel spreadsheet was used to evaluate the potential economic benefit of a wind power project in Elim.

Project Capital Cost

Capital and installation costs of wind turbines to serve Elim is estimated from AEA's 2015 *EvaluationModelREFR9Final (1)* Excel spreadsheet default assumption of $10,897/kW installed wind power capacity. With this assumption, capital cost for economic benefit calculation is $2.18M for a two turbine project.

Fuel Cost

A fuel price of $3.96/gallon was chosen for the initial HOMER analysis by reference to the AEA's 2015 *EvaluationModelREFR9Final (1)* Excel spreadsheet. This price reflects the average estimated fuel price in Elim between the 2018 (the assumed project start year) fuel price of $3.35/gallon and the 2036 (20-year project end year) fuel price of $4.79/gallon using diesel fuel price projection in the spreadsheet. This price projection includes an average CO_2-equivalent allowance cost of $0.67/gallon.

Economic Valuation

HOMER software was used in this wind-diesel analysis to model the wind resource, wind turbine energy production, effect on the diesel engines when operated with wind turbines, and excess wind energy that could be used to serve thermal loads. Although HOMER software is designed to evaluate economic valuation by ranking alternatives, including a base or "do nothing" alternative by net present cost, AEA economic valuation methodology differs in its assumptions of O&M costs, fuel cost for each year of the project life, and disposition of excess energy. Excess energy is valued in the ISER spreadsheet with an assumption that the power plant is not co-generation.   In other words, excess energy is valued without

consideration of possible thermal production loss due to reduced diesel engine loading as would occur in a co-generation system configuration.

In an effort to align economic valuation of project alternatives with Alaska Energy Authority methods, this feasibility analysis uses AEA's economic evaluation methods. The model is updated every July in preparation for the next round of Renewable Energy Fund requests for proposals in the form of an explanation report and an Excel spreadsheet. The latest version of the spreadsheet has a file name of *EvaluationModelREFR9Final (1)* and is available on AEA's website.

Project economic valuation

Site	No. Turbines	Project Cost	NPV Benefits	NPV Costs	B/C ratio	Diesel Fuel Saved (gal/yr)	Heat Oil Saved (gal/yr)	Petroleum Fuel Saved (gal/yr)
		(in $ millions)						
Met Tower	2	2.18	1.84	2.18	0.84	28,306	854	29,160
Airport Hill	2	2.18	2.6	2.18	1.19	33,350	1,638	34,988

Recommendations

Elim has a low-to-moderate wind resource for wind power development, but the new Northern Power Systems NPS100C-24 wind turbine is designed for lower wind class environments and modeling indicates very respectable energy production and turbine capacity factor in Elim, especially on the hill west of the airport. The very cold temperatures of Elim are a bonus due to the performance boost from increased aerodynamic lift across the rotor blades, compared to standard conditions.

Wind turbine site options are limited in Elim and although the met tower site would be a convenient location for wind turbines, the met tower study demonstrated and only marginal wind resource with high turbulence at that location. A preferred wind turbine site would be the hill west of the airport, presuming a new met tower study verifies the presumed 6.0 m/s wind resource, successful FAA obstruction permitting, and project capital costs are reasonable.

Appendix – Elim Wind Resource Assessment Report

Elim met tower, view southwest

Summary

The wind resource measured at the Elim met tower site is wind power Class 2 (marginal) with a mean annual wind speed of 5.12 m/s and a wind power density of 191 W/m^2 at 34 meters above ground level. This validates the AWS Truepower wind resource map which predicts Class 2 to 3 winds at the Elim met tower site.

Met tower data synopsis

Data dates	1/30/2014 to 9/14/2015 (19 months)
Wind speed mean, 34 m, annual	5.12 m/s (11.5 mph)
Wind power density mean, 34 m	191 W/m^2
Max. 10-min wind speed	17.5 m/s (39.1 mph)
Maximum 2-sec. wind gust	25.5 m/s (57.0 mph)
Weibull distribution parameters	k = 1.71, c = 5.54 m/s
Wind shear power law exponent	0.247 (low)
Surface roughness	0.74 meters (urban)
IEC 61400-1, 3rd ed. classification	Class IIIA
Turbulence intensity, mean (at 34 m)	0.145 (at 15 m/s)
Calm wind frequency (at 34 m)	41% (< 4 m/s) (19 mo. measurement period)

Site information

Site number	0054
Latitude/longitude	N 64° 37.290', W 162° 14.530'
Time offset	-9 hours from UTC (Yukon/Alaska time zone)
Site elevation	43 meters (141 ft.)
Datalogger type	NRG SymphoniePLUS3, 10-minute time step
Tower type	Tubular, 15 cm (6 in.) diameter, 34 meter (112 ft.) height

Tower sensor information

Channel	Sensor type	Designation	SN	Height	Boom	Multiplier	Offset	Orientation
1	NRG #40C anemometer	34 m A	219000	34.3 m	183 cm	0.749	0.36	060° T
2	NRG #40C anemometer	34 m B	219010	34.2 m	183 cm	0.754	0.35	340° T
3	NRG #40C anemometer	21 m	219009	21.1 m	183 cm	0.746	0.38	060° T
7	NRG #200P wind vane	Direction		33.0 m	183 cm	0.351	210	030° T
9	NRG #110S Temp C	Temp		2.5 m		0.136	-86.38	North
10	NRG RH5X rel. humidity	RH		2.5 m		0.097	0	
11	Li-Cor LI200 pyranometer	solar	PY 80401	2.5 m		1.368	0	

