WHEN TRUST MATTERS

Land Based Wind (LBW) and Solar Profile Modeling for the NYISO

Modeling Methodology & Validation

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About

DNV is an independent consultant and has been involved with the wind and solar sector globally for the past 30 years. We work across the full project life cycle and have, in diverse capacities, played a role or provided technical services to most of the world's wind and solar projects.

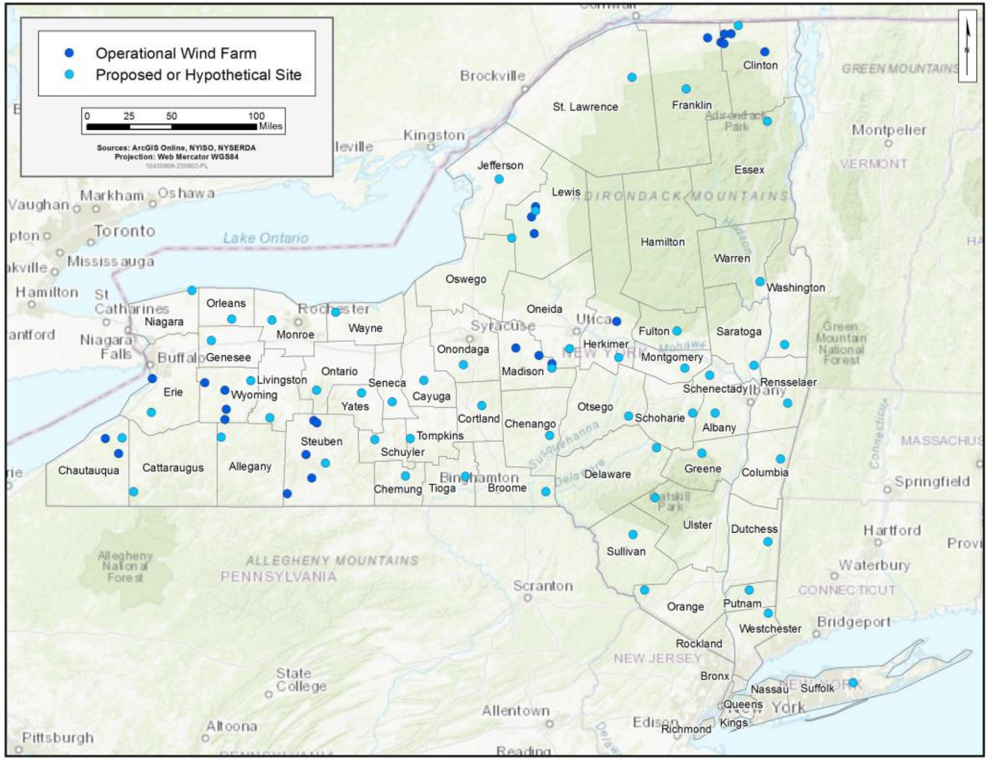
Relevant Expertise

Across the Northeastern U.S. DNV has conducted mesoscale modeling studies covering all offshore BOEM lease areas near New York, wind, solar and load modeling for the ISO-NE offshore wind integration planning advisory committee and most recently offshore wind profile modeling for the NYISO.

DNV has conducted more than 170 GW of onshore energy yield assessments in the U.S. Our energy assessment reports are trusted and relied upon for most of the project-financed projects in the U.S.

