Exh. DCG-7C
Dockets UE-170033/UG-170034
Witness: David C. Gomez
REDACTED VERSION

BEFORE THE WASHINGTON
UTILITIES AND TRANSPORTATION COMMISSION

WASHINGTON UTILITIES AND TRANSPORTATION COMMISSION, **Complainant,** **v.** **PUGET SOUND ENERGY,** **Respondent.**	**DOCKETS UE-170033 and UG-170034 (*Consolidated*)**

EXHIBIT TO
TESTIMONY OF

David C. Gomez

STAFF OF
WASHINGTON UTILITIES AND
TRANSPORTATION COMMISSION

PSE's Response to Staff DR No. 176, Attachments C through F, Vaisala Operational Reforecasts

CONFIDENTIAL PER PROTECTIVE ORDER – REDACTED VERSION

Vaisala 3TIER Services Operational Reforecast

PROJECT

Wild Horse : Kittitas County, Washington

using 127 Vestas V80-1.8MW wind turbines at $67\,m$

FOR

Puget Sound Energy

DATE

8 October, 2016

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1 INTRODUCTION

Vaisala has been retained by Puget Sound Energy to provide an operational reforecast for the Wild Horse wind farm, which is located in Kittitas County, Washington. This project is comprised of 127 Vestas V80-1.8MW turbines for a total project capacity of 228.6 MW.

The operational reforecast is an independent assessment of the future production of an operating project based on the historical production data and the climate. It considers the variability of the climate and the observed production data, including generation and availability data, as reported by the project. Vaisala offers two different Operational Reforecast products: a comprehensive analysis that quality controls the 10-minute SCADA data on a turbine specific basis, and a higher level analysis that relies solely on the monthly-mean operating reports of the project.

Since only monthly-mean production data are considered in this analysis, any potential turbine performance issues in the net metered generation data will be transferred into the operational reforecast process. In essence, it is a simulation of the future assuming the plant performs as it has in the past, making adjustments if it is known that operating conditions are expected to change from the past.

Assuming the plant continues to operate as it has in the past, the operational reforecast yields an estimated long-term potential net energy value of [redacted] GWh. Potential net energy refers to the energy the wind farm would produce if the total site availability is 100% and the curtailment loss is 0%. Total site availability includes machine availability, grid availability, and BOP availability.

For this analysis, results will be shown only in terms of potential net energy. The client will need to apply availability and curtailment losses to determine the expected net energy generation of the Wild Horse wind farm.

Project Size	228.6 MW
Number of Turbines	127
Turbine Type	Vestas V80-1.8MW
Hub Height	67 m
Potential Net Energy Generation	[redacted] GWh
Net Energy Generation	–
Aggregate Loss Factor	[redacted] %
Standard Error of 20-year Estimate	[redacted] %

Table 1: Project Overview

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2 PROJECT DESCRIPTION

The Wild Horse project is located in Kittitas County, Washington. The project is comprised of 127 Vestas V80-1.8MW turbines at $67\,m$ hub height for a total project capacity of $228.6\,MW$. The wind farm has been operating since January 2007.

The location of the Wild Horse wind farm is shown below in Figure 1.

Figure 1: Map of the Wild Horse project region.

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3 METHODOLOGY

To estimate the future net production values, the following two input data sources are utilized: historic production data, including generation and availability data, and 36 years of Numerical Weather Prediction (NWP) model data. Statistical corrections are applied to the normalized production data, based on a simulated climate index, in order to generate a long-term time series of estimated production values. The historic long-term production provides the basis for estimating future production. An outline of the basic approach follows:

- Production, availability and curtailment data are reviewed for quality and usefulness.
- Normalized production data, i.e. potential net energy data, are created by normalizing the net meter generation data to 100% site availability.
- Long-term climate variability is analyzed to determine an appropriate start date for each of 3 independent reanalysis data sets, assuming each has long-term characteristics consistent with the region.
- Utilizing the Weather Research and Forecasting Model (WRF), reanalysis data are downscaled to a $15\,km$ horizontal resolution.
- Time series data of air density and hub height wind speed are extracted from the WRF data set at a centrally located grid point within the project.
- The time series of hub height wind speeds are corrected to on-site conditions using on-site wind resource measurement data, if available.
- An air density corrected project power curve is used to convert the individual reanalysis-based time series to power. Power values are further scaled to expected long-term generation before aggregating by month. These monthly simulated production time series become climate power indices.
- Monthly observed normalized production data are adjusted for the long-term by applying the ratio of the long-term mean monthly profile derived from the 36 years of simulated data against the monthly profile derived over the short-term operational production period.
- The independent long-term estimates are then weighted by respective coefficients of determination; comparing monthly observed production against the simulated power indices.
- Historic trends of availability and curtailment data are analyzed to determine expected future trends. Turbine availability and curtailments are normalized out of the data set when applying the long-term correction factor. The expected future availability and curtailment are added back as loss factors when computing the reforecasted long-term mean net energy estimate.
- Uncertainty analysis is performed to develop the probability of exceedance values (P75, P90, etc.) of expected net energy generation.

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4 DATA VERIFICATION

4.1 On-site Resource Data

For operational projects where stand-alone met towers are waked by operating turbines, a broadly applicable view of the site's wind resource can be determined from the nacelle anemometers in the project. A project average time series of wind speed is determined by averaging the 10-min wind speed readings from every turbine in the project. The averaged time series is interpreted as a point reading at the arithmetic average of the latitude and longitude coordinates of all turbines. The nacelle wind resource time series is then used to validate and correct the raw NWP model data using a process of Model Output Statistics (MOS) correction. MOS uses regression equations to remove bias and adjust the variance of the raw model output to improve the match with the provided observational data. Nacelle wind resource measurement data were provided by the client during the period February 2014 through May 2016.

4.2 Operating Results Summary

A summary of historical park performance over the period January 2007 through June 2016 was provided by the client. The data included monthly generation data and various availability statistics. Specifically relevant for this analysis are the net generation, turbine and grid availability data, and curtailment values. The total site availability factor is calculated inclusive of the following: machine availability, balance of plant availability, and grid availability. Project curtailment is computed as the sum of the environmental curtailment and grid curtailment. Potential net energy generation is then derived by dividing the net metered generation data by the total site availability factor and then adding the total project curtailment. The result is a time series representative of the project with 100% availability and no curtailment.

Project generation data, turbine and grid availability data, curtailment data, and potential net generation data utilized by Vaisala are shown below in Table 2. Newly constructed wind farms typically have a break-in period during which availability, and potentially turbine performance, is lower than what would typically be seen over the long-term. This period often takes place during the first year of operations. When multiple years of operating data are provided, Vaisala identifies this initial stabilization period and removes it from the analysis, so that these data do not bias the long-term adjustment. No explicit stabilization period is visible in the early record. Six months of data have not been considered in the analysis because of low grid availability.

Operational generation data over the period January 2007 through December 2015 are used in the analysis. Months with relatively low total site availability values are not incorporated into the analysis, and so a potential net generation value is not computed for these months.

Date	Net Metered Generation (MWh)	Total Plant Availability (%)	Curtailment (MWh)	Potential Net Generation (MWh)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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Table 2: Observed net metered generation, plant availability, curtailment, and potential net generation data for Wild Horse. (continued on next page)

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Date	Net Metered Generation (MWh)	Total Plant Availability (%)	Curtailment (MWh)	Potential Net Generation (MWh)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 2: Observed net metered generation, plant availability, curtailment, and potential net generation data for Wild Horse. (continued on next page)

REDACTED VERSION

REDACTED VERSION

Date	Net Metered Generation (MWh)	Total Plant Availability (%)	Curtailment (MWh)	Potential Net Generation (MWh)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 2: Observed net metered generation, plant availability, curtailment, and potential net generation data for Wild Horse. Months with relatively low total site availability are not incorporated into the analysis and potential net generation is not computed. For these months the potential net generation data are shown as missing values.

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5 CLIMATE REVIEW

In order to place the production data into the climatological context, Vaisala performed a review of several long-term climate data sources. Vaisala primarily relies on global reanalysis data sets for understanding the long-term climate variability. The reanalysis data sets are derived from thousands of global observations, including ground-based weather stations, ocean surface buoys, satellites, and weather balloons. Vaisala uses three major reanalysis data sets that are each produced independently by different institutions. The data sets reviewed for this analysis are shown below in Table 3.

Data Set	Explained Variance (R^2)	Start Year	End Year
ECMWF ERA-I	[redacted]	1980	2015
MERRA	[redacted]	1981	2015
NCEP/NCAR	[redacted]	1988	2015

Table 3: Monthly explained variance with production data and reference period utilized for each reanalysis data set.

Vaisala considers each reanalysis data set when assessing the long-term climate and results using each data set are weighted by their correlation to observed project performance. Figure 2 shows the annual-mean wind speed values extracted from each reanalysis data set across the period of record. The reference period for each data set is optimized by taking into consideration how representative the entire record is of the recent climate at the site. The utilized reference period and correlation with observed project performance for each reanalysis data set is provided in Table 3.