Tower photographs

North face of met tower
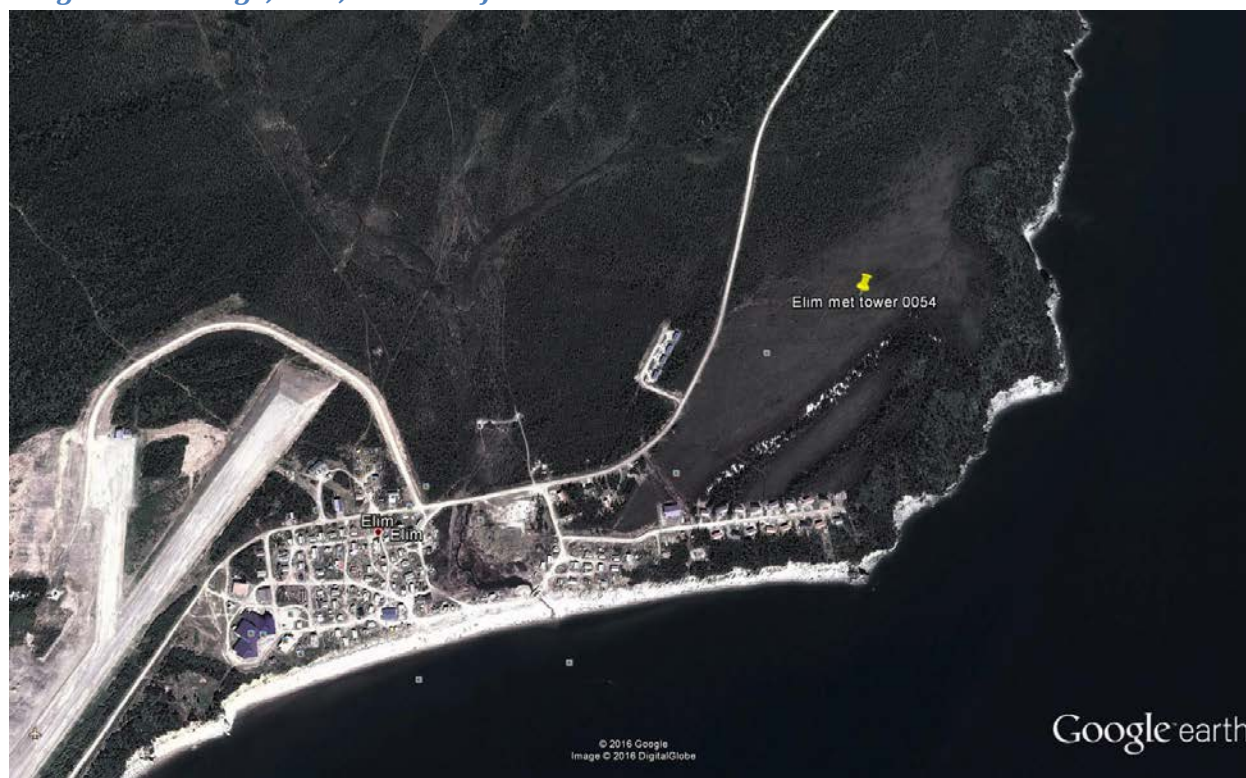

East face of met tower

South face of met tower

West face of met tower

Google Earth image, Elim, location of met tower

Data Quality Control

Data was filtered to remove presumed icing events that yield false zero wind speed data and non-variant wind direction data. Data that meet the following criteria are 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 the 34 meter A and B paired anemometers – data filtered when winds ± 15° from behind tower

Data is also manually filtered for obvious icing that the automatic filter didn't identify, and invalid or low quality data for situations such as logger initialization and other situations.

For the Elim data set, anemometer icing was surprisingly minimal but wind vane icing was quite high with the sensor out-of-service for long periods of time during the mid-winter months. It is unusual to observe so much obvious icing behavior in a wind vane but not in the anemometers.

Sensor data recovery table

Data Column	Possible Records	Valid Records	Recovery Rate (%)	Icing	Invalid	Tower shading
Speed 34 m A	85,156	84,619	99.4%	537	0	0
Speed 34 m B	85,156	84,596	99.3%	555	5	0

Data Column	Possible Records	Valid Records	Recovery Rate (%)	Icing	Invalid	Tower shading
Speed 20 m	85,156	84,608	99.4%	548	0	0
Direction 33 m	85,156	72,648	85.3%	12,508	0	0
Temperature	85,156	85,156	100.0%	0	0	0
Relative humidity	53,902	53,902	100.0%	0	0	0
Pyranometer	85,156	85,156	100.0%	0	0	0

In addition, for paired anemometers, data is normally filtered for tower shadow but the typically distinctive speed ratio dual signature indicating tower shadow was not present, due perhaps to the turbulent air at the site. For this reason, the 34 meter anemometers were not filtered for tower shadow even the different measured mean wind speed indicates that some shadow was present.

Tower shading rose, 34 m anemometers
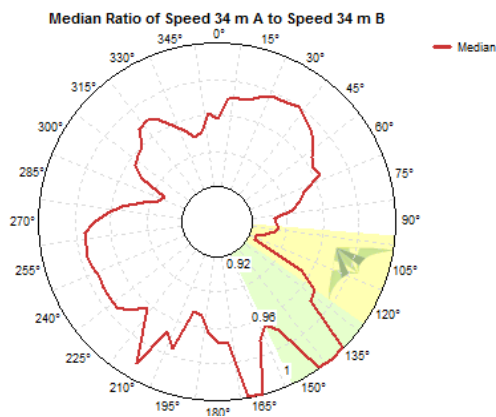
Elim tower shadow rose
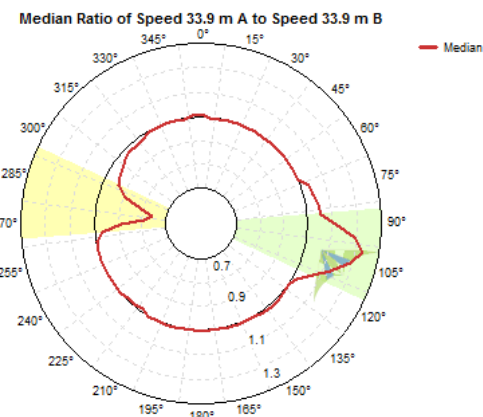
Typical tower shadow rose

Wind Speed

Anemometer data obtained from the met tower, from the perspectives of both mean wind speed and mean wind power density, indicate a marginal wind resource at the met tower site. The table below presents raw and filtered anemometer (icing only) wind speed data.

Anemometer data summary

Variable	Speed 34 m A	Speed 34 m B	Speed 20 m
Measurement height (m)	34.3	34.2	21.1
Raw mean wind speed (m/s)	4.80	4.94	4.25
Filtered mean wind speed (m/s)	4.82	4.97	4.28
MoMM wind speed (m/s)	4.99	5.12	4.41
Max 10-min wind speed (m/s)	17.5	17.4	15.3
Max 2-sec. gust wind speed (m/s)	25.4	25.5	25.3
Weibull k	1.61	1.71	1.57
Weibull c (m/s)	5.34	5.55	4.73
Mean power density (W/m²)	164	172	117
MoMM power density (W/m²)	183	191	130

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| Variable	Speed 34 m A	Speed 34 m B	Speed 20 m
Mean energy content (kWh/m²/yr)	1,434	1,505	1,027
MoMM energy content (kWh/m²/yr)	1,603	1,670	1,141
Energy pattern factor	2.3	2.2	2.3
Frequency of calms (< 4.0 m/s)	44.2	42.5	51.7

MoMM = mean of monthly means (annualized)

Time Series

Time series calculations indicate higher wind speeds during the autumn months compared to the remainder of the year. Interestingly, summer wind speeds are nearly as high as during mid-winter. The daily wind profile (annual basis) indicates relatively even wind speeds throughout the day with slightly higher wind speeds during night hours.