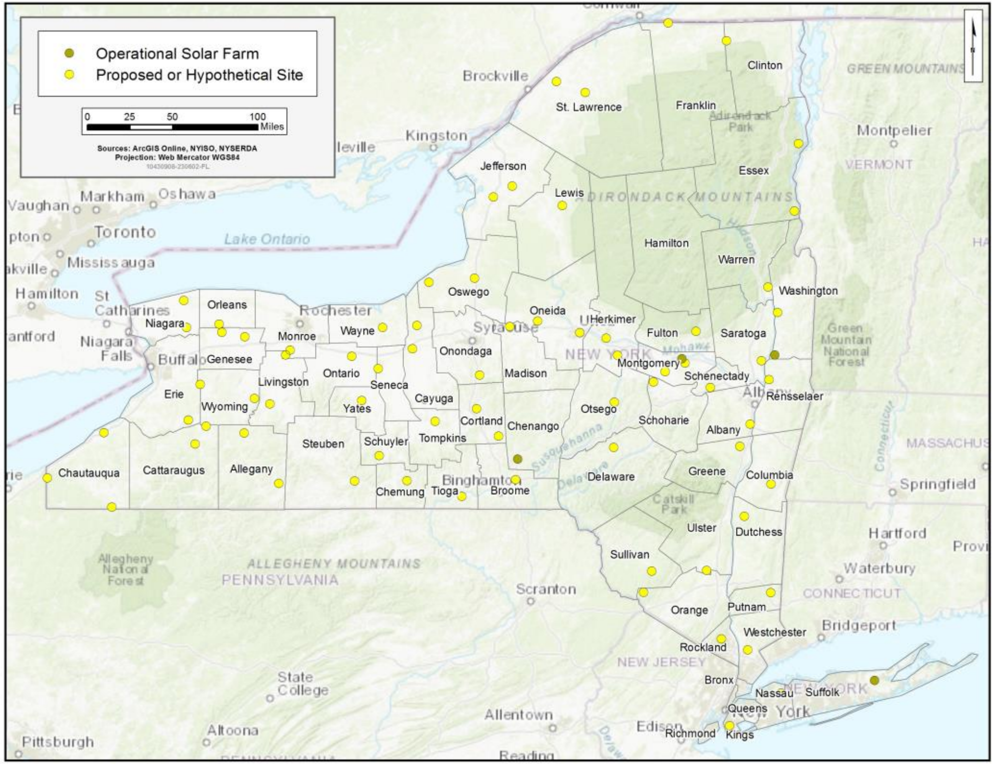
Project Description

- Hourly profiles of Land Based Wind (LBW) and Solar generation (2000 – 2022)
- Complimentary to offshore profile modeling work completed in early 2023.
  - 7 Offshore wind farm lease areas
  - https://www.nyiso.com/documents/20142/36079056/4%20NYISO_OffshoreWind_Hourly_NetCapacityFactor.xlsx/
  - Offshore Wind Profile Development – Summary (nyiso.com)
- 57 geopolitical counties
- Modeled hourly production at 79 LBW projects.
  - 25 Existing & 54 proposed or hypothetical wind projects



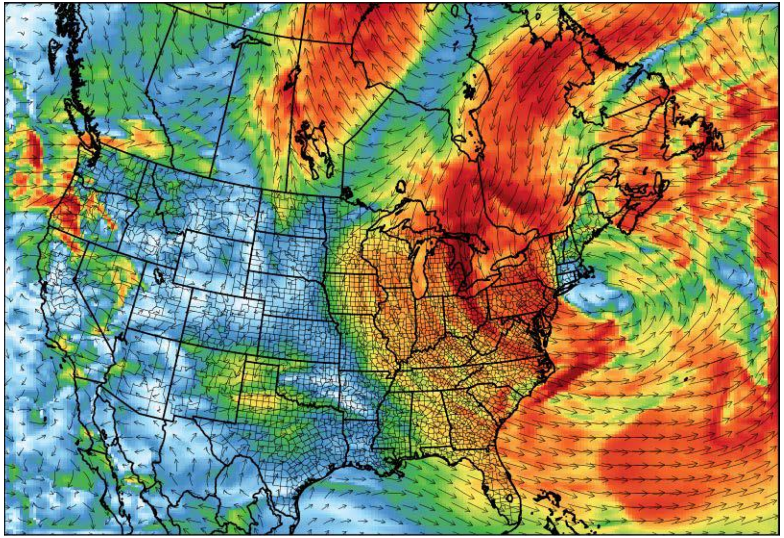
Project Description

- Modeled hourly production at 77 utility scale solar projects.
  - 4 Existing & 73 proposed or hypothetical solar projects
- Proposed projects from NYISO, NYSERDA or FAA lists of turbine locations
- High resolution weather model data
- Satellite measured irradiance
- Power modeling
  - Wind: High level wind-to-power model
  - Solar: High level open-source solar model



Weather Model – Wind

- DNV Wind Mapping System
  - The Weather Research and Forecasting (WRF) model, a state-of-the-art community mesoscale (regional) model
  - 2 km (horizontal) resolution - hourly
  - Calibrated using DNV's database of project wind speed estimates and the Global Wind Atlas (GWA)
- Inputs
  - NASA's Modern Era Retrospective-analysis for Research and Applications Version 2 (MERRA-2)
  - Global 500 m resolution land use, surface aerodynamic roughness and terrain elevation data.
  - Daily global 25 km analyses of lake and sea-surface temperatures.
  - 3-hourly global 25 km analyses of soil temperature and soil moisture, snow cover and snow depth.
  - Spectral nudging to preserve consistency between the large-scale state of the regional model and the driving global reanalysis weather patterns



Same weather model used for Offshore Wind Profiles

Wind Calibration

Wind Project Locations

- Bias correction using DNV's Windicative wind speed estimation tool
  - ➢ Calibrated version of Global Wind Atlas (GWA)
  - ➢ DNV's database of regional wind speed and shear values
  - ➢ No on-site measurements

NY Mesonet Stations

- Calibration using Analog Ensemble model
  - ➢ Adjusted using station measurements at 10 m
  - ➢ Did not use vertical extrapolation of wind speed estimates from GWA or DNV Windicative.