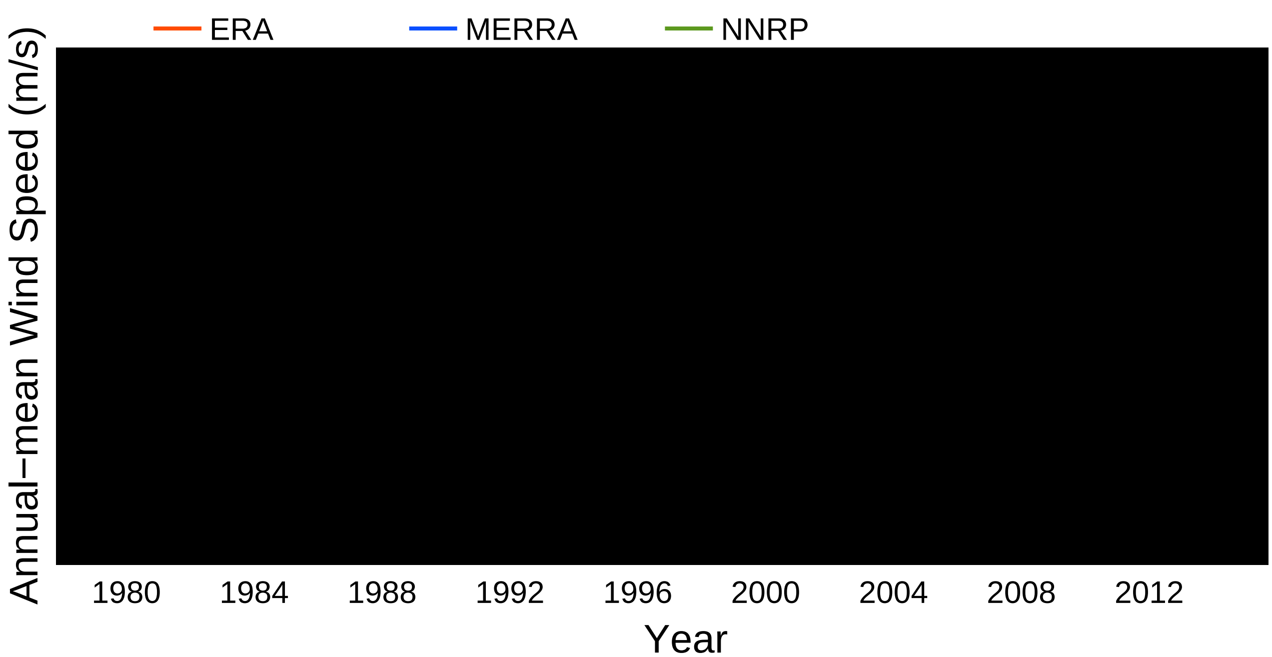

Figure 2: Annual-mean time series plot of considered reanalysis data sets.

6 REFORECAST RESULTS

The 113 months of utilized normalized observed production are independently indexed against the 36 years of simulated power from each reanalysis data set. Concurrent months are binned by calendar month to arrive at a short-term monthly average for both the normalized production data and the three sets of simulated data. The ratio of monthly long-term energy over the short-term (observed) energy from a reanalysis data set is used as an adjustment factor for each mean calendar month for the observed, normalized production data and then annualized for a long-term annual-mean generation. The three independent long-term estimates are combined by weighting each value against the coefficient of determination between the 113 months of observed, normalized production data, and respective reanalysis power data set.

This analysis is presenting results only in terms of the potential net energy generation, and thus is not considering the availability or curtailment loss factors. The long-term mean potential net energy generation estimate for the Wild Horse wind farm is estimated to be [redacted] *GWh*.

	Wildhorse
Potential Net Energy Generation (GWh)	[redacted]
Nameplate Capacity (MW)	228.6
Loss Factors	
Total Site Availability	[redacted] %
Curtailment	[redacted] %
Aggregate Loss Factor	[redacted] %
Net Energy Generation (GWh)	–

Table 4: Net energy generation results.

6.1 Long-term Variability

The long-term variability of the simulated potential net energy is shown within this section. Figure 3 shows the long-term mean seasonality via a box-and-whisker plot of the monthly-mean potential net energy data. The shaded boxes are bounded by the P25 and P75 values for each month, and the whiskers denote the minimum and maximum values. The median for each month is denote by the black line within the shaded box. Table 5 shows the numerical values plotted within Figure 3.

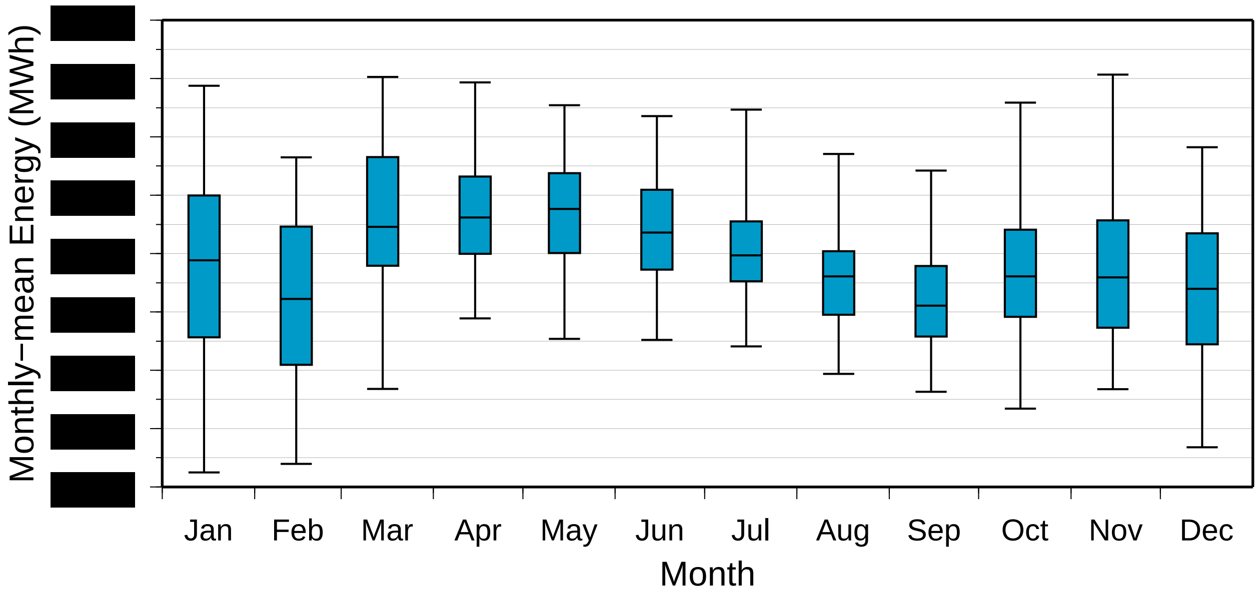

Figure 3: Box-and-whisker plot of monthly-mean simulated potential net energy. This figure displays the expected variability of the monthly-mean data. Median values are denoted by the solid line within each shaded box. Upper and lower boundaries of the shaded box correspond to the 75% and 25% quartiles, while the whiskers denote the maximum and minimum monthly-mean potential net energy values.

	Minimum	P75	Median	P25	Maximum
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 5: Minimum, P75, median, P25, and maximum potential net energy values (MWh) for each calendar month.

6.2 Seasonal Profile

The operational reforecast of the Wild Horse annual profile is detailed in this section. Because the reforecast methodology is indexed against individual calendar months, the operational reforecast can illuminate the project's annual profile. Table 6 shows the annual profile in terms of the potential net energy for Wild Horse.

	Potential Net Energy Generation (MWh)	% of Annual Production
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
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Table 6: Long-term monthly-mean estimates of potential net energy (MWh) and % of annual production.

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7 UNCERTAINTY ANALYSIS

The following types of uncertainty are analyzed and incorporated into the analysis: production normalization, climate variability, and model uncertainty.

7.1 Production Normalization Uncertainty

The production normalization uncertainty covers the uncertainty associated with adjusting the net production data for plant availability and curtailment. The long-term analysis is based on the potential power production data, i.e. the production data normalized by the plant availability and curtailment. The uncertainty of the potential power production data is directly related to the plant availability and curtailment, since the potential production values are unknown during periods when the wind plant was not available for producing power. Thus, lower plant availability leads to higher production data uncertainty. In addition, this also covers the uncertainties associated with future changes to turbine efficiencies and availabilities.

7.2 Climate Variability Uncertainty

The climate variability includes two components: temporal variation and future changes in climate.

Temporal uncertainty is based on the inter-annual variability (standard deviation) of the annual-mean energy-based NWP time series corresponding long-term means. It is assumed that each year of the annual-mean potential power time series is independent from the next.

Future changes in climate includes the possibility of future climate varying from the historic climate. Climate change is associated with potential shifts in the climate over the next twenty years. Change in the climate may have positive or negative impacts to the production data. The magnitude of climate change uncertainty is based on how the most recent five years of data compares to the prior long-term record. Based on these factors, a climate change uncertainty value is assessed.

7.3 Model Uncertainty

The model uncertainty describes the uncertainty associated with estimating the long-term MOS-corrected potential net generation time series. The model uncertainty is derived from four components: the quality of the production data, the period of record of the production data, the error of the MOS-corrected data during the production period, and the sensitivity of the MOS calculation.