34 m B anemometer data summary

Year	Month	Raw Mean (m/s)	Filtered Mean (m/s)	Max (m/s)	Gust (m/s)	Std. Dev. (m/s)	Weibull K (-)	Weibull c (m/s)
2014	Feb	5.93	6.16	14.1	21.5	2.84	2.24	6.90
2014	Mar	5.72	5.72	15.2	23.5	3.01	1.86	6.37
2014	Apr	5.14	5.13	11.7	16.0	2.37	2.25	5.76
2014	May	4.11	4.11	12.4	14.7	2.23	1.91	4.63
2014	Jun	4.01	4.01	9.7	14.7	2.00	2.10	4.53
2014	Jul	5.18	5.18	16.8	21.5	3.00	1.78	5.82
2014	Aug	4.04	4.04	15.7	20.6	2.17	1.92	4.55
2014	Sep	4.73	4.73	17.1	20.6	2.63	1.86	5.32
2014	Oct	5.92	5.92	17.4	23.5	2.85	2.17	6.67
2014	Nov	5.56	5.68	14.7	22.5	3.49	1.57	6.28
2014	Dec	7.07	7.07	16.2	25.5	3.64	1.95	7.91
2015	Jan	4.88	4.88	16.3	24.5	3.72	1.15	5.07
2015	Feb	6.16	6.55	17.2	23.5	3.60	1.77	7.29
2015	Mar	4.23	4.25	11.5	16.7	2.54	1.55	4.66
2015	Apr	4.48	4.48	12.4	17.4	2.37	1.90	5.02
2015	May	3.35	3.35	12.3	16.0	2.03	1.63	3.72
2015	Jun	4.86	4.86	12.2	19.0	2.46	2.02	5.46
2015	Jul	4.01	4.01	13.1	15.3	1.96	2.12	4.51
2015	Aug	4.98	4.98	16.9	20.6	2.80	1.85	5.61
2015	Sep	4.62	4.62	12.1	16.7	2.47	1.85	5.16
	All Data	4.94	4.97	17.4	25.5	2.92	1.71	5.55
	MoMM	5.09	5.12					

*Monthly time series, mean wind speeds (gap-filled wind data)*
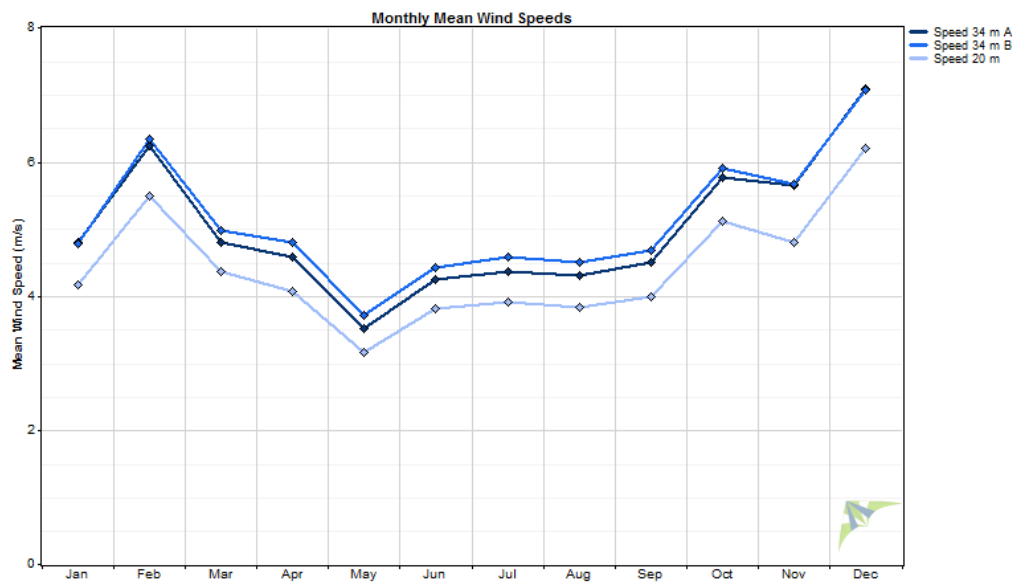
Daily wind profile (all data)
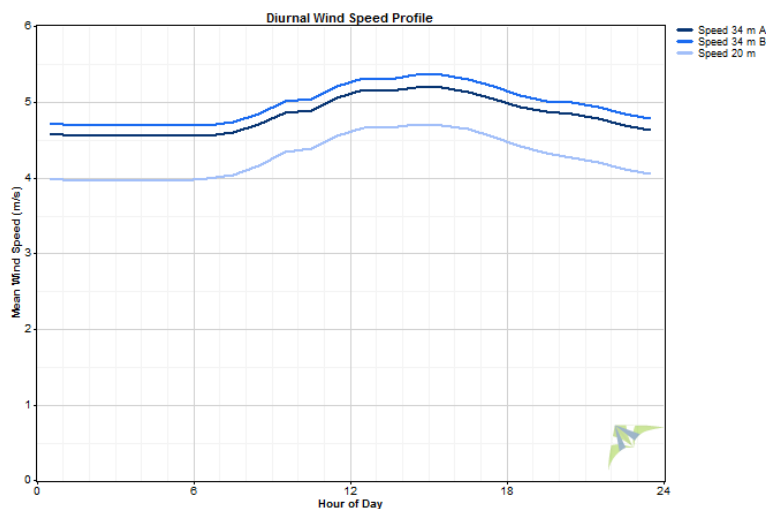
Probability Distribution Function

The probability distribution function (PDF), or histogram, of the Elim met tower site wind speed indicates a shape curve dominated by moderate wind speeds and is somewhat reflective of a "normal" shape curve, known as the Rayleigh distribution (Weibull k = 2.0), which is defined as the standard wind distribution for wind power analysis. As seen below in the wind speed distribution of the 34 meter B anemometer, the most frequently occurring wind speeds are between 3.0 and 6.0 m/s with no 10-minute average wind events exceeding 20 m/s (note that the cutout speed of most wind turbines is 25 m/s; see following Occurrence by wind speed bin table).

PDF of 34 m B anemometer (all data)
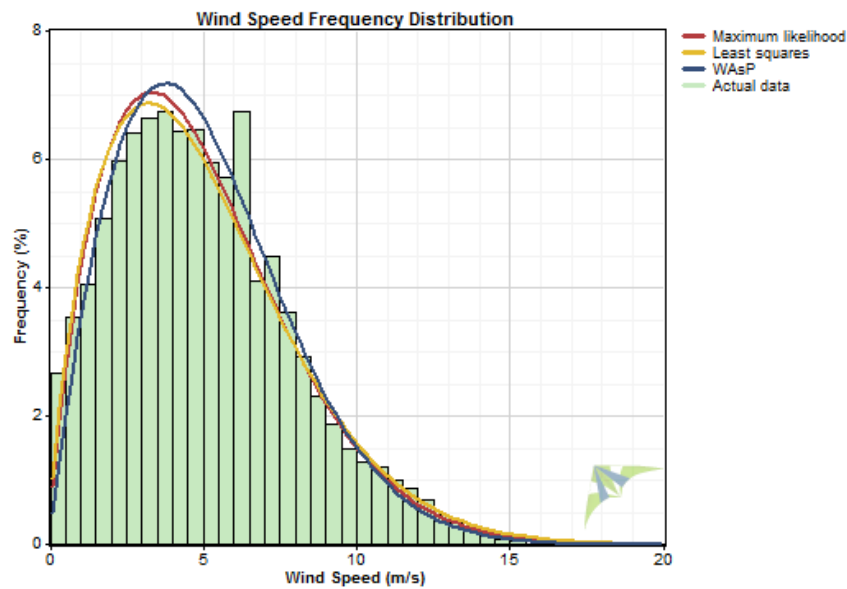
Comparative Weibull k shape curve table
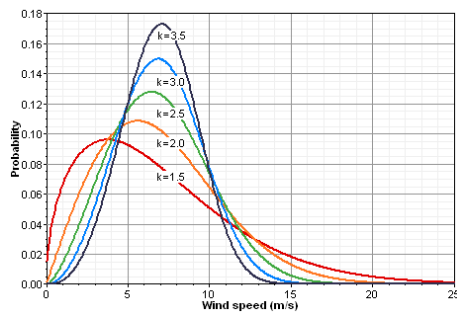