Average hub height wind speed bias for un-calibrated and calibrated data at 5 tall towers

Mean Bias in un-corrected data	Mean Bias in calibrated data
0.95 m/s	0.24 m/s

Table 2-4 Mean Bias Error for un-calibrated and calibrated data at 10 m NY Mesonet stations

Mean Bias Error		
Raw (un-corrected) WRF	Calibrated (using GWA)[1]	Calibrated (using DNV analog ensemble)
1.30 m/s	0.42 m/s	-0.01 m/s

1 This method was the only option available for the modeled data at the wind project locations

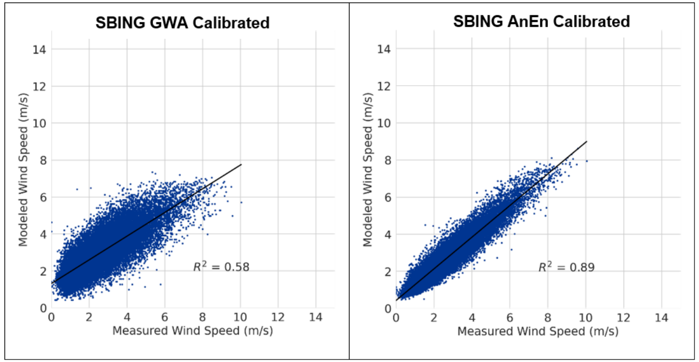


Figure 2-4 Performance of GWA and AnEn Calibrated Modeled Wind Speeds at BING

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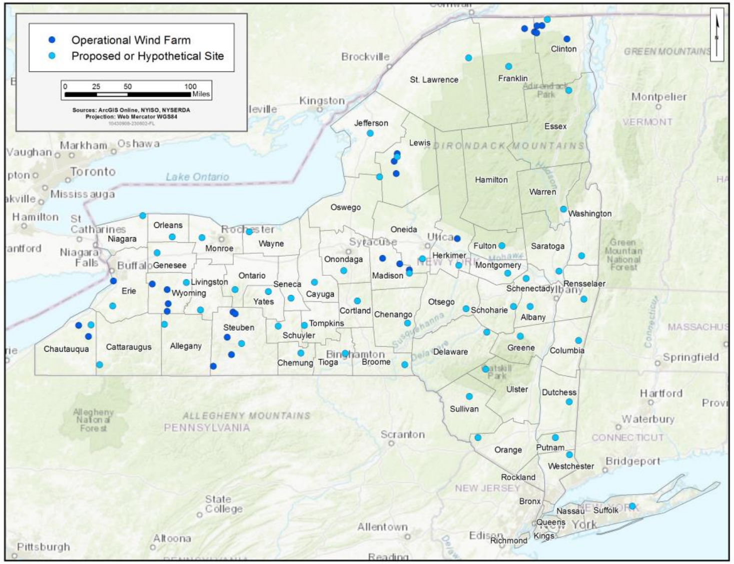
Wind Power Modeling

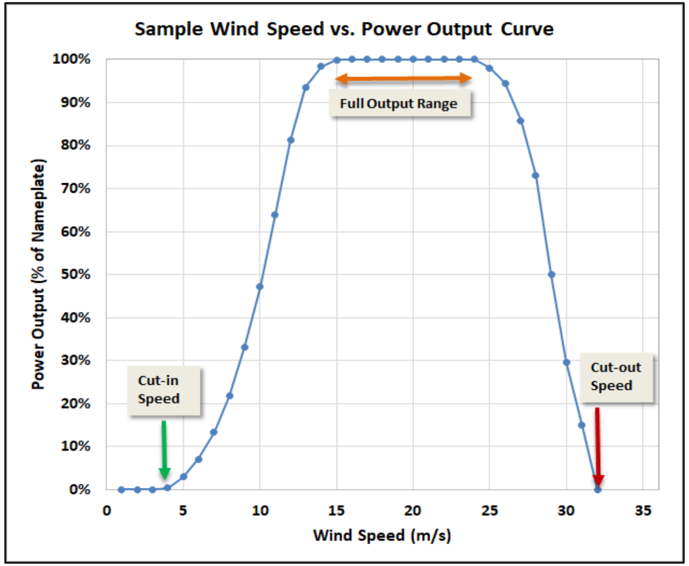
- Wind Turbine
  - Generic power curves for IEC design Class 1, 2 and 3 turbine: Scaled to project capacity
  - Representative of turbines in next 3 to 5 years
  - Hub height for hypothetical projects: 100 m
- Turbine Layouts
  - Not modeled explicitly
  - Representative project area
- Wind-to-Power Model
  - Energy production based on relationship of simulated wind speed and wind farm power curve
  - Accounts for seasonal and diurnal air density changes

