TECHNICAL REPORT

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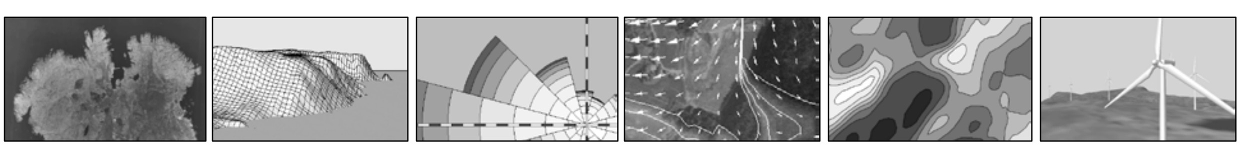

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REVISION HISTORY

version	date	Summary
A	04/18/2025	Original issue

EXECUTIVE SUMMARY

At the height of 5m in XXX solar park, the frequency for wind speed over 29.0 mph is 158 times per year. When the triggering wind speed is 29.0 mph, the extreme wind ahead is 43.5 mph.

At the height of 10m, the frequency for wind speed over 29.0 mph is 202.6 times per year. When the triggering wind speed is 29.0 mph, the extreme wind ahead is 47.4 mph.

The triggering wind speed is defined as the minimum 3 second average wind gust that occurs from any direction at 5m or 10m.

The extreme wind ahead is defined statistically as the wind speed within the next 5 minutes that is equal to or less than the extreme wind ahead with a 95% certainty of not being exceeded on the project site.

The probability is 85% that the actual value will be less than those assessed value.

Height	Trigger wind speed (mph)	Frequency (times/yr)	Extreme wind ahead (mph) P85
5 m	29.0	158	46.6
10 m	29.0	202.6	50.8

Result of triggering wind speed and extreme wind ahead

CONTENTS

1 Introduction

The purpose of this project is to forecast the extreme wind conditions at a solar park for single axis trackers for development of programmable wind stow strategies.

The single axis tracker has the benefit of collecting solar energy for the longer period of the day, compensating for the east-west movement of the sun, reducing the energy loss, comparing with fixed mount rack for solar panels.

Due to greater exposure and changing positioning, the single axis tracker requires careful design and operation regarding to wind loading.

The single axis tracker is designed to stow to a programmable safe mode to sustain higher extreme wind pressures. The triggering event to activate the safe mode is that the wind speed reaches the triggering wind speed regardless of the wind direction measured on site.

The triggering wind speed is defined as the minimum 3 second average wind gust that occurs from any direction at 5m or 10m.

It usually takes several minutes for a single axis tracker to position itself from the operational mode to the safe mode. Thus, it is important to forecast the extreme wind during these critical few minutes as preventive measure.

Wind naturally fluctuates in speed and direction constantly. As a result, the wind speed in the few minutes following a triggering wind speed could be either higher or lower than the triggering wind speed itself.

The extreme wind ahead is defined statistically as the wind speed within the next 5 minutes that is equal to or less than the extreme wind ahead with a 95% certainty of not being exceeded on the project site.

WindSim AS applied the statistical and physical models in the analysis to study the triggering wind speed and the extreme wind ahead in the following steps:

- Nearby regional reference wind conditions (Airports, Military Bases, etc.)
- On-site wind conditions
- Analysis on the triggering wind speed and future extreme wind
- Uncertainty of the assessment

1.1 Site

XXX Solar Park is located near XXX, XXX, United States with coordinates XXXXN, XXXXW. The location of solar park is shown in Figure 1.1. The site is located in the non-hurricane region, methodology for non-hurricane applies.

Figure 1.1 The location of the solar park

1.2 Methodology

The extreme wind analysis has four major steps.

1.2.1 Step 1, analysis of nearby regional reference wind conditions

The regional reference wind near the solar park is the starting point for extreme wind analysis. The accuracy of the assessment may depend largely on the availability and the quality of the reference wind nearby.

In this step, the area of 200km x 200km, cantering solar park is examined to identify reference wind nearby.

The reference wind is Standardized Extreme Wind Speed (SEWS) database /2/. The database is processed and managed by Statistical Engineering Division from National Institute of Standards and Technology (NIST). The raw data is from National Climatic Data Centre (NCDC). Integrated Surface Hourly (ISH) Data Set 3505 is used from the raw data. The raw data is recorded by the weather stations, which are Automated Weather Observing System (AWOS), operated mostly by Federal Aviation Administration (FAA), and Automated Surface Observing System (ASOS), which are operated and controlled cooperatively in the United States by the National Weather Service (NWS), Federal Aviation Administration (FAA), and Department of Defence (DOD).