The uncertainty associated with the quality of the production data is a function of the averaging period of the generation data incorporated into the analysis. Generally speaking, using data with a longer averaging period will increase this uncertainty, e.g. monthly generation data will have higher uncertainty than 10-minute SCADA data.

Based on prior split-sample validation analyses performed by Vaisala, it is known that the uncertainty of the MOS algorithm decreases as the period of the training data increases. Therefore, the training period component of the model uncertainty is determined by the length of record of the production data. To understand the error of the MOS calculation, the root mean squared error (RMSE) is computed between the monthly-mean MOS-corrected data and the observed production data over concurrent time periods. And lastly, the sensitivity component of model uncertainty is derived by computing multiple iterations of MOS, using perturbed input data, and computing the standard deviation of error across the resulting time series. The four components of model uncertainty are statistically aggregated together yielding the total model uncertainty for a 20-year return period.

7.4 Pooled Uncertainty

A quadratic sum is computed of the individual uncertainty values described above to derive the total uncertainty value for the Wild Horse Wind Farm. Table 7 summarizes these calculations.

Project Uncertainty	1-year	5-year	10-year	20-year
Production Normalization	[redacted]	[redacted]	[redacted]	[redacted]
Climate Variability	[redacted]	[redacted]	[redacted]	[redacted]
Model	[redacted]	[redacted]	[redacted]	[redacted]
Total Uncertainty	[redacted]	[redacted]	[redacted]	[redacted]

Table 7: Standard error of future production estimate (%) at Wild Horse.

7.5 Probability of Exceedances

Based on the estimated total project uncertainties, Table 8 presents the probability of exceedance levels associated with the P50 project estimate for the 1-year, 5-year, 10-year, and 20-year cases.

P-level	1-year	5-year	10-year	20-year
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 8: Probability of exceedance values (GWh) at Wild Horse.

8 CONCLUSION

Vaisala has conducted an operational reforecast of the Wild Horse wind farm within Kittitas County, Washington. The reforecast is based on the client provided historical monthly summaries of production, availability, and curtailment data in combination with Vaisala's long-term NWP model data. A power index derived from three NWP model simulations driven by independent reanalysis data sets was utilized to adjust the normalized production data for the long-term. The expected long-term mean potential net annual energy production value, i.e. the net P50, is estimated to be [redacted] GWh. Using the uncertainty assessment results, probability of exceedance values were calculated. The 20-year P90 potential net energy value for the Wild Horse project is [redacted] GWh.

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Vaisala 3TIER Services Operational Reforecast

PROJECT

Whiskey Ridge : Kittitas County, Washington

using 22 Vestas V80-2.0MW wind turbines at 67 m

FOR

Puget Sound Energy

DATE

7 October, 2016

CONTACT

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1 INTRODUCTION

Vaisala has been retained by Puget Sound Energy to provide an operational reforecast for the Whiskey Ridge wind farm, which is located in Kittitas County, Washington. This project is comprised of 22 Vestas V80-2.0MW turbines for a total project capacity of $44.0\,MW$.

The operational reforecast is an independent assessment of the future production of an operating project based on the historical production data and the climate. It considers the variability of the climate and the observed production data, including generation and availability data, as reported by the project. Vaisala offers two different Operational Reforecast products: a comprehensive analysis that quality controls the 10-minute SCADA data on a turbine specific basis, and a higher level analysis that relies solely on the monthly-mean operating reports of the project.

Since only monthly-mean production data are considered in this analysis, any potential turbine performance issues in the net metered generation data will be transferred into the operational reforecast process. In essence, it is a simulation of the future assuming the plant performs as it has in the past, making adjustments if it is known that operating conditions are expected to change from the past.

Assuming the plant continues to operate as it has in the past, the operational reforecast yields an estimated long-term potential net energy value of [redacted] GWh. Potential net energy refers to the energy the wind farm would produce if the total site availability is 100% and the curtailment loss is 0%. Total site availability includes machine availability, grid availability, and BOP availability.

For this analysis, results will be shown only in terms of potential net energy. The client will need to apply availability and curtailment losses to determine the expected net energy generation of the Whiskey Ridge wind farm.

Project Size	$44.0\,MW$
Number of Turbines	22
Turbine Type	Vestas V80-2.0MW
Hub Height	$67\,m$
Potential Net Energy Generation	[redacted] GWh
Net Energy Generation	–
Aggregate Loss Factor	[redacted] %
Standard Error of 20-year Estimate	[redacted] %

Table 1: Project Overview

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Project Description

2 PROJECT DESCRIPTION

The Whiskey Ridge project is located in Kittitas County, Washington. The project is comprised of 22 Vestas V80-2.0MW turbines at $67\,m$ hub height for a total project capacity of $44.0\,MW$. The wind farm has been operating since January 2010.

The location of the Whiskey Ridge wind farm is shown below in Figure 1.

Figure 1: Map of the Whiskey Ridge project region.

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3 METHODOLOGY

To estimate the future net production values, the following two input data sources are utilized: historic production data, including generation and availability data, and 36 years of Numerical Weather Prediction (NWP) model data. Statistical corrections are applied to the normalized production data, based on a simulated climate index, in order to generate a long-term time series of estimated production values. The historic long-term production provides the basis for estimating future production. An outline of the basic approach follows:

- Production, availability and curtailment data are reviewed for quality and usefulness.
- Normalized production data, i.e. potential net energy data, are created by normalizing the net meter generation data to 100% site availability.
- Long-term climate variability is analyzed to determine an appropriate start date for each of 3 independent reanalysis data sets, assuming each has long-term characteristics consistent with the region.
- Utilizing the Weather Research and Forecasting Model (WRF), reanalysis data are downscaled to a $15\,km$ horizontal resolution.
- Time series data of air density and hub height wind speed are extracted from the WRF data set at a centrally located grid point within the project.
- The time series of hub height wind speeds are corrected to on-site conditions using on-site wind resource measurement data, if available.
- An air density corrected project power curve is used to convert the individual reanalysis-based time series to power. Power values are further scaled to expected long-term generation before aggregating by month. These monthly simulated production time series become climate power indices.
- Monthly observed normalized production data are adjusted for the long-term by applying the ratio of the long-term mean monthly profile derived from the 36 years of simulated data against the monthly profile derived over the short-term operational production period.
- The independent long-term estimates are then weighted by respective coefficients of determination; comparing monthly observed production against the simulated power indices.
- Historic trends of availability and curtailment data are analyzed to determine expected future trends. Turbine availability and curtailments are normalized out of the data set when applying the long-term correction factor. The expected future availability and curtailment are added back as loss factors when computing the reforecasted long-term mean net energy estimate.
- Uncertainty analysis is performed to develop the probability of exceedance values (P75, P90, etc.) of expected net energy generation.

4 DATA VERIFICATION

4.1 On-site Resource Data

For operational projects where stand-alone met towers are waked by operating turbines, a broadly applicable view of the site's wind resource can be determined from the nacelle anemometers in the project. A project average time series of wind speed is determined by averaging the 10-min wind speed readings from every turbine in the project. The averaged time series is interpreted as a point reading at the arithmetic average of the latitude and longitude coordinates of all turbines. The nacelle wind resource time series is then used to validate and correct the raw NWP model data using a process of Model Output Statistics (MOS) correction. MOS uses regression equations to remove bias and adjust the variance of the raw model output to improve the match with the provided observational data. Nacelle wind resource measurement data were provided by the client during the period January 2011 through September 2014.

4.2 Operating Results Summary

A summary of historical park performance over the period January 2010 through June 2016 was provided by the client. The data included monthly generation data and various availability statistics. Specifically relevant for this analysis are the net generation, turbine and grid availability data, and curtailment values. The total site availability factor is calculated inclusive of the following: machine availability, balance of plant availability, and grid availability. Project curtailment is computed as the sum of the environmental curtailment and grid curtailment. Potential net energy generation is then derived by dividing the net metered generation data by the total site availability factor and then adding the total project curtailment. The result is a time series representative of the project with 100% availability and no curtailment.

Project generation data, turbine and grid availability data, curtailment data, and potential net generation data utilized by Vaisala are shown below in Table 2. Newly constructed wind farms typically have a break-in period during which availability, and potentially turbine performance, is lower than what would typically be seen over the long-term. This period often takes place during the first year of operations. When multiple years of operating data are provided, Vaisala identifies this initial stabilization period and removes it from the analysis, so that these data do not bias the long-term adjustment. No explicit stabilization period is visible in the early record. Eight months of data have not been considered in the analysis because of low grid availability.

Operational generation data over the period January 2010 through June 2016 are used in the analysis. Months with relatively low total site availability values are not incorporated into the analysis, and so a potential net generation value is not computed for these months.

Date	Net Metered Generation (MWh)	Total Plant Availability (%)	Curtailment (MWh)	Potential Net Generation (MWh)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 2: Observed net metered generation, plant availability, curtailment, and potential net generation data for Whiskey Ridge. (continued on next page)

REDACTED VERSION

Date	Net Metered Generation (MWh)	Total Plant Availability (%)	Curtailment (MWh)	Potential Net Generation (MWh)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 2: Observed net metered generation, plant availability, curtailment, and potential net generation data for Whiskey Ridge. Months with relatively low total site availability are not incorporated into the analysis and potential net generation is not computed. For these months the potential net generation data are shown as missing values.