Weibull values table, 34m B anemometer

Algorithm	Weibull k (-)	Weibull c (m/s)	Mean (m/s)	Proportion Above 7.985 m/s	Power Density (W/m2)	R Squared (-)
Maximum likelihood	1.71	5.55	4.95	0.436	169	0.960
Least squares	1.66	5.61	5.01	0.441	182	0.961
WAsP	1.86	5.69	5.05	0.459	163	0.953
Actual data	(84,596 time steps)		4.97	0.459	163	

Occurrence by wind speed bin (34 m B anemometer)

Bin Endpoints (m/s) Lower	Upper	Occurrences No.	Percent	Cumu-lative Percent	Bin Endpoints (m/s) Lower	Upper	Occurrences No.	Percent	Cumu-lative Percent
0	1	5274	6.23%	6.2%	9	10	2862	3.38%	93.5%
1	2	7737	9.15%	15.4%	10	11	2129	2.52%	96.0%
2	3	10488	12.40%	27.8%	11	12	1612	1.91%	97.9%
3	4	11354	13.42%	41.2%	12	13	984	1.16%	99.0%

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Bin Endpoints (m/s)		Occurrences		Cumu- lative	Bin Endpoints (m/s)		Occurrences		Cumu- lative
Lower	Upper	No.	Percent	Percent	Lower	Upper	No.	Percent	Percent
4	5	10928	12.92%	54.1%	13	14	502	0.59%	99.6%
5	6	9907	11.71%	65.8%	14	15	213	0.25%	99.9%
6	7	9199	10.87%	76.7%	15	16	70	0.08%	100.0%
7	8	6868	8.12%	84.8%	16	17	21	0.02%	100.0%
8	9	4444	5.25%	90.1%	17	18	4	0.00%	100.0%

Cumulative distribution function
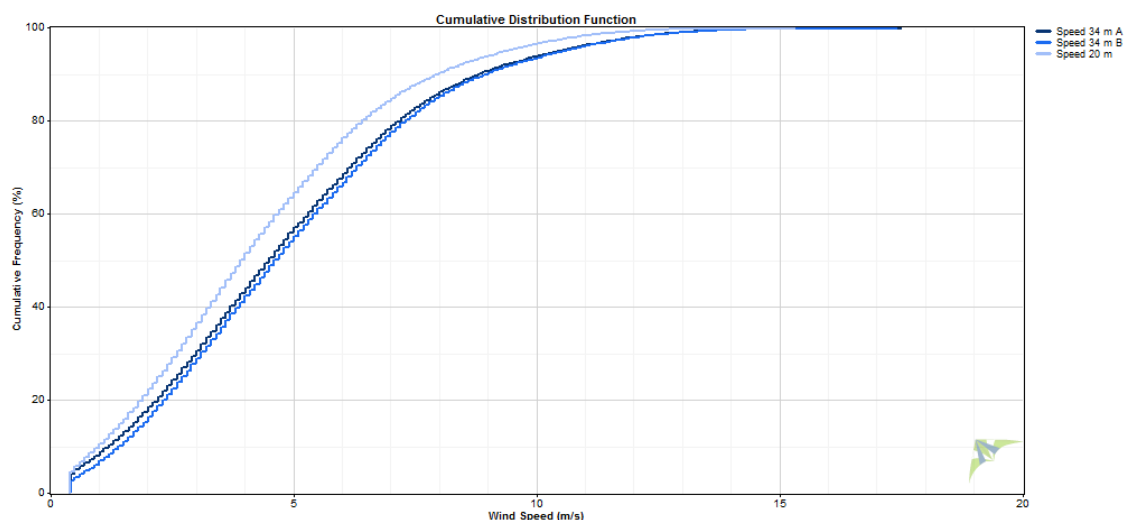
Wind Direction

Wind frequency rose data indicates that wind at the Elim met tower site is primarily bi-directional, with northeasterly and southwesterly winds predominating. The mean value rose indicates that both northeasterly and southwesterly winds are of relatively high intensity winds, but with more frequent northeasterly winds, the dominant energy winds are from that direction.

Calm frequency, the percent of time that winds at the 34-meter level are less than 4 m/s, a typical cut-in speed of larger wind turbines, was a high 41 percent during the 19-month test period.

Note that the wind rose measured at the met tower site correlates fairly well with that observed by the automated weather station at the nearby Elim Airport, although airport winds are more northerly. This is a curious anomaly, but AWS Truepower wind data validates the met tower site wind rose of prevailing northeasterly winds.