The data is processed by NIST for standardization of elevation, averaging time, terrain roughness, with quality control. The final dataset includes 1865 sites in the United States, representing the time series of 3 second averaging extreme wind at 10m height at roughness of 0.03. The length of the record depends on the data, and it may range from several years to more than 30 years.

The selected data has been verified and quality controlled by WindSim AS. Typically, the extreme wind events over 70mph are compared with reports for storm paths, deaths, injuries, and property damage, from Storm Data Publication from National Centres for Environmental Information (NCEI), from National Oceanic and Atmospheric Administration (NOAA) /3/.

Usually one or more SEWS are in the area of 200km x 200km.

The quality of SEWS is investigated by comparing nearby SEWS points in case the data period is less than 10 years, and by comparing Storm Data Publication when the wind speed record is over 80mph.

1.2.2 Step 2, analysis of on-site wind conditions

Wind is correlated to each other within the micro scale wind pattern zone. The ratio between wind speed at two locations nearby from one direction is roughly a constant, independent to the wind speed.

The purpose of this step is to transfer the regional reference wind condition to the solar park by WindSim flow modelling. Thus, the basic assumption is that the extreme wind at solar park is correlated with the regional reference wind nearby.

Because the wind flow is affected by the local terrain, the digital terrain model including elevation and roughness is set for the simulation.

The elevation data comes from National Elevation Dataset (NED), which is the primary elevation data by United States Geological Survey (USGS). NED data are available in USA at resolutions of 1 arc-second (about 30 meters) and 1/3 arc-second (about 10 meters), and in limited areas at 1/9 arc-second (about 3 meters) /5/.

The roughness is converted mainly from National Land Cover Database 2011 (NLCD 2011) /6/, created by Multi-Resolution Land Characteristics (MRLC) Consortium. It has multiple-class land cover classification scheme that has been applied consistently across the United States at a spatial resolution of 30 meters.

Near the US border area, when the NLCD 2011 is not available, Global Land Cover 30 (GLC30) dataset, which is managed by National Geomatics Center of China (NGCC), is complemented /7/.

Based on the digital terrain model, the simulation domain is generated covering the air above it. The entire large simulation domain is then further divided into small boxes, and each small box is represented by a node. Boundary conditions are applied to the nodes on the surfaces of the simulation domain, and Reynolds Averaged Navier-Stokes (RANS) equations are applied to each node within the simulation domain, before the numerical simulation started by iteration to solve the wind flow from each wind direction /8/.

Once the flow model is completed, the wind speed and direction at any point within the simulation domain is known. Then the speed-up ratio and direction shift between reference wind place and solar park point can be calculated. As the reference wind is created in the first step, the on-site wind condition at the solar park is generated.

1.2.3 Step 3, analysis of triggering wind speed and extreme wind ahead

In this step, a time series of wind speed and direction, with 1-minute time steps at the solar park from step 2, is used for analysis. If multiple SEWS are used, the on-site wind condition is combined.

The triggering wind speed is defined as the minimum 3 second average wind gust that occurs from any direction at 5m or 10m.

It is calculated from the on-site wind conditions. The development of the equipment of each SEWS is considered during the calculation. The development can be classified as three periods.

The first period is defined as prior to ASOS and typically ranges from the early 1970's to the mid-1990's. Wind speeds were collected via anemometer/chart recorder system. The extreme wind is not recorded as frequently as later periods. This period is not included in the calculation due to uncertainty and inaccuracy in the measuring equipment.

The second period is ASOS, which typically ranges from the mid-1990's to the mid 2000's. This data was sampled at 1 sample per second (1 Hz) for digital equipment and a 5-second block averages (average of 5 consecutive samples) for cup anemometer equipment. The extreme wind is well recorded during this period and is therefore included in the calculation.

The third period begins in the mid to late 2000's and uses sonic anemometers installed at a few of the ISH stations, along with the cup anemometers. The data recorded by sonic anemometers is sampled at 1 Hz and digitally output at 3-s moving average peak wind. The extreme wind is well recorded, and this period is included in the calculation.