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5 CLIMATE REVIEW

In order to place the production data into the climatological context, Vaisala performed a review of several long-term climate data sources. Vaisala primarily relies on global reanalysis data sets for understanding the long-term climate variability. The reanalysis data sets are derived from thousands of global observations, including ground-based weather stations, ocean surface buoys, satellites, and weather balloons. Vaisala uses three major reanalysis data sets that are each produced independently by different institutions. The data sets reviewed for this analysis are shown below in Table 3.

Data Set	Explained Variance (R^2)	Start Year	End Year
ECMWF ERA-I	[redacted]	1980	2015
MERRA	[redacted]	1980	2015
NCEP/NCAR	[redacted]	1988	2015

Table 3: Monthly explained variance with production data and reference period utilized for each reanalysis data set.

Vaisala considers each reanalysis data set when assessing the long-term climate and results using each data set are weighted by their correlation to observed project performance. Figure 2 shows the annual-mean wind speed values extracted from each reanalysis data set across the period of record. The reference period for each data set is optimized by taking into consideration how representative the entire record is of the recent climate at the site. The utilized reference period and correlation with observed project performance for each reanalysis data set is provided in Table 3.

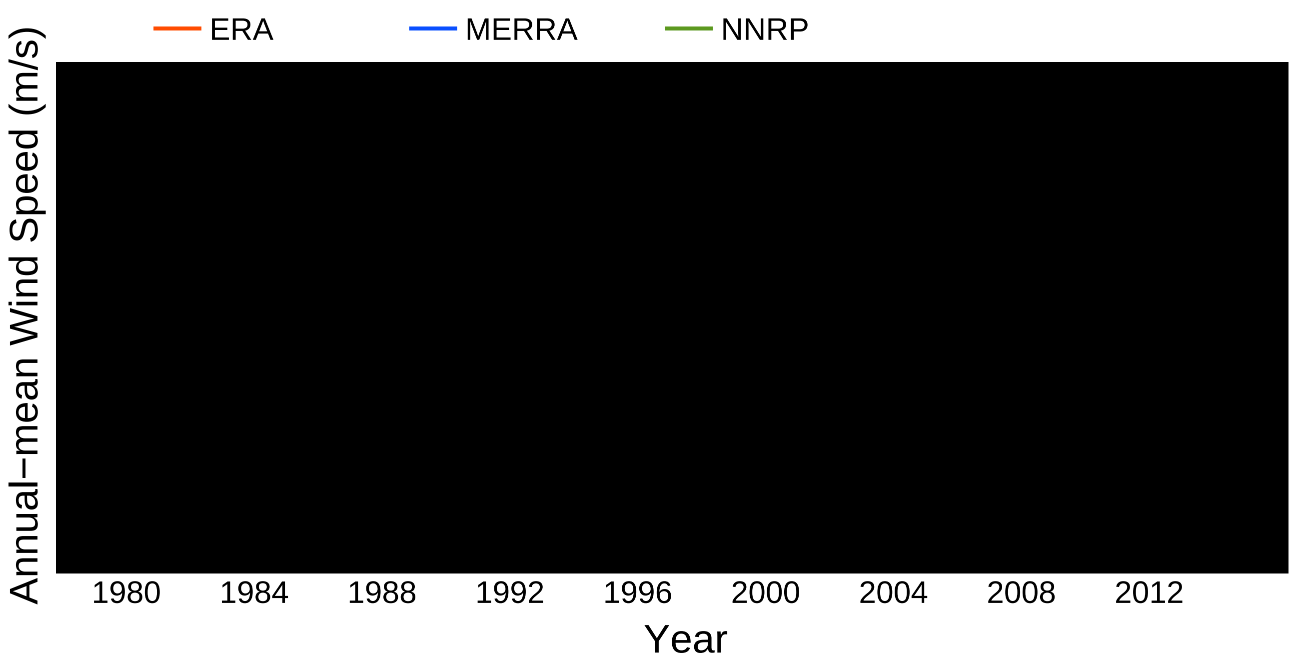

Figure 2: Annual-mean time series plot of considered reanalysis data sets.

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6 REFORECAST RESULTS

The 78 months of utilized normalized observed production are independently indexed against the 36 years of simulated power from each reanalysis data set. Concurrent months are binned by calendar month to arrive at a short-term monthly average for both the normalized production data and the three sets of simulated data. The ratio of monthly long-term energy over the short-term (observed) energy from a reanalysis data set is used as an adjustment factor for each mean calendar month for the observed, normalized production data and then annualized for a long-term annual-mean generation. The three independent long-term estimates are combined by weighting each value against the coefficient of determination between the 78 months of observed, normalized production data, and respective reanalysis power data set.

This analysis is presenting results only in terms of the potential net energy generation, and thus is not considering the availability or curtailment loss factors. The long-term mean potential net energy generation estimate for the Whiskey Ridge wind farm is estimated to be [redacted] GWh.

	Whiskeyridge
Potential Net Energy Generation (GWh)	[redacted]
Nameplate Capacity (MW)	44.0
Loss Factors	
Total Site Availability	[redacted] %
Curtailment	[redacted] %
Aggregate Loss Factor	[redacted] %
Net Energy Generation (GWh)	–

Table 4: Net energy generation results.

6.1 Long-term Variability

The long-term variability of the simulated potential net energy is shown within this section. Figure 3 shows the long-term mean seasonality via a box-and-whisker plot of the monthly-mean potential net energy data. The shaded boxes are bounded by the P25 and P75 values for each month, and the whiskers denote the minimum and maximum values. The median for each month is denote by the black line within the shaded box. Table 5 shows the numerical values plotted within Figure 3.

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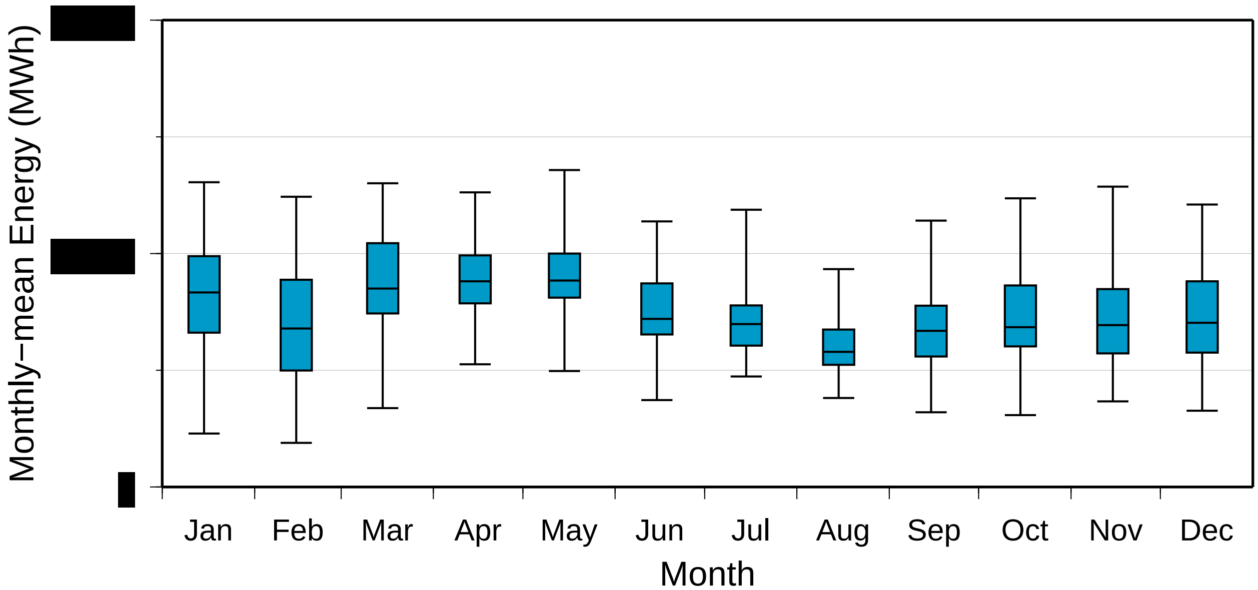

Figure 3: Box-and-whisker plot of monthly-mean simulated potential net energy. This figure displays the expected variability of the monthly-mean data. Median values are denoted by the solid line within each shaded box. Upper and lower boundaries of the shaded box correspond to the 75% and 25% quartiles, while the whiskers denote the maximum and minimum monthly-mean potential net energy values.

	Minimum	P75	Median	P25	Maximum
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 5: Minimum, P75, median, P25, and maximum potential net energy values (MWh) for each calendar month.

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6.2 Seasonal Profile

The operational reforecast of the Whiskey Ridge annual profile is detailed in this section. Because the reforecast methodology is indexed against individual calendar months, the operational reforecast can illuminate the project's annual profile. Table 6 shows the annual profile in terms of the potential net energy for Whiskey Ridge.

	Potential Net Energy Generation (MWh)	% of Annual Production
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Table 6: Long-term monthly-mean estimates of potential net energy (MWh) and % of annual production.