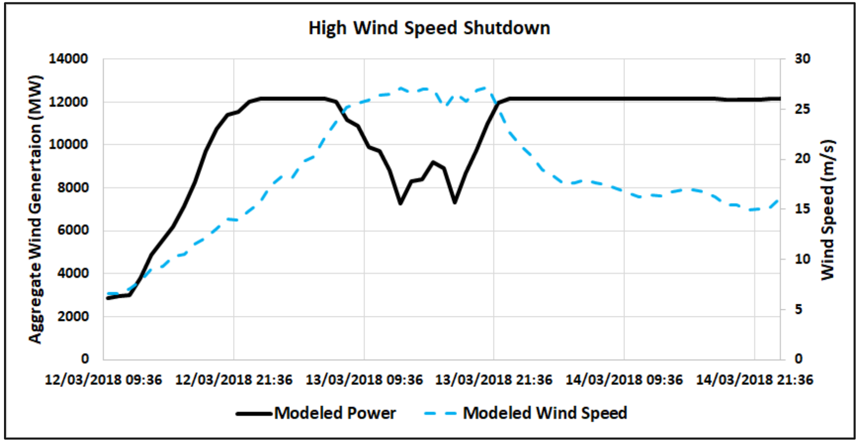


Modeling does not account for site-specific or microscale surface roughness, turbine rotor diameter and thrust curves, turbulence & turbine wake interactions.

Wind Turbine Power Curve Basics

Wind Speed (m/s)	Percent of Nameplate Power
0	0.00%
1	0.00%
2	0.00%
3	0.40%
4	3.00%
5	7.10%
6	13.30%
7	21.80%
8	33.10%
9	47.20%
10	63.90%
11	81.30%
12	93.60%
13	98.40%
14	100.00%
15	100.00%
16	100.00%
17	100.00%
18	100.00%
19	100.00%
20	100.00%
21	100.00%
22	100.00%
23	100.00%
24	98.00%
25	94.60%
26	85.80%
27	73.00%
28	50.00%
29	29.60%
30	15.00%
31	0.00%





Wind Farm Loss Modeling

- Wake and Blockage Losses
  - Wake loss: Reduction in wind speed/energy due to impact of the turbines on each other
  - Blockage loss: Resistance on the wind flow created by the turbines, deflecting flow above and around the wind farm
  - **Regional averages applied (not explicitly modeled)**
- Availability
  - Stochastically modeled on time series basis.
  - Groups of turbines become unavailable for several consecutive timesteps (hours/days) until they come back online.
  - Applied randomly throughout the time series
- Other Applied Losses
  - Electrical efficiency
  - Turbine performance losses (degradation, hysteresis, site specific power curve adjustment, turbine degradation)
  - Environmental losses (icing, temperature shutdown)

Losses not considered

- Curtailment due to avian risk
- Grid / economic curtailment
- Grid congestion
- Downtime due to extreme events
- Project specific environmental losses
- Explicitly modeled wake losses

Application of Loss Factors

- Bulk Losses
  - Wake, turbine performance, environmental, electrical
  - Direct application of all bulk losses -> unrealistic maximum power limit
  - Wake, performance, environmental accounted for by adjusting underlying wind speeds until the target P50 is reached
  - Electrical applied as flat loss
- Time varying losses
  - Availability
- Net P50 = Gross P50 - all losses