For the extreme wind ahead, the concurrent period for current wind and wind ahead within 5 minutes is generated.

The current wind is based on triggering wind speed with 10mph wind speed bin. It is assumed that the distribution of the future wind follows normal distribution, and the average wind and standard deviation (SD) is calculated based on the wind ahead in the concurrent period.

Extreme Wind Ahead (P95) = Average wind + 1.65 x SD.

1.2.4 Step 4, analysis of assessment uncertainty

Uncertainty in extreme wind assessment is a vital part of the result. It gives confidence analysis to the accuracy of the extreme wind estimate. The potential causes of uncertainty are divided into four categories:

1. Wind record
2. Long term representativeness
3. Flow model
4. Extreme wind model

Wind record: This is the uncertainty in the wind speed as measured by anemometers after data validation and adjustments. It reflects not only the uncertainty in the sensitivity of the instruments when operating under ideal wind conditions, but also their performance in the field. When SWES is used, it is assumed that the equipment has high accuracy, is well calibrated, the installation is according to the standard, the maintenance is well conducted, and the data collection and treatment is free of error. Based on historical comparisons of wind records versus actual results, the total uncertainty for actual extreme wind relative to equipment measurements is 3.0%.

Long term representativeness: This uncertainty is associated with the length of the recording period, historical data availability, and representativeness of the long-term wind regime. Based on the study for 21 sites /12/, it is calculated that yearly variability in the annual extreme wind data is 15%. Therefore, the uncertainty of the period of X years is calculated as 15%/sqrt(X). The concurrent period generated by SWES is typically 10% to 20% of the possible concurrent period. The shorter period is used to evaluate the extreme wind. The uncertainty of using shorter periods compared to the full record is studied by using cup anemometers at the met mast for wind farm development at 5 locations with 10 minutes time step at various heights from 30m to 80m. The results of the study show that factoring for a 2.0% uncertainty is most appropriate.

Flow model: This uncertainty is associated with the WindSim flow modelling. It depends on suitability of the flow model to the flow pattern, model gridding, governing equations, boundary conditions, flow similarity, terrain similarity, and distance between reference wind and on-site wind locations. The uncertainty is estimated as 0.1% per km for simple terrains, and 0.15% per km for complex terrains.

Extreme wind model: It relies on the mathematical expression of the extreme wind. The uncertainty is estimated as 2.0% for the assumption of normal distribution. The sample size is important for creditable statistics because extreme wind events are rare. To capture a large sample size, 10mph wind speed bin is used. The uncertainty of using 10mph wind speed bins compared to 2mph wind speed bins is studied by using cup anemometers at the met mast for wind farm development at 5 locations with 10 minutes time step at various heights from 30m to 80m. The results of these studies show that accounting for a 2.0% uncertainty is appropriate.

Each uncertainty has been factored into the results of this report. Each uncertainty is assumed to be independent, and the total uncertainty is calculated by root-sum-square basis. The extreme wind estimation is assumed to follow a normal distribution, and the probability of non-exceedance is estimated as

Extreme Wind (P90) = Extreme Wind (P50) x (1 + 1.28 x Uncertainty);
Extreme Wind (P95) = Extreme Wind (P50) x (1 + 1.65 x Uncertainty).

The expected Extreme Wind PXX implies that there is a probability of XX% that the outcome will be less than PXX and a probability of (100-XX)% that the outcome will be more.

2 Wind Conditions

2 SEWS are located within the area 150km x150km around the potential solar park. The coordinates and wind conditions are in Table 2.1 and Figure 2.1.

Name	Easting (m)	Northing (m)	Height (m)	Recording period (year)	50 - year Extreme wind speed (mph)
Weather Station XXX	XXX	XXX	6.1	27	68.2
Weather Station XXX	XXX	XXX	8.0	10	75.2

Table 2.1 Location of reference wind conditions (UTM Zone 17, WGS 84)