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7 UNCERTAINTY ANALYSIS

The following types of uncertainty are analyzed and incorporated into the analysis: production normalization, climate variability, and model uncertainty.

7.1 Production Normalization Uncertainty

The production normalization uncertainty covers the uncertainty associated with adjusting the net production data for plant availability and curtailment. The long-term analysis is based on the potential power production data, i.e. the production data normalized by the plant availability and curtailment. The uncertainty of the potential power production data is directly related to the plant availability and curtailment, since the potential production values are unknown during periods when the wind plant was not available for producing power. Thus, lower plant availability leads to higher production data uncertainty. In addition, this also covers the uncertainties associated with future changes to turbine efficiencies and availabilities.

7.2 Climate Variability Uncertainty

The climate variability includes two components: temporal variation and future changes in climate.

Temporal uncertainty is based on the inter-annual variability (standard deviation) of the annual-mean energy-based NWP time series corresponding long-term means. It is assumed that each year of the annual-mean potential power time series is independent from the next.

Future changes in climate includes the possibility of future climate varying from the historic climate. Climate change is associated with potential shifts in the climate over the next twenty years. Change in the climate may have positive or negative impacts to the production data. The magnitude of climate change uncertainty is based on how the most recent five years of data compares to the prior long-term record. Based on these factors, a climate change uncertainty value is assessed.

7.3 Model Uncertainty

The model uncertainty describes the uncertainty associated with estimating the long-term MOS-corrected potential net generation time series. The model uncertainty is derived from four components: the quality of the production data, the period of record of the production data, the error of the MOS-corrected data during the production period, and the sensitivity of the MOS calculation.

The uncertainty associated with the quality of the production data is a function of the averaging period of the generation data incorporated into the analysis. Generally speaking, using data with a longer averaging period will increase this uncertainty, e.g. monthly generation data will have higher uncertainty than 10-minute SCADA data.

Based on prior split-sample validation analyses performed by Vaisala, it is known that the uncertainty of the MOS algorithm decreases as the period of the training data increases. Therefore, the training period component of the model uncertainty is determined by the length of record of the production data. To understand the error of the MOS calculation, the root mean squared error (RMSE) is computed between the monthly-mean MOS-corrected data and the observed production data over concurrent time periods. And lastly, the sensitivity component of model uncertainty is derived by computing multiple iterations of MOS, using perturbed input data, and computing the standard deviation of error across the resulting time series. The four components of model uncertainty are statistically aggregated together yielding the total model uncertainty for a 20-year return period.

7.4 Pooled Uncertainty

A quadratic sum is computed of the individual uncertainty values described above to derive the total uncertainty value for the Whiskey Ridge Wind Farm. Table 7 summarizes these calculations.

Project Uncertainty	1-year	5-year	10-year	20-year
Production Normalization	[redacted]	[redacted]	[redacted]	[redacted]
Climate Variability	[redacted]	[redacted]	[redacted]	[redacted]
Model	[redacted]	[redacted]	[redacted]	[redacted]
Total Uncertainty	[redacted]	[redacted]	[redacted]	[redacted]

Table 7: Standard error of future production estimate (%) at Whiskey Ridge.

7.5 Probability of Exceedances

Based on the estimated total project uncertainties, Table 8 presents the probability of exceedance levels associated with the P50 project estimate for the 1-year, 5-year, 10-year, and 20-year cases.

P-level	1-year	5-year	10-year	20-year
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 8: Probability of exceedance values (GWh) at Whiskey Ridge.

8 CONCLUSION

Vaisala has conducted an operational reforecast of the Whiskey Ridge wind farm within Kittitas County, Washington. The reforecast is based on the client provided historical monthly summaries of production, availability, and curtailment data in combination with Vaisala's long-term NWP model data. A power index derived from three NWP model simulations driven by independent reanalysis data sets was utilized to adjust the normalized production data for the long-term. The expected long-term mean potential net annual energy production value, i.e. the net P50, is estimated to be [redacted] GWh. Using the uncertainty assessment results, probability of exceedance values were calculated. The 20-year P90 potential net energy value for the Whiskey Ridge project is [redacted] GWh.

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Vaisala 3TIER Services Operational Reforecast

PROJECT

Lower Snake River : Garfield County, Washington

using 149 Siemens SWT 101-2.3MW wind turbines at $80\,m$

FOR

Puget Sound Energy

DATE

8 October, 2016

CONTACT

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Seattle, WA 98121
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1 INTRODUCTION

Vaisala has been retained by Puget Sound Energy to provide an operational reforecast for the Lower Snake River wind farm, which is located in Garfield County, Washington. This project is comprised of 149 Siemens SWT 101-2.3MW turbines for a total project capacity of 342.7 MW.

The operational reforecast is an independent assessment of the future production of an operating project based on the historical production data and the climate. It considers the variability of the climate and the observed production data, including generation and availability data, as reported by the project. Vaisala offers two different Operational Reforecast products: a comprehensive analysis that quality controls the 10-minute SCADA data on a turbine specific basis, and a higher level analysis that relies solely on the monthly-mean operating reports of the project.

Since only monthly-mean production data are considered in this analysis, any potential turbine performance issues in the net metered generation data will be transferred into the operational reforecast process. In essence, it is a simulation of the future assuming the plant performs as it has in the past, making adjustments if it is known that operating conditions are expected to change from the past.

Assuming the plant continues to operate as it has in the past, the operational reforecast yields an estimated long-term potential net energy value of [redacted] GWh. Potential net energy refers to the energy the wind farm would produce if the total site availability is 100% and the curtailment loss is 0%. Total site availability includes machine availability, grid availability, and BOP availability.

For this analysis, results will be shown only in terms of potential net energy. The client will need to apply availability and curtailment losses to determine the expected net energy generation of the Lower Snake River wind farm.

Project Size	342.7 MW
Number of Turbines	149
Turbine Type	Siemens SWT 101-2.3MW
Hub Height	80 m
Potential Net Energy Generation	[redacted] GWh
Net Energy Generation	–
Aggregate Loss Factor	[redacted] %
Standard Error of 20-year Estimate	[redacted] %

Table 1: Project Overview

REDACTED VERSION

REDACTED VERSION

2 PROJECT DESCRIPTION

The Lower Snake River project is located in Garfield County, Washington. The project is comprised of 149 Siemens SWT 101-2.3MW turbines at $80\,m$ hub height for a total project capacity of $342.7\,MW$. The wind farm has been operating since March 2012.

The location of the Lower Snake River wind farm is shown below in Figure 1.

Figure 1: Map of the Lower Snake River project region.

3 METHODOLOGY

To estimate the future net production values, the following two input data sources are utilized: historic production data, including generation and availability data, and 36 years of Numerical Weather Prediction (NWP) model data. Statistical corrections are applied to the normalized production data, based on a simulated climate index, in order to generate a long-term time series of estimated production values. The historic long-term production provides the basis for estimating future production. An outline of the basic approach follows:

- Production, availability and curtailment data are reviewed for quality and usefulness.
- Normalized production data, i.e. potential net energy data, are created by normalizing the net meter generation data to 100% site availability.
- Long-term climate variability is analyzed to determine an appropriate start date for each of 3 independent reanalysis data sets, assuming each has long-term characteristics consistent with the region.
- Utilizing the Weather Research and Forecasting Model (WRF), reanalysis data are downscaled to a $15\,km$ horizontal resolution.
- Time series data of air density and hub height wind speed are extracted from the WRF data set at a centrally located grid point within the project.
- The time series of hub height wind speeds are corrected to on-site conditions using on-site wind resource measurement data, if available.
- An air density corrected project power curve is used to convert the individual reanalysis-based time series to power. Power values are further scaled to expected long-term generation before aggregating by month. These monthly simulated production time series become climate power indices.
- Monthly observed normalized production data are adjusted for the long-term by applying the ratio of the long-term mean monthly profile derived from the 36 years of simulated data against the monthly profile derived over the short-term operational production period.
- The independent long-term estimates are then weighted by respective coefficients of determination; comparing monthly observed production against the simulated power indices.
- Historic trends of availability and curtailment data are analyzed to determine expected future trends. Turbine availability and curtailments are normalized out of the data set when applying the long-term correction factor. The expected future availability and curtailment are added back as loss factors when computing the reforecasted long-term mean net energy estimate.
- Uncertainty analysis is performed to develop the probability of exceedance values (P75, P90, etc.) of expected net energy generation.

4 DATA VERIFICATION

4.1 On-site Resource Data

For operational projects where stand-alone met towers are waked by operating turbines, a broadly applicable view of the site's wind resource can be determined from the nacelle anemometers in the project. A project average time series of wind speed is determined by averaging the 10-min wind speed readings from every turbine in the project. The averaged time series is interpreted as a point reading at the arithmetic average of the latitude and longitude coordinates of all turbines. The nacelle wind resource time series is then used to validate and correct the raw NWP model data using a process of Model Output Statistics (MOS) correction. MOS uses regression equations to remove bias and adjust the variance of the raw model output to improve the match with the provided observational data. Nacelle wind resource measurement data were provided by the client during the period January 2013 through December 2015.