Wind frequency rose
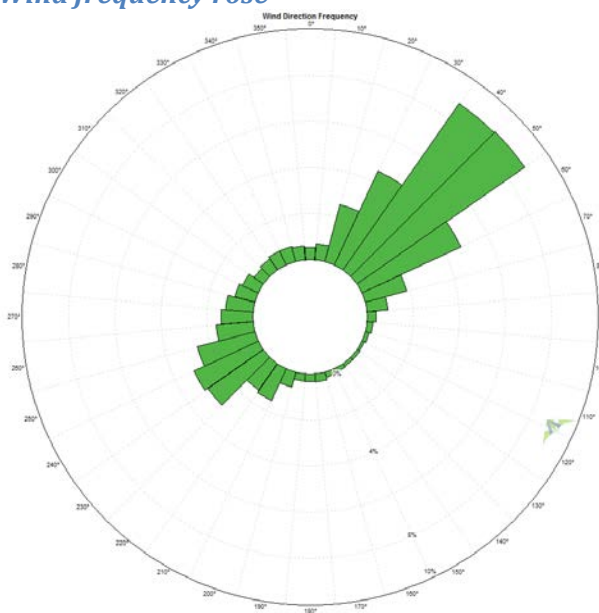
Mean value rose
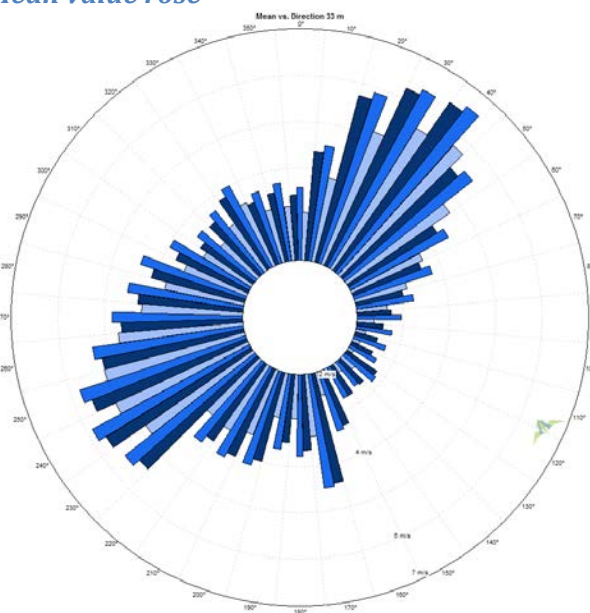
## *Wind energy rose*
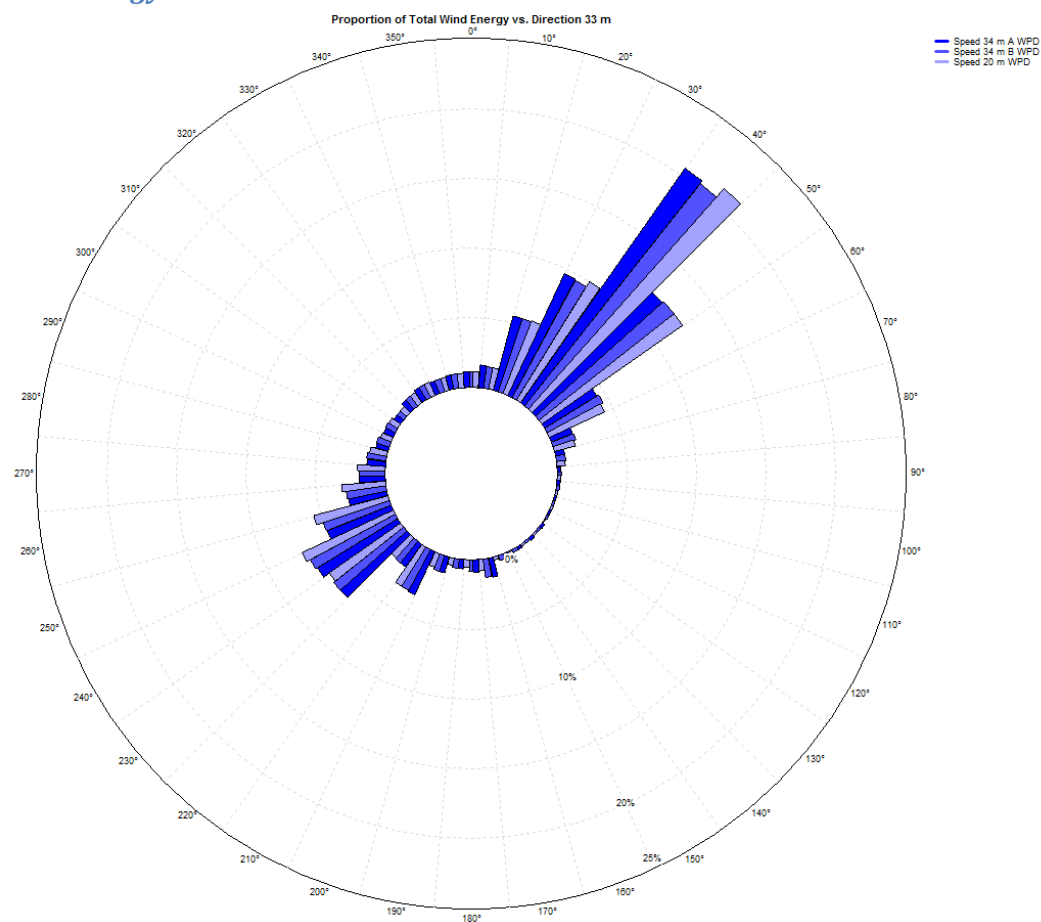
*Elim Airport wind frequency rose*
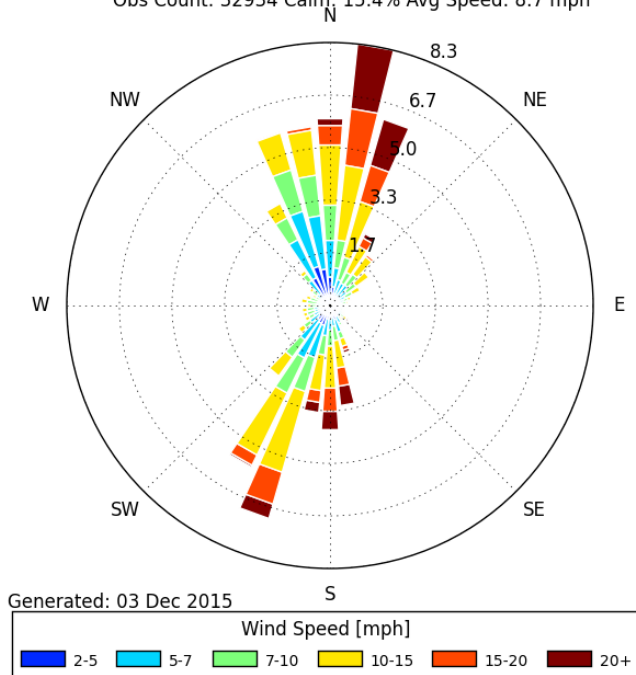
Wind Shear and Roughness

Wind shear at the Elim met tower site was calculated with the 34 m A and 20 m anemometers, both of which were oriented east-northeast. The calculated power law exponent of 0.247 indicates high wind shear at the site. The calculated surface roughness at the site is 0.74 m (the height above ground where wind speed would be zero) for a roughness class of 3.66 (description: large city with tall buildings). Clearly the dense trees to the north of the site dramatically affected the wind shear profile.

Vertical wind shear profile
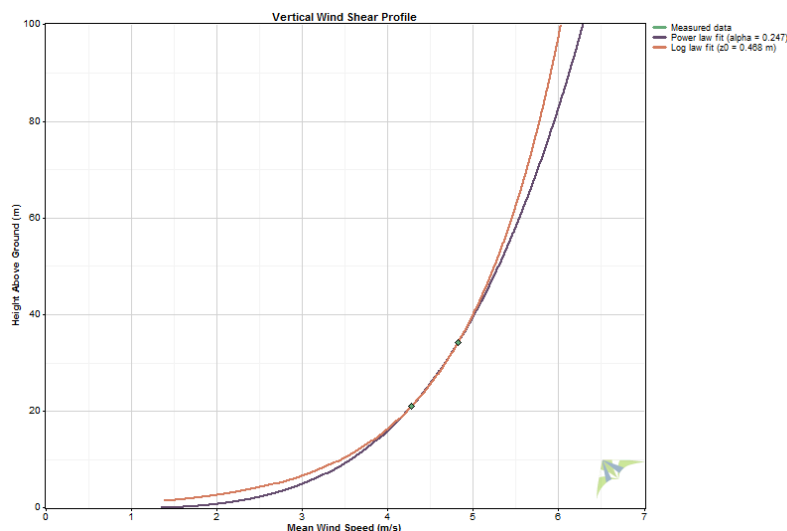
## Wind shear by direction sector graph
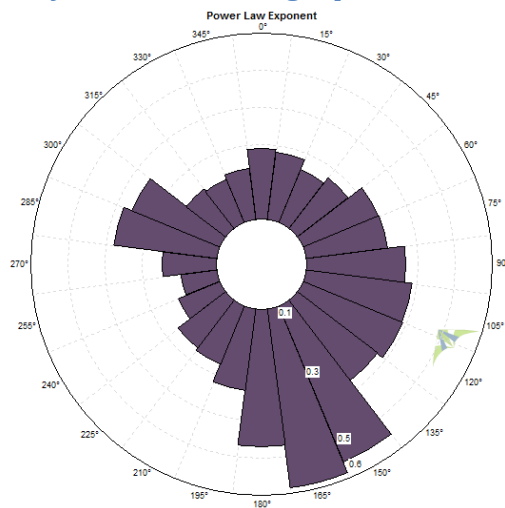
Extreme Winds