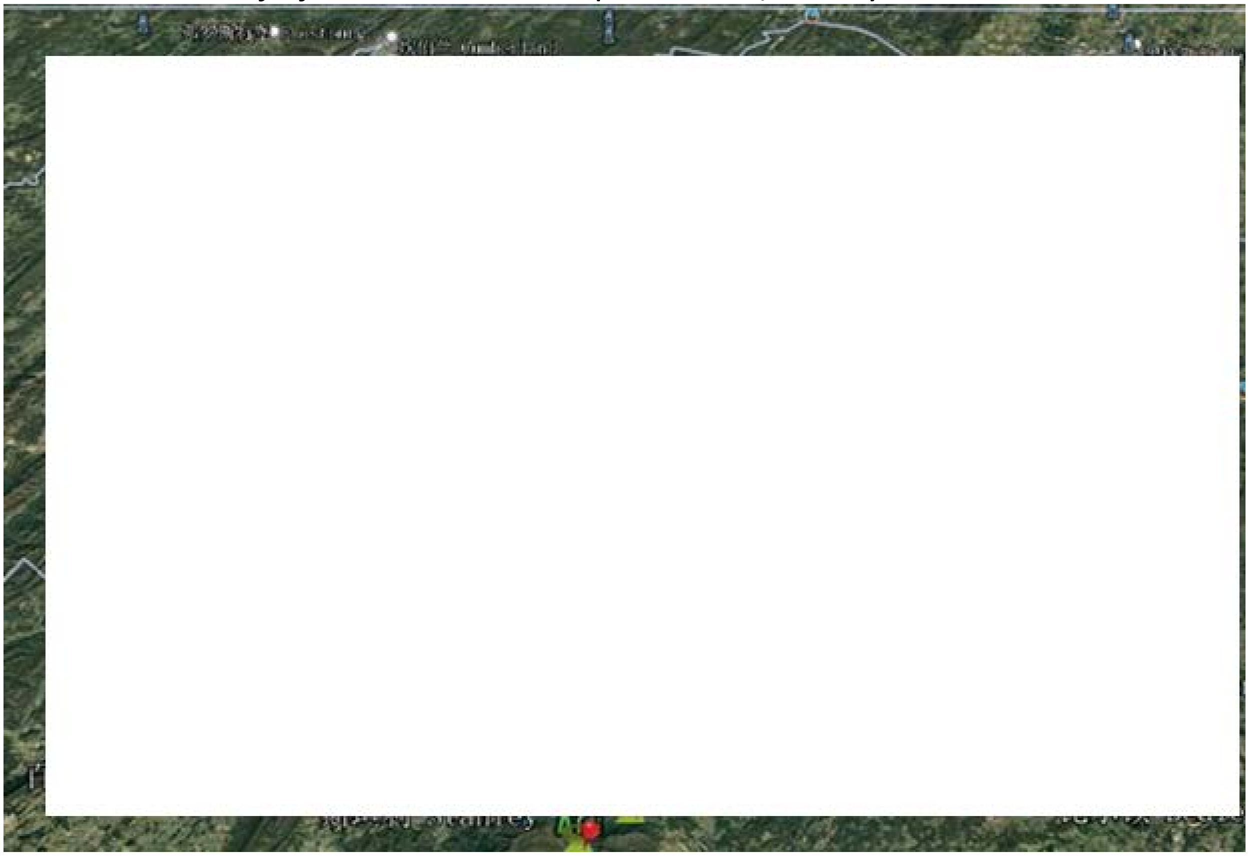

Figure 2.1 Location of reference wind condition, solar park and simulation domain

3 CFD Modelling

The detail of the digital terrain model is shown in Table 3.1, Table 3.2, Table 3.3 and Figure 3.1.

Parameter	Information
Extension	.gws
Type	Grid
Projection	UTM Zone 17
Horizontal Datum	WGS 84

Table 3.1 Geo information of the digital terrain model

Corner	Easting (m)	Northing (m)
Northeast	XXX	XXX
Southwest	XXX	XXX
	East-West (m)	**North-South (m)**
Distance	XXX	XXX
Resolution	XXX	XXX

Table 3.2 Coordinates and distance of digital terrain model (UTM Zone 17, WGS 84)