4.2 Operating Results Summary

A summary of historical park performance over the period March 2012 through July 2016 was provided by the client. The data included monthly generation data and various availability statistics. Specifically relevant for this analysis are the net generation, turbine and grid availability data, and curtailment values. The total site availability factor is calculated inclusive of the following: machine availability, balance of plant availability, and grid availability. Project curtailment is computed as the sum of the environmental curtailment and grid curtailment. Potential net energy generation is then derived by dividing the net metered generation data by the total site availability factor and then adding the total project curtailment. The result is a time series representative of the project with 100% availability and no curtailment.

Project generation data, turbine and grid availability data, curtailment data, and potential net generation data utilized by Vaisala are shown below in Table 2. Newly constructed wind farms typically have a break-in period during which availability, and potentially turbine performance, is lower than what would typically be seen over the long-term. This period often takes place during the first year of operations. When multiple years of operating data are provided, Vaisala identifies this initial stabilization period and removes it from the analysis, so that these data do not bias the long-term adjustment. No explicit stabilization period is apparent in the data record, but the first month of operational data is not considered in the analysis. One additional month is also not incorporated into the analysis because of relatively low plant availability.

Operational generation data over the period April 2012 through December 2015 are used in the analysis. Months with relatively low total site availability values are not incorporated into the analysis, and so a potential net generation value is not computed for these months.

Date	Net Metered Generation (MWh)	Total Plant Availability ($\%$)	Curtailment (MWh)	Potential Net Generation (MWh)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 2: Observed net metered generation, plant availability, curtailment, and potential net generation data for Lower Snake River. (continued on next page)

REDACTED VERSION

REDACTED VERSION

Date	Net Metered Generation (MWh)	Total Plant Availability (%)	Curtailment (MWh)	Potential Net Generation (MWh)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 2: Observed net metered generation, plant availability, curtailment, and potential net generation data for Lower Snake River. Months with relatively low total site availability are not incorporated into the analysis and potential net generation is not computed. For these months the potential net generation data are shown as missing values.

REDACTED VERSION

5 CLIMATE REVIEW

In order to place the production data into the climatological context, Vaisala performed a review of several long-term climate data sources. Vaisala primarily relies on global reanalysis data sets for understanding the long-term climate variability. The reanalysis data sets are derived from thousands of global observations, including ground-based weather stations, ocean surface buoys, satellites, and weather balloons. Vaisala uses three major reanalysis data sets that are each produced independently by different institutions. The data sets reviewed for this analysis are shown below in Table 3.

Data Set	Explained Variance (R^2)	Start Year	End Year
ECMWF ERA-I	[redacted]	1997	2015
MERRA	[redacted]	1997	2015
NCEP/NCAR	[redacted]	1997	2015

Table 3: Monthly explained variance with production data and reference period utilized for each reanalysis data set.

Vaisala considers each reanalysis data set when assessing the long-term climate and results using each data set are weighted by their correlation to observed project performance. Figure 2 shows the annual-mean wind speed values extracted from each reanalysis data set across the period of record. The reference period for each data set is optimized by taking into consideration how representative the entire record is of the recent climate at the site. The utilized reference period and correlation with observed project performance for each reanalysis data set is provided in Table 3.

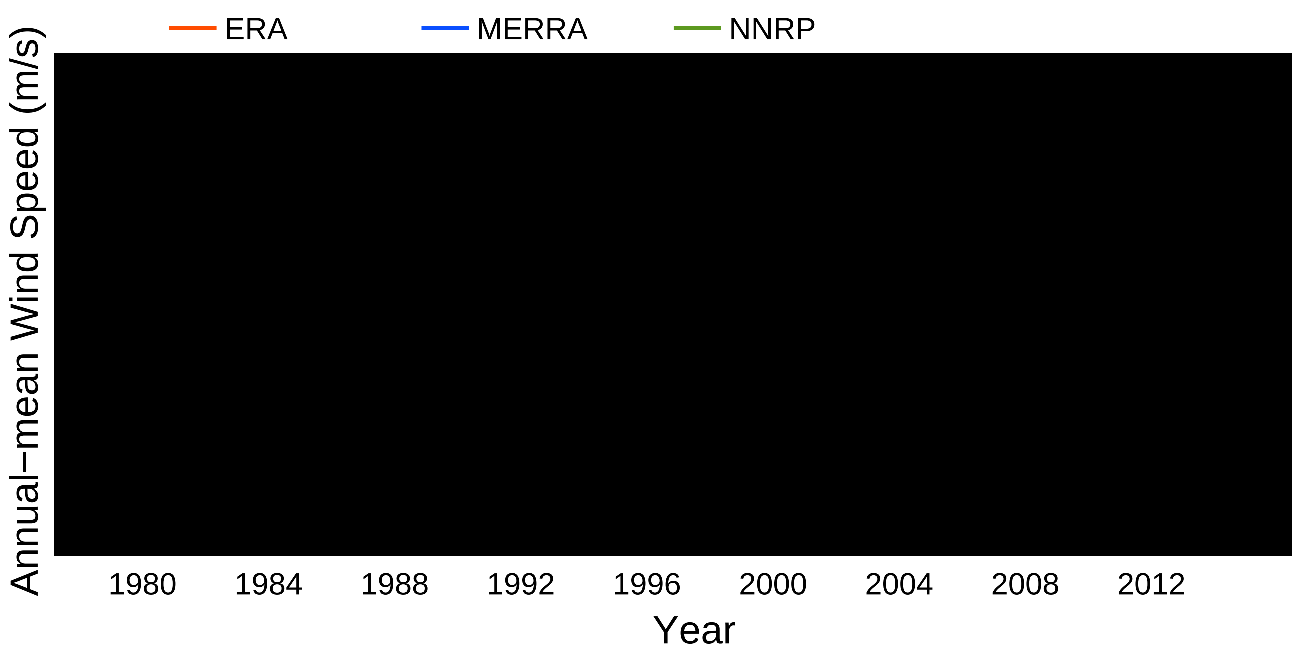

Figure 2: Annual-mean time series plot of considered reanalysis data sets.

6 REFORECAST RESULTS

The 52 months of utilized normalized observed production are independently indexed against the 36 years of simulated power from each reanalysis data set. Concurrent months are binned by calendar month to arrive at a short-term monthly average for both the normalized production data and the three sets of simulated data. The ratio of monthly long-term energy over the short-term (observed) energy from a reanalysis data set is used as an adjustment factor for each mean calendar month for the observed, normalized production data and then annualized for a long-term annual-mean generation. The three independent long-term estimates are combined by weighting each value against the coefficient of determination between the 52 months of observed, normalized production data, and respective reanalysis power data set.

This analysis is presenting results only in terms of the potential net energy generation, and thus is not considering the availability or curtailment loss factors. The long-term mean potential net energy generation estimate for the Lower Snake River wind farm is estimated to be $849.9\,GWh$.

	Lowersnakeriver
Potential Net Energy Generation (GWh)	[redacted]
Nameplate Capacity (MW)	342.7
Loss Factors	
Total Site Availability	[redacted] %
Curtailment	[redacted] %
Aggregate Loss Factor	[redacted] %
Net Energy Generation (GWh)	–

Table 4: Net energy generation results.

6.1 Long-term Variability

The long-term variability of the simulated potential net energy is shown within this section. Figure 3 shows the long-term mean seasonality via a box-and-whisker plot of the monthly-mean potential net energy data. The shaded boxes are bounded by the P25 and P75 values for each month, and the whiskers denote the minimum and maximum values. The median for each month is denote by the black line within the shaded box. Table 5 shows the numerical values plotted within Figure 3.

REDACTED VERSION

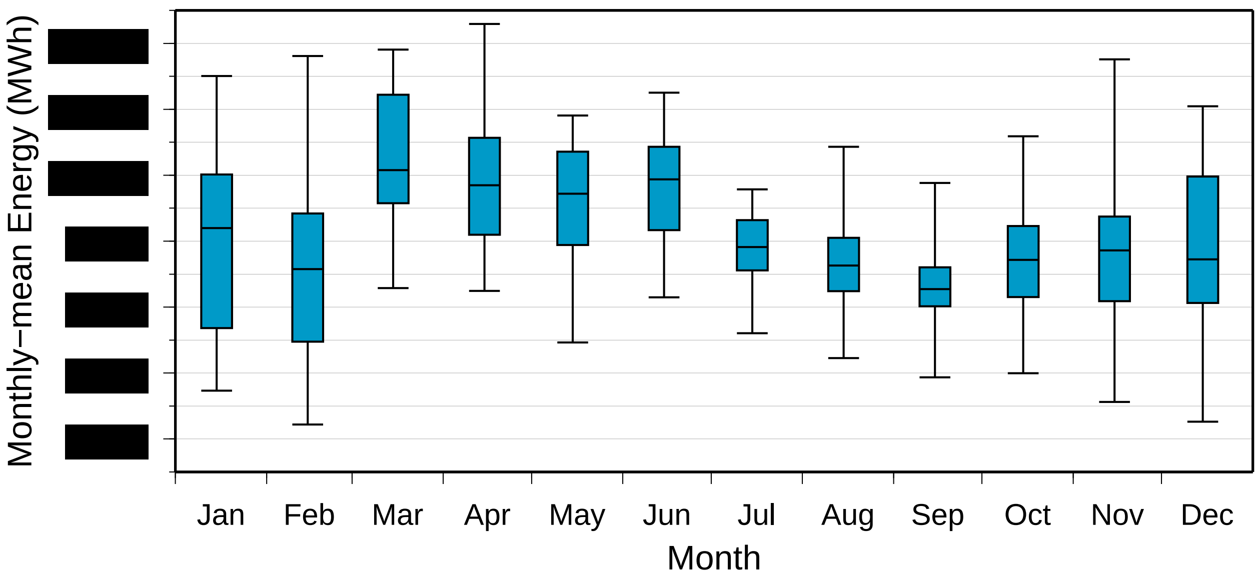

Figure 3: Box-and-whisker plot of monthly-mean simulated potential net energy. This figure displays the expected variability of the monthly-mean data. Median values are denoted by the solid line within each shaded box. Upper and lower boundaries of the shaded box correspond to the 75% and 25% quartiles, while the whiskers denote the maximum and minimum monthly-mean potential net energy values.