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 instead of annual maximum winds. Nineteen months of data however are minimal at best and hence results should be viewed with caution. Nevertheless, with data available the predicted Vref in a 50 year return period (in other words, predicted to occur once every 50 years) by this method is 24.3 m/s. This easily classifies Elim as Class III by International Electrotechnical Commission 61400-1, 3rd edition (IEC3) criteria.

Site extreme wind probability table, 34 m B data

| Period (years)	V_{ref} (m/s)	Gust (m/s)	IEC 61400-1, 3rd ed. Class	V_{ref}, m/s
3	18.5	25.7	I	50.0
10	21.4	29.7	II	42.5
20	22.1	30.7	III	37.5
30	23.4	32.4	S	designer-specified
50	24.3	33.7		
100	25.5	35.4		
average gust factor:	1.39			

A second technique to calculate extreme wind probability, Method of Independent Storms, yields a similar calculation of (50 year return period) V_{ref} = 19.4 m/s.

Method of Independent Storms
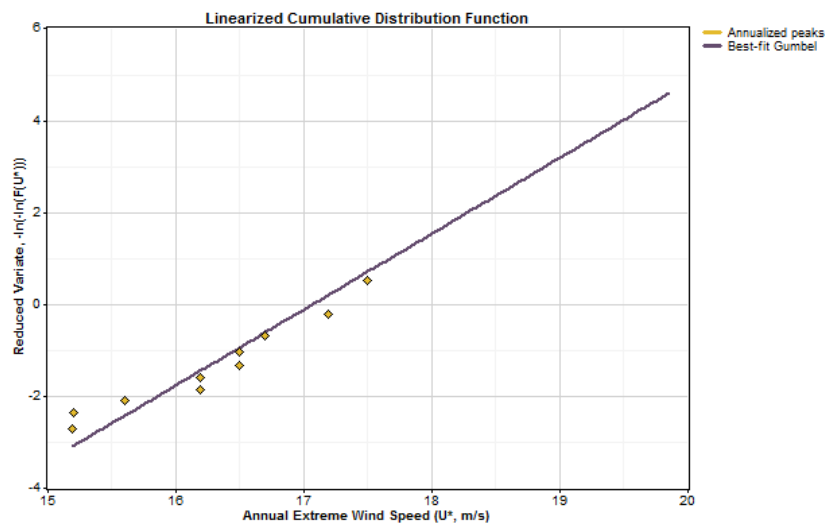
A third method, referred to as EWTS II (European Wind Turbine Standards II) ignores recorded peak wind speeds and calculates V_{ref} from the Weibull k factor. There are three variations of this method – exact, Gumbel and Davenport – and for the Elim wind data V_{ref} is calculated between 27.7 and 30.0 m/s.

EWTS II plot
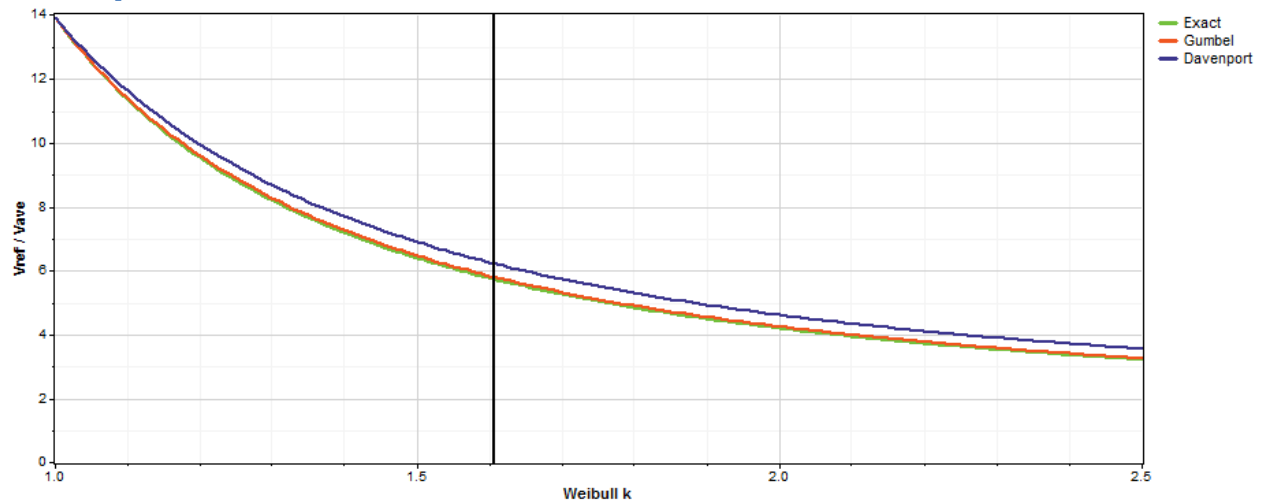
Note that IEC extreme wind probability classification is one criteria – with turbulence the other – that describes a site with respect to suitability for particular wind turbine models. Note that the IEC3 Class III extreme wind classification indicates low potential for damaging winds and that turbines installed at this location can be rated as IEC3 Class III.
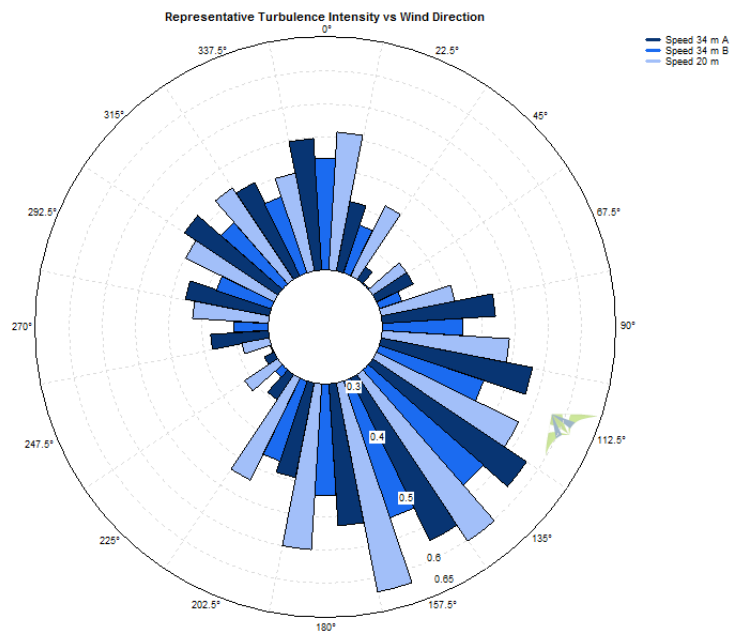
Turbulence

The turbulence intensity (TI) at the Elim met tower site is quite high with a mean turbulence intensity of 0.15 and a representative turbulence intensity of 0.18 at 15 m/s wind speed, indicating turbulent air for

wind turbine operations. This equates to an International Electrotechnical Commission (IEC) 61400-1, 3rd Edition (2005) turbulence category A to B, which is the top and middle defined categories.