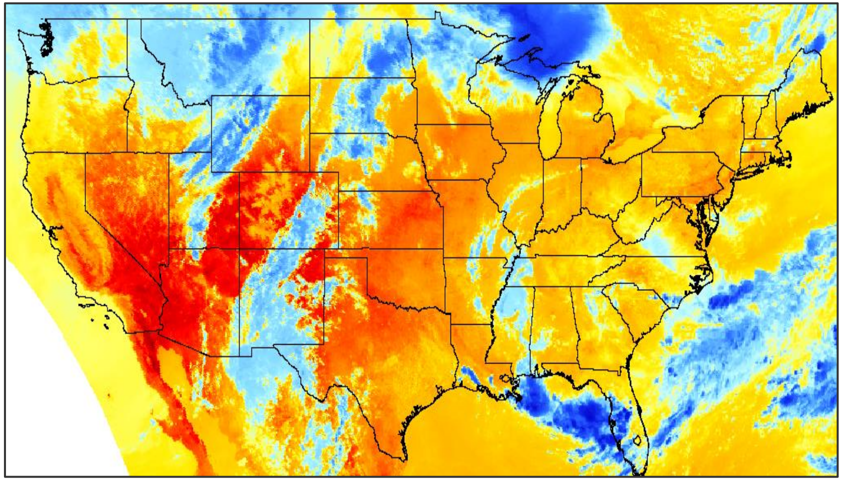
Assumed wake, performance, environmental, electrical and availability losses.

Wake	Turbine Performance	Environmental	Bulk Electrical Efficiency	Availability
94.1%	**96.0%**	**97.3%**	**97.5%**	**94.9%**

Solar Irradiance

- Satellite derived solar irradiance
  - 3-km resolution
  - Accounts for atmospheric aerosol and water vapor

- Average hourly solar irradiance across each project area
  - Global Horizontal Irradiance (GHI)
  - Diffuse Horizontal Irradiance (DHI)
  - Direct Normal Irradiance (DNI)



Example of satellite irradiance data (GHI, W/m^2)

Solar Power Modeling

- DNV's Solar Resource Compass (SRC) used to estimate initial Net P50 for each project.
  - ➢ High-level project configuration
- Modeling for both fixed and single axis tracker
- Community supported solar power conversion model
  - ➢ Open-source algorithms published by Sandia National Labs[1]
  - ➢ Losses due to temperature, wire resistance, inverter clipping included
  - ➢ Seasonal soiling due to dust and snow
- PV time series scaled to estimated Net P50

Basic PV system configuration for single axis tracker and fixed tilt mounting arrangements

Parameter	Single Axis Tracker	Fixed Tilt
Maximum Panel Tilt	60 degrees East-West	24 degrees
Array Axis Azimuth	180 degrees	
Panel Module Type	Monocrystalline Silicon	
Inverter Type	Central Inverter	
Mounting System	Ground Mounted Single Axis Tracker	Ground Mounted Fixed Tilt
DC/AC ratio	1.3	

1 – pvlib (Holmgren et al. 2018; https://doi.org/10.21105/joss.00884)

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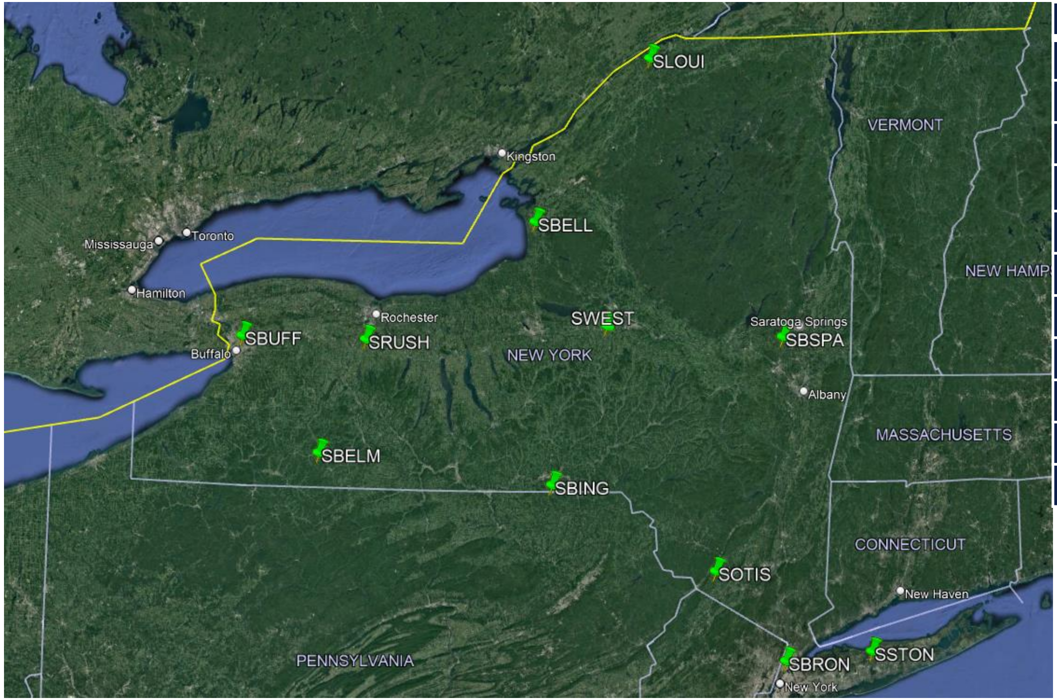
Validation