	Minimum	P75	Median	P25	Maximum
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 5: Minimum, P75, median, P25, and maximum potential net energy values (MWh) for each calendar month.

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6.2 Seasonal Profile

The operational reforecast of the Lower Snake River annual profile is detailed in this section. Because the reforecast methodology is indexed against individual calendar months, the operational reforecast can illuminate the project's annual profile. Table 6 shows the annual profile in terms of the potential net energy for Lower Snake River.

	Potential Net Energy Generation (MWh)	% of Annual Production
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Table 6: Long-term monthly-mean estimates of potential net energy (MWh) and % of annual production.

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7 UNCERTAINTY ANALYSIS

The following types of uncertainty are analyzed and incorporated into the analysis: production normalization, climate variability, and model uncertainty.

7.1 Production Normalization Uncertainty

The production normalization uncertainty covers the uncertainty associated with adjusting the net production data for plant availability and curtailment. The long-term analysis is based on the potential power production data, i.e. the production data normalized by the plant availability and curtailment. The uncertainty of the potential power production data is directly related to the plant availability and curtailment, since the potential production values are unknown during periods when the wind plant was not available for producing power. Thus, lower plant availability leads to higher production data uncertainty. In addition, this also covers the uncertainties associated with future changes to turbine efficiencies and availabilities.

7.2 Climate Variability Uncertainty

The climate variability includes two components: temporal variation and future changes in climate.

Temporal uncertainty is based on the inter-annual variability (standard deviation) of the annual-mean energy-based NWP time series corresponding long-term means. It is assumed that each year of the annual-mean potential power time series is independent from the next.

Future changes in climate includes the possibility of future climate varying from the historic climate. Climate change is associated with potential shifts in the climate over the next twenty years. Change in the climate may have positive or negative impacts to the production data. The magnitude of climate change uncertainty is based on how the most recent five years of data compares to the prior long-term record. Based on these factors, a climate change uncertainty value is assessed.

7.3 Model Uncertainty

The model uncertainty describes the uncertainty associated with estimating the long-term MOS-corrected potential net generation time series. The model uncertainty is derived from four components: the quality of the production data, the period of record of the production data, the error of the MOS-corrected data during the production period, and the sensitivity of the MOS calculation.

The uncertainty associated with the quality of the production data is a function of the averaging period of the generation data incorporated into the analysis. Generally speaking, using data with a longer averaging period will increase this uncertainty, e.g. monthly generation data will have higher uncertainty than 10-minute SCADA data.

Based on prior split-sample validation analyses performed by Vaisala, it is known that the uncertainty of the MOS algorithm decreases as the period of the training data increases. Therefore, the training period component of the model uncertainty is determined by the length of record of the production data. To understand the error of the MOS calculation, the root mean squared error (RMSE) is computed between the monthly-mean MOS-corrected data and the observed production data over concurrent time periods. And lastly, the sensitivity component of model uncertainty is derived by computing multiple iterations of MOS, using perturbed input data, and computing the standard deviation of error across the resulting time series. The four components of model uncertainty are statistically aggregated together yielding the total model uncertainty for a 20-year return period.

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7.4 Pooled Uncertainty

A quadratic sum is computed of the individual uncertainty values described above to derive the total uncertainty value for the Lower Snake River Wind Farm. Table 7 summarizes these calculations.

Project Uncertainty	1-year	5-year	10-year	20-year
Production Normalization	[redacted]	[redacted]	[redacted]	[redacted]
Climate Variability	[redacted]	[redacted]	[redacted]	[redacted]
Model	[redacted]	[redacted]	[redacted]	[redacted]
Total Uncertainty	[redacted]	[redacted]	[redacted]	[redacted]

Table 7: Standard error of future production estimate (%) at Lower Snake River.

7.5 Probability of Exceedances

Based on the estimated total project uncertainties, Table 8 presents the probability of exceedance levels associated with the P50 project estimate for the 1-year, 5-year, 10-year, and 20-year cases.

P-level	1-year	5-year	10-year	20-year
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 8: Probability of exceedance values (GWh) at Lower Snake River.

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8 CONCLUSION

Vaisala has conducted an operational reforecast of the Lower Snake River wind farm within Garfield County, Washington. The reforecast is based on the client provided historical monthly summaries of production, availability, and curtailment data in combination with Vaisala's long-term NWP model data. A power index derived from three NWP model simulations driven by independent reanalysis data sets was utilized to adjust the normalized production data for the long-term. The expected long-term mean potential net annual energy production value, i.e. the net P50, is estimated to be [redacted] GWh. Using the uncertainty assessment results, probability of exceedance values were calculated. The 20-year P90 potential net energy value for the Lower Snake River project is [redacted] GWh.

REDACTED VERSION

REDACTED VERSION

Vaisala 3TIER Services Operational Reforecast

PROJECT

Hopkinsridge : Columbia County, Washington

using 87 Vestas V80-1.8MW wind turbines at 67 m

FOR

Puget Sound Energy

DATE

8 October, 2016

CONTACT

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www.vaisala.com/energy

VAISALA

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Disclaimer

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Contents

REDACTED VERSION

1 INTRODUCTION

Vaisala has been retained by Puget Sound Energy to provide an operational reforecast for the Hopkinsridge wind farm, which is located in Columbia County, Washington. This project is comprised of 87 Vestas V80-1.8MW turbines for a total project capacity of 156.6 MW.

The operational reforecast is an independent assessment of the future production of an operating project based on the historical production data and the climate. It considers the variability of the climate and the observed production data, including generation and availability data, as reported by the project. Vaisala offers two different Operational Reforecast products: a comprehensive analysis that quality controls the 10-minute SCADA data on a turbine specific basis, and a higher level analysis that relies solely on the monthly-mean operating reports of the project.

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Assuming the plant continues to operate as it has in the past, the operational reforecast yields an estimated long-term potential net energy value of [redacted] GWh. Potential net energy refers to the energy the wind farm would produce if the total site availability is 100% and the curtailment loss is 0%. Total site availability includes machine availability, grid availability, and BOP availability.

For this analysis, results will be shown only in terms of potential net energy. The client will need to apply availability and curtailment losses to determine the expected net energy generation of the Hopkinsridge wind farm.

Project Size	156.6 MW
Number of Turbines	87
Turbine Type	Vestas V80-1.8MW
Hub Height	67 m
Potential Net Energy Generation	[redacted] GWh
Net Energy Generation	–
Aggregate Loss Factor	[redacted] %
Standard Error of 20-year Estimate	[redacted] %

Table 1: Project Overview

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2 PROJECT DESCRIPTION

The Hopkinsridge project is located in Columbia County, Washington. The project is comprised of 87 Vestas V80-1.8MW turbines at $67\,m$ hub height for a total project capacity of $156.6\,MW$. The wind farm has been operating since December 2005.

The location of the Hopkinsridge wind farm is shown below in Figure 1.

Figure 1: Map of the Hopkinsridge project region.

REDACTED VERSION

3 METHODOLOGY

To estimate the future net production values, the following two input data sources are utilized: historic production data, including generation and availability data, and 36 years of Numerical Weather Prediction (NWP) model data. Statistical corrections are applied to the normalized production data, based on a simulated climate index, in order to generate a long-term time series of estimated production values. The historic long-term production provides the basis for estimating future production. An outline of the basic approach follows:

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4.2 Operating Results Summary

A summary of historical park performance over the period December 2005 through July 2016 was provided by the client. The data included monthly generation data and various availability statistics. Specifically relevant for this analysis are the net generation, turbine and grid availability data, and curtailment values. The total site availability factor is calculated inclusive of the following: machine availability, balance of plant availability, and grid availability. Project curtailment is computed as the sum of the environmental curtailment and grid curtailment. Potential net energy generation is then derived by dividing the net metered generation data by the total site availability factor and then adding the total project curtailment. The result is a time series representative of the project with 100% availability and no curtailment.