Land Cover	Roughness length (m)
Open Water	0.0003
Perennial Ice/Snow	0.0010
Developed, Open Space	0.0300
Developed, Low Intensity	0.0300
Developed, Medium Intensity	0.3000
Developed, High Intensity	0.5000
Barren Land (Rock/Sand/Clay)	0.0100
Unconsolidated Shore	0.0500
Deciduous Forest	0.4000
Evergreen Forest	0.4000
Mixed Forest	0.4000
Dwarf Scrub	0.0500
Shrub/Scrub	0.1000
Grassland/Herbaceous	0.0500
Grassland/Herbaceous	0.0500
Lichens	0.0020
Moss	0.0020
Pasture/Hay	0.0300
Cultivated Crops	0.0300
Woody Wetlands	0.2000
Palustrine Forested Wetland	0.3000
Palustrine Scrub/Shrub Wetland	0.1000
Estuarine Forested Wetland	0.3000
Estuarine Scrub/Shrub Wetland	0.1000
Emergent Herbaceous Wetlands	0.1000

Table 3.3 Roughness table for digital roughness model

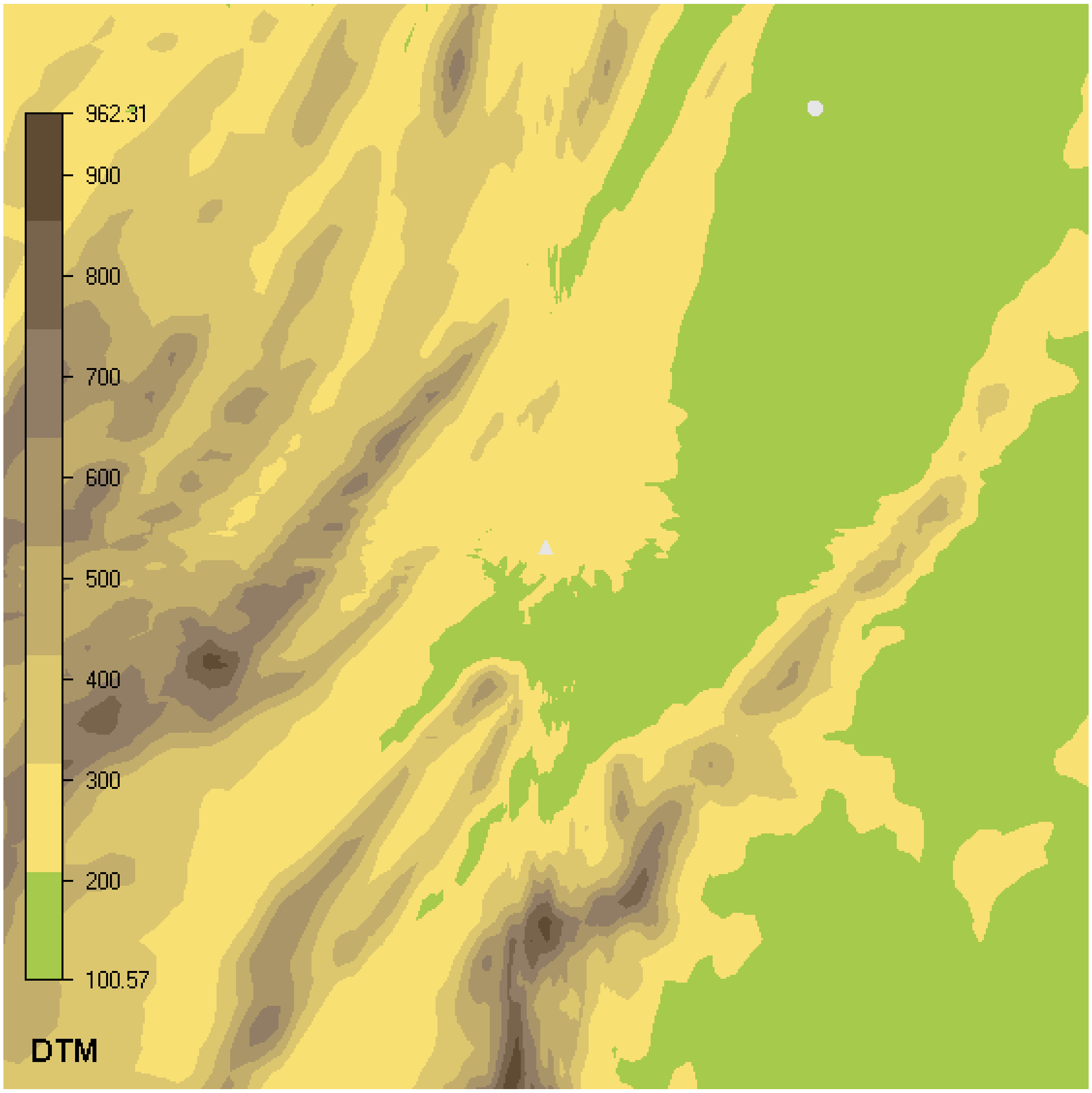

Figure 3.1 Digital elevation model (triangle is the solar park, dot is the reference wind)

The CFD flow model generates results for wind speed and direction at any point within the simulation domain. Figure 3.2 depicts the air winding down the hills and solar park along the way in a site.