- 5 DNV Tall Towers
  - ➢ Accuracy of modeled wind speed data at hub height
  - ➢ 80 m to 100 m
- 11 NY Mesonet stations
  - ➢ Accuracy of wind speed and direction @ 10m
  - ➢ Temperature
  - ➢ Irradiance
- Comparison to actual generation

NY State Mesonet Locations



Station ID
SSTON
SBUFF
SBRON
SBELL
SWEST
SLOUI
SBELM
SRUSH
SBSPA
SOTIS
SBING

Tall Towers

- 5 Tall Towers (80m – 100 m)
  - Statewide Coverage
  - 2 to 5 years
- Modeled (calibrated) Wind Speeds

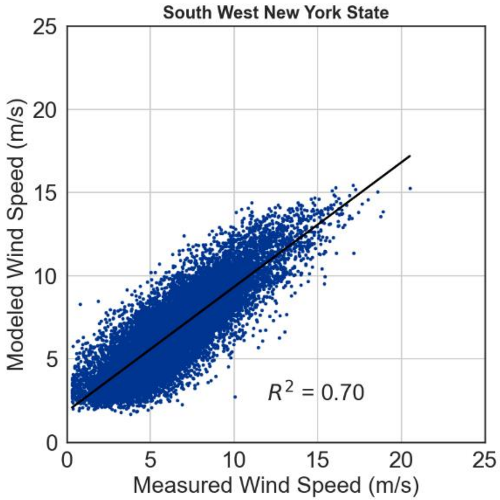
Error Stats

- Mean Bias Error (MBE): 0.24 m/s
  - Slight over prediction
  - Within 95% confidence limit
- Mean Absolute Error (MAE): 1.3 m/s
- RMSE: 1.7 m/s

Table 3-2 Mean Bias Error of modeled data at DNV Tall Tower locations

	MBE (m/s)
Mean	0.24
Standard deviation	0.30
95% Confidence Limit	0.59

Calibrated Modeled vs Measured Wind Speeds at 100 m at Tall Tower in southern New York



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NY Mesonet Wind Speed

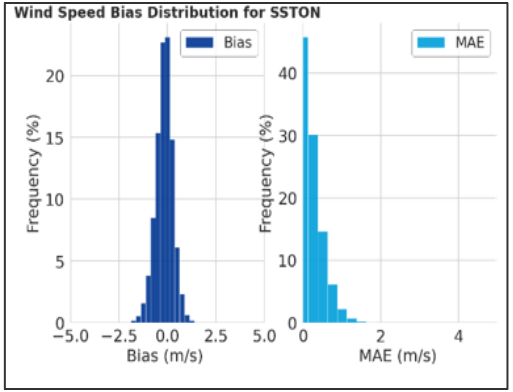
- Good agreement
- 2 years of overlap
- Modeled (calibrated) Wind Speeds

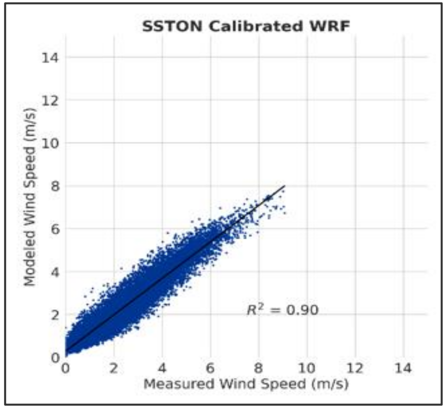
Error Stats

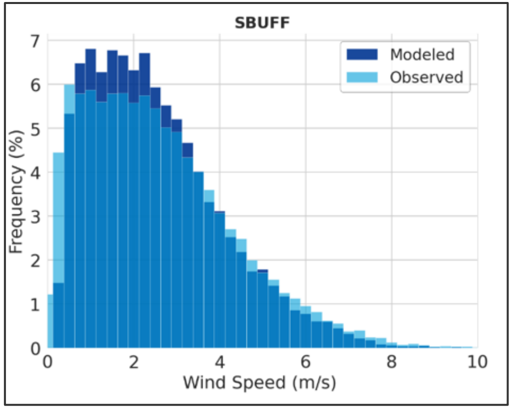
- Average bias at 10 m mesonet stations: 0.42 m/s
  - Within 95% confidence limit of 1.7 m/s
- R-squared: 0.87 to 0.90
- Measurements indicated greater frequency of low wind speeds
  - Model cannot capture localized terrain and roughness (trees)
  - Known limitation in WRF community