Turbulence table, wind speeds > 4 m/s

| Wind Speed Sensor	Height (m)	All Speed Bins				15 m/s Speed Bin				IEC 3 ed. Turbulence Category
		Mean TI	Standard Deviation of TI	Repres. TI	Peak TI	Data Points	Mean TI	Standard Deviation of TI	Repres. TI	
Speed 34 m A	34.3 m	0.16	0.040	0.22	0.64	109	0.15	0.031	0.18	A
Speed 34 m B	34.2 m	0.16	0.040	0.21	0.63	135	0.14	0.031	0.18	B
Speed 20 m	21.1 m	0.18	0.050	0.24	0.71	11	0.15	0.029	0.19	A

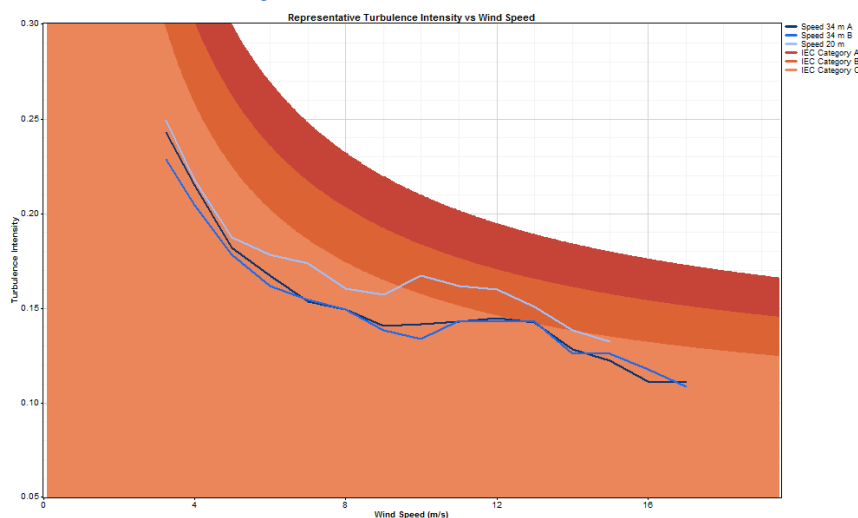### *Turbulence rose*

Turbulence intensity, all direction sectors
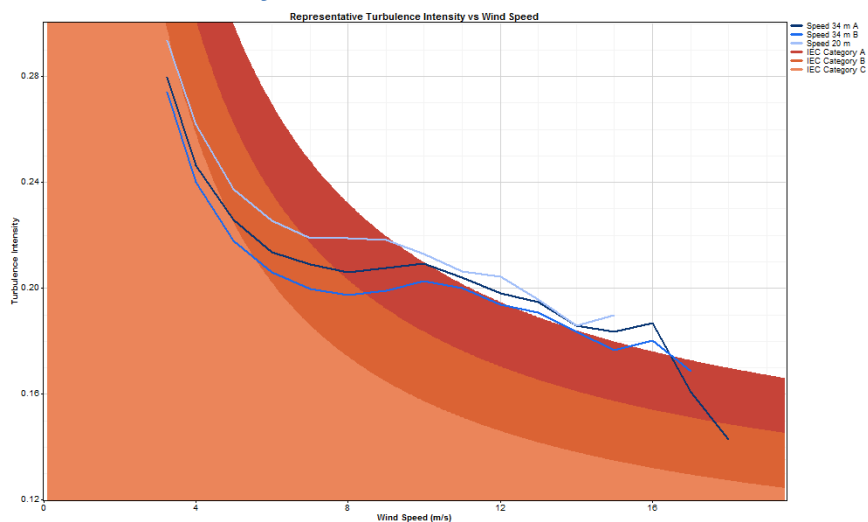
Turbulence intensity, 22.5° to 67.5° True
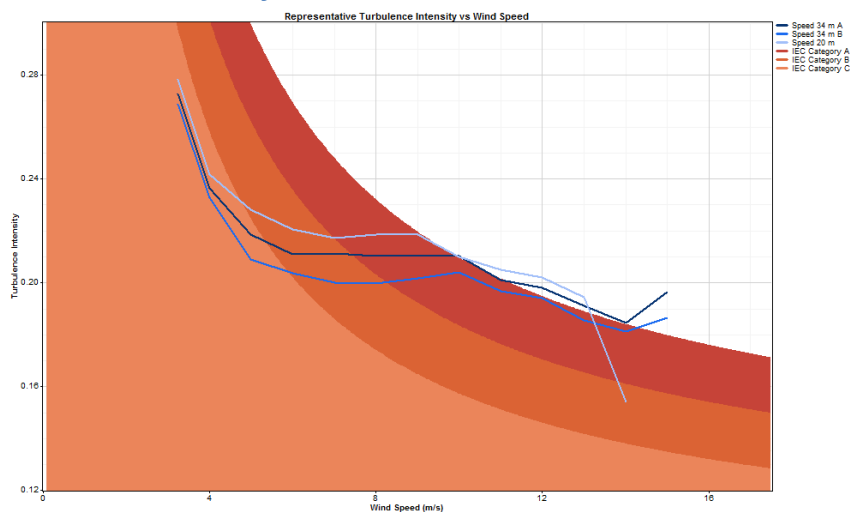
Turbulence intensity, 225° to 255° True

# Temperature, Density, and Relative Humidity

Elim experiences warm summers and cold winters. Calculated mean air density of 1.285 kg/m³ exceeds the 1.219 kg/m³ standard air density for 43-meter elevation by 5.4 percent. This is advantageous in wind power operations as wind turbines produce more power at low temperatures (high air density) than at standard temperature and density.