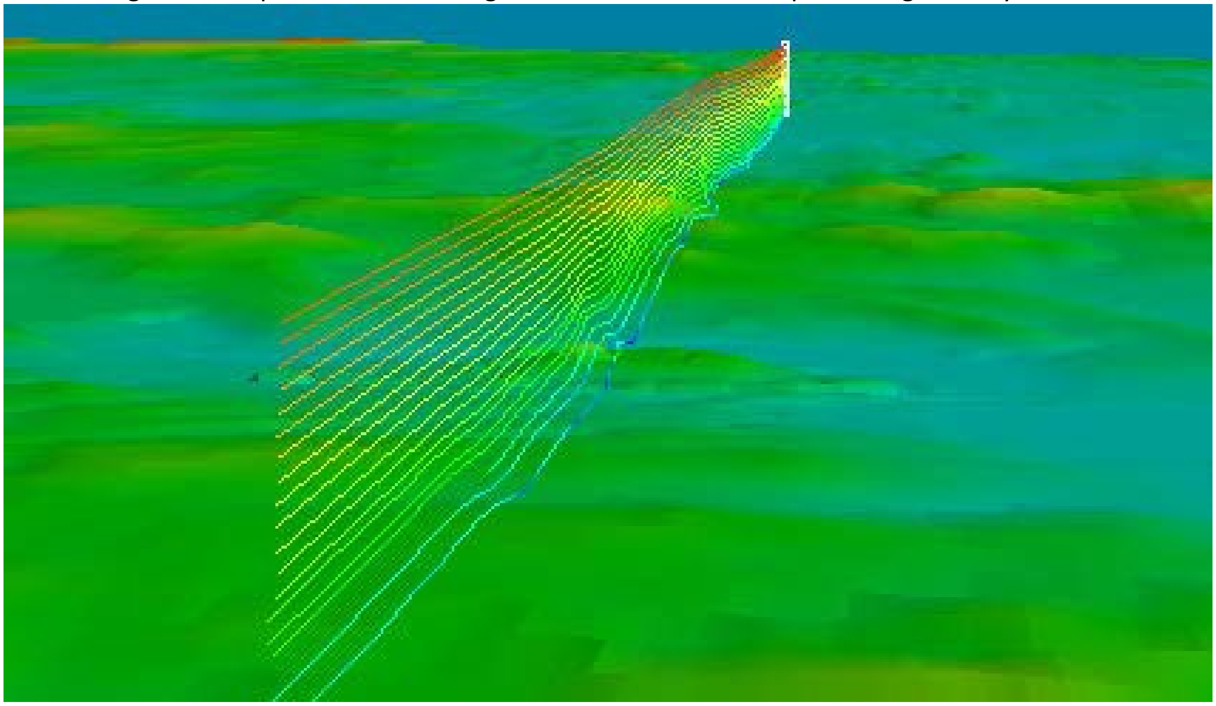

Figure 3.2 Wind flow in CFD model in a site

4 Extreme wind analysis

4.1 Extreme wind forecast at 5m, with 29 mph triggering wind speed

The weather stations XXX is used as reference station to generate on-site wind for assessment. 37 total years of wind speed data are used for frequency analysis and extreme wind ahead analysis.

During the 37 years, the wind speed over 29.0 mph happened 5848 times. It gives the frequency for wind speed over 29 mph at m as 158 times per year.

When the triggering wind speed is 29.0 mph, the concurrent period is generated with 10mph wind speed bins resulting in 1658 concurrent records. This represents 6% of the 5848 total possible records during the 37 years.

The average wind ahead within 5 minutes is calculated as 37.2 mph after triggering wind speed.

The standard deviation of the wind ahead is calculated as 3.8 mph.

The extreme wind ahead is calculated as 43.5 mph. There is a 95% probability that the wind speed within the next 5 minutes is equal to or less than the extreme wind ahead. The results are shown in Table 4.1, Figure 4.1 and Figure 4.2.