Project generation data, turbine and grid availability data, curtailment data, and potential net generation data utilized by Vaisala are shown below in Table 2. Newly constructed wind farms typically have a break-in period during which availability, and potentially turbine performance, is lower than what would typically be seen over the long-term. This period often takes place during the first year of operations. When multiple years of operating data are provided, Vaisala identifies this initial stabilization period and removes it from the analysis, so that these data do not bias the long-term adjustment. A stabilization period from December 2005 through July 2006 is identified in the data record. An additional 15 months of data have not been considered in the analysis because of low plant availability.

Operational generation data over the period August 2006 through December 2015 are used in the analysis. Months with relatively low total site availability values are not incorporated into the analysis, and so a potential net generation value is not computed for these months.

Date	Net Metered Generation (MWh)	Total Plant Availability (%)	Curtailment (MWh)	Potential Net Generation (MWh)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 2: Observed net metered generation, plant availability, curtailment, and potential net generation data for Hopkinsridge. (continued on next page)

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Date	Net Metered Generation (MWh)	Total Plant Availability (%)	Curtailment (MWh)	Potential Net Generation (MWh)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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Table 2: Observed net metered generation, plant availability, curtailment, and potential net generation data for Hopkinsridge. (continued on next page)

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Date	Net Metered Generation (MWh)	Total Plant Availability (%)	Curtailment (MWh)	Potential Net Generation (MWh)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
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[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 2: Observed net metered generation, plant availability, curtailment, and potential net generation data for Hopkinsridge. Months with relatively low total site availability are not incorporated into the analysis and potential net generation is not computed. For these months the potential net generation data are shown as missing values.

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5 CLIMATE REVIEW

In order to place the production data into the climatological context, Vaisala performed a review of several long-term climate data sources. Vaisala primarily relies on global reanalysis data sets for understanding the long-term climate variability. The reanalysis data sets are derived from thousands of global observations, including ground-based weather stations, ocean surface buoys, satellites, and weather balloons. Vaisala uses three major reanalysis data sets that are each produced independently by different institutions. The data sets reviewed for this analysis are shown below in Table 3.

Data Set	Explained Variance (R^2)	Start Year	End Year
ECMWF ERA-I	[redacted]	1997	2015
MERRA	[redacted]	1997	2015
NCEP/NCAR	[redacted]	1997	2015

Table 3: Monthly explained variance with production data and reference period utilized for each reanalysis data set.

Vaisala considers each reanalysis data set when assessing the long-term climate and results using each data set are weighted by their correlation to observed project performance. Figure 2 shows the annual-mean wind speed values extracted from each reanalysis data set across the period of record. The reference period for each data set is optimized by taking into consideration how representative the entire record is of the recent climate at the site. The utilized reference period and correlation with observed project performance for each reanalysis data set is provided in Table 3.

[redacted]

Figure 2: Annual-mean time series plot of considered reanalysis data sets.

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6 REFORECAST RESULTS

The 80 months of utilized normalized observed production are independently indexed against the 36 years of simulated power from each reanalysis data set. Concurrent months are binned by calendar month to arrive at a short-term monthly average for both the normalized production data and the three sets of simulated data. The ratio of monthly long-term energy over the short-term (observed) energy from a reanalysis data set is used as an adjustment factor for each mean calendar month for the observed, normalized production data and then annualized for a long-term annual-mean generation. The three independent long-term estimates are combined by weighting each value against the coefficient of determination between the 80 months of observed, normalized production data, and respective reanalysis power data set.

This analysis is presenting results only in terms of the potential net energy generation, and thus is not considering the availability or curtailment loss factors. The long-term mean potential net energy generation estimate for the Hopkinsridge wind farm is estimated to be [redacted] *GWh*.

	Hopkinsridge
Potential Net Energy Generation (GWh)	[redacted]
Nameplate Capacity (MW)	156.6
Loss Factors	
Total Site Availability	[redacted] %
Curtailment	[redacted] %
Aggregate Loss Factor	[redacted] %
Net Energy Generation (GWh)	–

Table 4: Net energy generation results.

6.1 Long-term Variability

The long-term variability of the simulated potential net energy is shown within this section. Figure 3 shows the long-term mean seasonality via a box-and-whisker plot of the monthly-mean potential net energy data. The shaded boxes are bounded by the P25 and P75 values for each month, and the whiskers denote the minimum and maximum values. The median for each month is denote by the black line within the shaded box. Table 5 shows the numerical values plotted within Figure 3.

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[redacted]

Figure 3: Box-and-whisker plot of monthly-mean simulated potential net energy. This figure displays the expected variability of the monthly-mean data. Median values are denoted by the solid line within each shaded box. Upper and lower boundaries of the shaded box correspond to the 75% and 25% quartiles, while the whiskers denote the maximum and minimum monthly-mean potential net energy values.

REDACTED

	Minimum	P75	Median	P25	Maximum
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 5: Minimum, P75, median, P25, and maximum potential net energy values (MWh) for each calendar month.

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6.2 Seasonal Profile

The operational reforecast of the Hopkinsridge annual profile is detailed in this section. Because the reforecast methodology is indexed against individual calendar months, the operational reforecast can illuminate the project's annual profile. Table 6 shows the annual profile in terms of the potential net energy for Hopkinsridge.

	Potential Net Energy Generation (MWh)	% of Annual Production
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

Table 6: Long-term monthly-mean estimates of potential net energy (MWh) and % of annual production.

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7 UNCERTAINTY ANALYSIS

The following types of uncertainty are analyzed and incorporated into the analysis: production normalization, climate variability, and model uncertainty.

7.1 Production Normalization Uncertainty

The production normalization uncertainty covers the uncertainty associated with adjusting the net production data for plant availability and curtailment. The long-term analysis is based on the potential power production data, i.e. the production data normalized by the plant availability and curtailment. The uncertainty of the potential power production data is directly related to the plant availability and curtailment, since the potential production values are unknown during periods when the wind plant was not available for producing power. Thus, lower plant availability leads to higher production data uncertainty. In addition, this also covers the uncertainties associated with future changes to turbine efficiencies and availabilities.

7.2 Climate Variability Uncertainty

The climate variability includes two components: temporal variation and future changes in climate.

Temporal uncertainty is based on the inter-annual variability (standard deviation) of the annual-mean energy-based NWP time series corresponding long-term means. It is assumed that each year of the annual-mean potential power time series is independent from the next.

Future changes in climate includes the possibility of future climate varying from the historic climate. Climate change is associated with potential shifts in the climate over the next twenty years. Change in the climate may have positive or negative impacts to the production data. The magnitude of climate change uncertainty is based on how the most recent five years of data compares to the prior long-term record. Based on these factors, a climate change uncertainty value is assessed.

7.3 Model Uncertainty

The model uncertainty describes the uncertainty associated with estimating the long-term MOS-corrected potential net generation time series. The model uncertainty is derived from four components: the quality of the production data, the period of record of the production data, the error of the MOS-corrected data during the production period, and the sensitivity of the MOS calculation.

The uncertainty associated with the quality of the production data is a function of the averaging period of the generation data incorporated into the analysis. Generally speaking, using data with a longer averaging period will increase this uncertainty, e.g. monthly generation data will have higher uncertainty than 10-minute SCADA data.

Based on prior split-sample validation analyses performed by Vaisala, it is known that the uncertainty of the MOS algorithm decreases as the period of the training data increases. Therefore, the training period component of the model uncertainty is determined by the length of record of the production data. To understand the error of the MOS calculation, the root mean squared error (RMSE) is computed between the monthly-mean MOS-corrected data and the observed production data over concurrent time periods. And lastly, the sensitivity component of model uncertainty is derived by computing multiple iterations of MOS, using perturbed input data, and computing the standard deviation of error across the resulting time series. The four components of model uncertainty are statistically aggregated together yielding the total model uncertainty for a 20-year return period.

7.4 Pooled Uncertainty

A quadratic sum is computed of the individual uncertainty values described above to derive the total uncertainty value for the Hopkinsridge Wind Farm. Table 7 summarizes these calculations.

Project Uncertainty	1-year	5-year	10-year	20-year
Production Normalization	[redacted]	[redacted]	[redacted]	[redacted]
Climate Variability	[redacted]	[redacted]	[redacted]	[redacted]
Model	[redacted]	[redacted]	[redacted]	[redacted]
Total Uncertainty	[redacted]	[redacted]	[redacted]	[redacted]

Table 7: Standard error of future production estimate (%) at Hopkinsridge.

7.5 Probability of Exceedances

Based on the estimated total project uncertainties, Table 8 presents the probability of exceedance levels associated with the P50 project estimate for the 1-year, 5-year, 10-year, and 20-year cases.

P-level	1-year	5-year	10-year	20-year
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table 8: Probability of exceedance values (GWh) at Hopkinsridge.

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8 CONCLUSION

Vaisala has conducted an operational reforecast of the Hopkinsridge wind farm within Columbia County, Washington. The reforecast is based on the client provided historical monthly summaries of production, availability, and curtailment data in combination with Vaisala's long-term NWP model data. A power index derived from three NWP model simulations driven by independent reanalysis data sets was utilized to adjust the normalized production data for the long-term. The expected long-term mean potential net annual energy production value, i.e. the net P50, is estimated to be [redacted] GWh. Using the uncertainty assessment results, probability of exceedance values were calculated. The 20-year P90 potential net energy value for the Hopkinsridge project is [redacted] GWh.

REDACTED