Table 3-4 Average modeled wind speed error

Station	MBE (m/s)	MAE (m/s)	RMSE (m/s)
SSTON	0.0	0.3	0.4
SBUFF	0.0	0.4	0.6
SBRON	0.0	0.4	0.5
SBELL	0.0	0.5	0.7
SWEST	0.0	0.5	0.6
SLOUI	0.0	0.4	0.5
SBELM	0.0	0.4	0.5
SRUSH	0.0	0.4	0.6
SBSPA	0.0	0.4	0.5
SOTIS	0.0	0.3	0.4
SBING	0.0	0.4	0.5







Wind Direction

- On average, good agreement
  - ➢ Some locations (SSTON) have small differences
  - ➢ Differences are likely due to local surface roughness or terrain effects.
- Measured data wind rose uses 15-minute records
- Modeled data based on hourly data

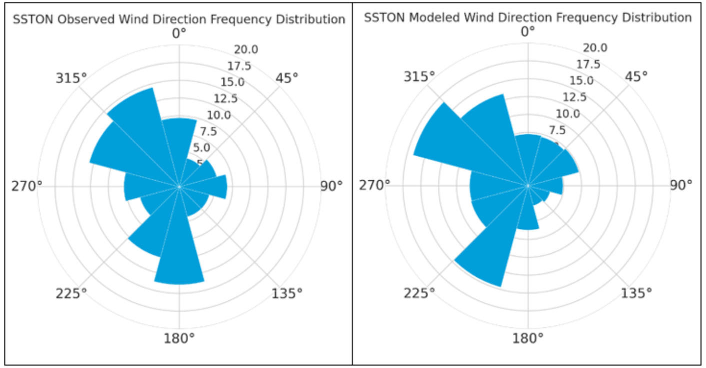


Figure 3-23 Wind Direction Frequency Distribution for Measured and Modeled data at SSTON

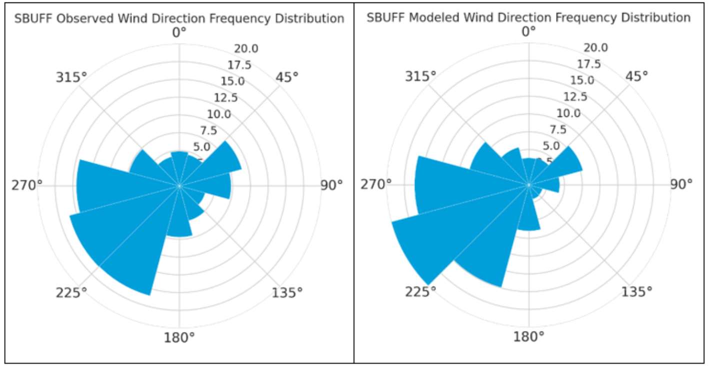


Figure 3-24 Wind Direction Frequency Distribution for Measured and Modeled data at SBUFF

Wind Speed Ramp Rates

- Agreement between modeled and measured
- Measured show broader distribution and larger ramp rates/variation in hourly wind speeds.
  - ➢ Expected due to mesoscale data at 2 km (smoothing effect)

Table 3-5 Measured and Modeled 1-hour Wind Speed Ramp Rate Quantiles

	SSTON		SBUFF	
Percent Rank	**Modeled (m/s)**	**Measured (m/s)**	**Modeled (m/s)**	**Measured (m/s)**
Minimum	-2.6	-4.1	-4.0	-5.8
10th	-0.4	-0.6	-0.6	-0.8
20th	-0.3	-0.4	-0.3	-0.5
30th	-0.2	-0.2	-0.2	-0.3
40th	-0.1	-0.1	-0.1	-0.1
50th	0.0	0.0	0.0	0.0
60th	0.1	0.1	0.1	0.2
70th	0.2	0.2	0.2	0.3
80th	0.3	0.4	0.4	0.5
90th	0.4	0.6	0.6	0.8
99th	0.9	1.3	1.2	1.7
Maximum	2.0	4.2	2.6	4.6