Temperature and density table

Month	Temp Mean (°C)	Min (°C)	Max (°C)	Temp Mean (°F)	Min (°F)	Max (°F)	Density Mean (kg/m3)	Min (kg/m3)	Max (kg/m3)
Jan	-11.7	-31.1	2.6	10.9	-24.0	36.7	1.344	1.272	1.451
Feb	-9.4	-27.9	4.9	15.1	-18.2	40.8	1.331	1.261	1.431
Mar	-11.3	-32.0	5.8	11.7	-25.6	42.4	1.341	1.257	1.456

| Month	Temp			Temp			Density		
	Mean (°C)	Min (°C)	Max (°C)	Mean (°F)	Min (°F)	Max (°F)	Mean (kg/m3)	Min (kg/m3)	Max (kg/m3)
Apr	-2.6	-21.8	13.1	27.3	-7.2	55.6	1.297	1.223	1.397
May	5.5	-5.0	23.2	41.9	23.0	73.8	1.258	1.181	1.308
Jun	10.7	-2.4	28.1	51.3	27.7	82.6	1.234	1.160	1.296
Jul	13.2	1.6	26.5	55.8	34.9	79.7	1.222	1.164	1.276
Aug	12.2	-1.6	25.2	54.0	29.1	77.4	1.227	1.170	1.291
Sep	8.0	-2.3	17.3	46.4	27.9	63.1	1.245	1.204	1.294
Oct	-1.5	-11.1	9.3	29.3	12.0	48.7	1.290	1.239	1.339
Nov	-4.2	-18.8	6.0	24.4	-1.8	42.8	1.304	1.254	1.380
Dec	-9.0	-21.8	4.0	15.8	-7.2	39.2	1.328	1.264	1.396
Annual	0.0	-32.0	28.1	32.0	-25.6	82.6	1.285	1.160	1.456

Elim temperature boxplot graph
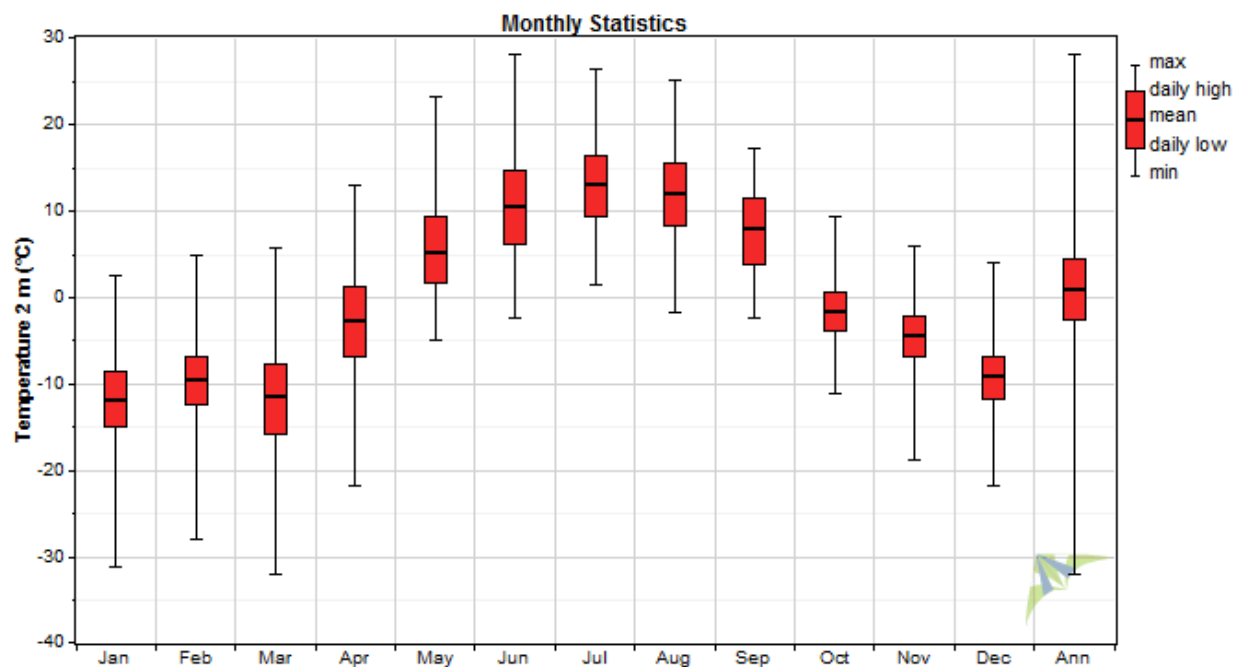
Wind Speed Scatterplot

The wind speed versus temperature scatterplot of the Elim met tower data indicates a fairly even distribution of wind speeds at temperatures between approximately -25° C and 20° C. Color coding of the scatterplot indicates that northeasterly winds tend to be cold (below freezing) and southwesterly winds tend to be warm (near or above freezing).

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Wind speed/temperature (color code indicates wind direction)
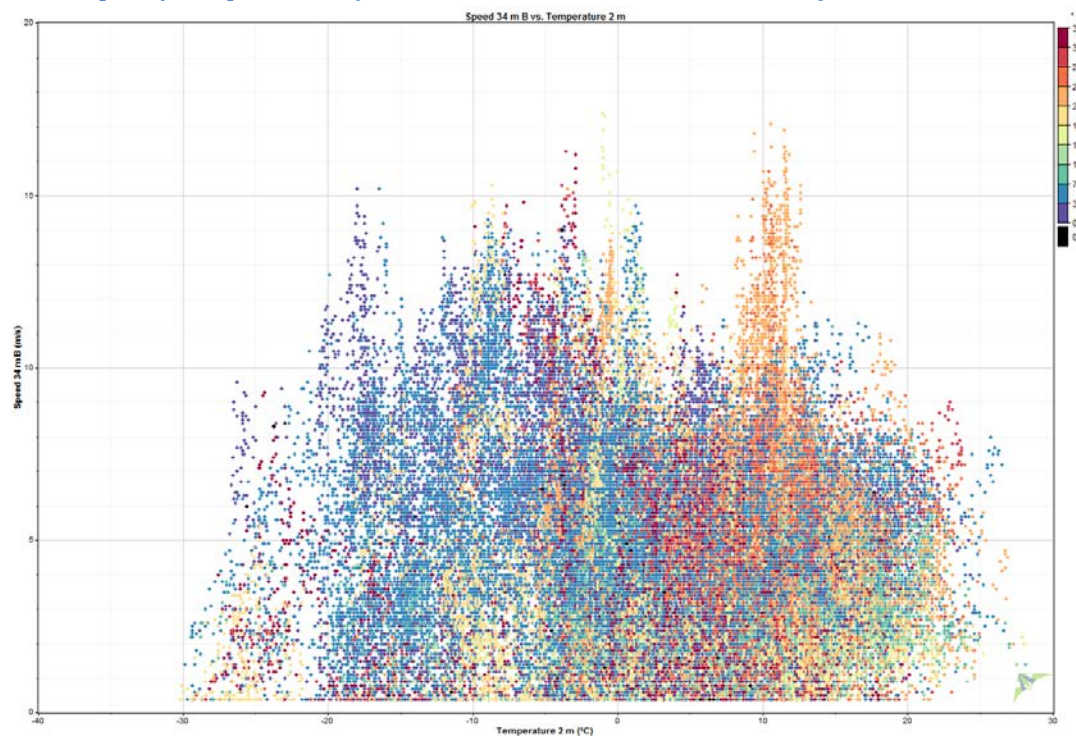
Solar Resource

The met tower was equipped with a pyranometer to measure the solar resource. Note in the Dmap below that local apparent noon occurs at about 2:00 p.m. This is due to the unusual nature of the Alaska time zone where western Alaska especially is significantly displaced from standard time zone positioning. Also note the near 24 hours of daylight at summer solstice in June and the very low light levels at winter solstice in December.

Pyranometer Dmap