Triggering Wind Speed	**Triggering Wind Speed Bin Min**	**Triggering Wind Speed Bin Max**	**Mean Wind Speed Ahead**	**SD of Wind Speed Ahead**	**Extreme Wind Ahead**	**Number of Record**	**Total Possible Record**
mph	**mph**	**mph**	**mph**	**mph**	**mph**		
29.0	25.0	35.0	37.2	3.8	**43.5**	1658	5848

Table 4.1 Result of triggering wind speed and extreme wind ahead at 5m

The recording period is 37 years in total, the average distance between reference wind and solar park is 45km, and the site is considered simple based on a topographic study. The uncertainty analysis results are shown in Table 4.2 and Table 4.3.

	Item	**Unit**	**Uncertainty**
	Total Uncertainties	%	7.0
1	Wind record	%	3.0
2	Long term representativeness	%	2.9
3	Flow model	%	4.9
4	Extreme wind model	%	2.8

Table 4.2 Uncertainty analysis at 3.5m

Future Extreme Wind (mph)	5m
P50	43.5
P85	46.6
P90	47.4
P95	48.5

Table 4.3 Extreme wind with probability of non-exceedance analysis at 5m

4.2 Extreme wind forecast at 10m, with 29 mph triggering wind speed

The weather stations XXX is used as reference station to generate on-site wind for assessment. 37 total years of wind speed data are used for frequency analysis and extreme wind ahead analysis.

During the 37 years, the wind speed over 29.0 mph happened 7498 times. It gives the frequency for wind speed over 29 .0 mph at 10m as 202.6 times per year.

When the triggering wind speed is 29.0 mph, the concurrent period is generated with 10mph wind speed bins resulting in 786 concurrent records. This represents 10.5% of the 7498 total possible records during the 37 years.

The average wind ahead within 5 minutes is calculated as 40.8 mph after triggering wind speed.

The standard deviation of the wind ahead is calculated as 4.0 mph.

The extreme wind ahead is calculated as 47.4 mph. There is a 95% probability that the wind speed within the next 5 minutes is equal to or less than the extreme wind ahead. The results are shown in Table 4.4, Figure 4.3 and Figure 4.4.

Triggering Wind Speed	Triggering Wind Speed Bin Min	Triggering Wind Speed Bin Max	Mean Wind Speed Ahead	SD of Wind Speed Ahead	Extreme Wind Ahead	Number of Record	Total Possible Record
mph	**mph**	**mph**	**mph**	**mph**	**mph**		
29.0	24.9	34.9	40.8	4.00	**47.4**	786	7498

Table 4.4 Result of triggering wind speed and extreme wind ahead at 10m

The recording period is 37 years in total, the average distance between reference wind and solar park is 45km, and the site is considered simple based on a topographic study. The uncertainty analysis results are shown in Table 4.5 and Table 4.6.

	Item	**Unit**	**Uncertainty**
	Total Uncertainties	%	7.0
1	Wind record	%	3.0
2	Long term representativeness	%	2.9
3	Flow model	%	4.9
4	Extreme wind model	%	2.8

Table 4.5 Uncertainty analysis at 10m

Future Extreme Wind (mph)	10m
P50	47.4
P85	50.8
P90	51.6
P95	52.9

Table 4.6 Extreme wind with probability of non-exceedance analysis at 10m

5 Conclusions and Recommendations

1. Weather station is used as the reference wind for the extreme wind study. P85 value is used in the result.

2. At the height of 5m in XXX solar park, the frequency for wind speed over 29.0 mph is 158 times per year. When the triggering wind speed is 29.0 mph, the extreme wind ahead is 46.6 mph.

3. At the height of 10m, the frequency for wind speed over 29.0 mph is 202.6 times per year. When the triggering wind speed is 29.0 mph, the extreme wind ahead is 50.8 mph.

4. The extreme wind ahead is defined statistically as the wind speed within the next 5 minutes that is equal to or less than the extreme wind ahead with a 95% certainty of not being exceeded on the project site.

5. The uncertainty for the extreme wind ahead assessment is 7.0%.

6 Deliverables

The deliverables of this project are:

- 250418_XXX_100: Project report

7 References

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/5/ National Elevation Dataset, USGS, https://lta.cr.usgs.gov/NED

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