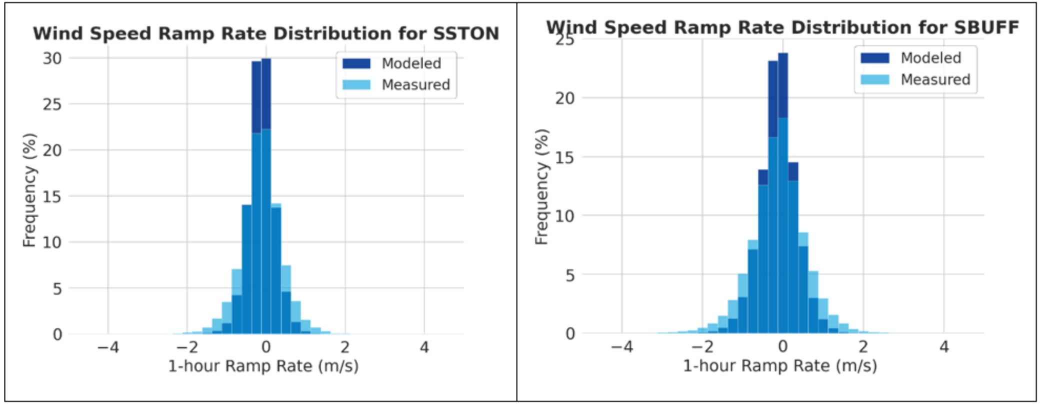


Figure 3-34 Measured and Modeled 1-hour Wind Speed Ramp Distribution for SSTON and SBUFF

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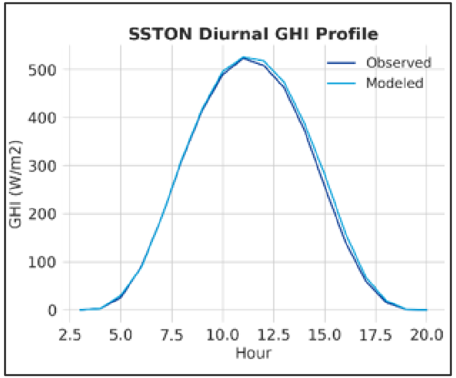
Solar Resource Comparison

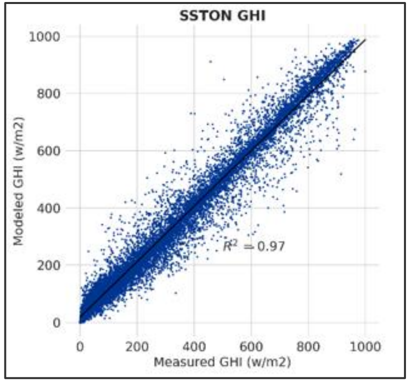
- Day-time records only (GHI)
- Biased high by about 4.1%
  - ➢ Within pyranometer uncertainty of ± 5%
- Normalized MBE, Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (nRMSE)
  - ➢ Normalized by daily mean for each site
- MAPE of 13.8%
  - ➢ Within expected range (7% - 15%)
- nRMSE of 20.8%
  - ➢ Within expected range (11% - 24%)

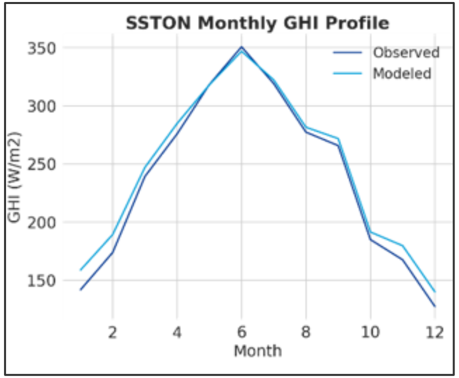
- Diurnal and seasonal profiles in agreement
  - ➢ Satellite-derived irradiance higher in winter
- Hourly R-squared: 0.93 – 0.97

Table 3-7 Average error in hourly (satellite-based) GHI

Station	MBE (%)	MAPE (%)	nRMSE (%)
SSTON	2.7	10.1	15.5
SBUFF	7.2	14.6	21.7
SBRON	3.6	13.1	19.2
SBELL	4.6	14.5	22.0
SWEST	3.4	14.2	21.3
SLOUI	4.0	13.3	20.0
SBELM	3.1	15.0	22.3
SRUSH	4.0	13.7	21.0
SBSPA	8.9	15.4	22.4
SOTIS	2.2	12.9	20.4
SBING	1.5	14.9	22.7





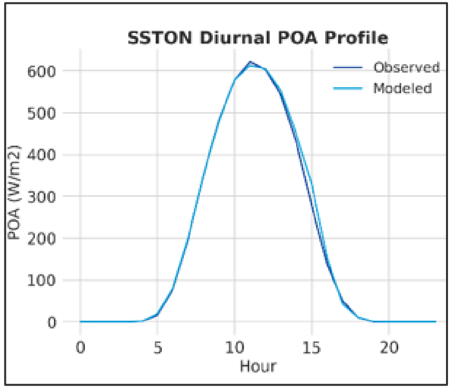


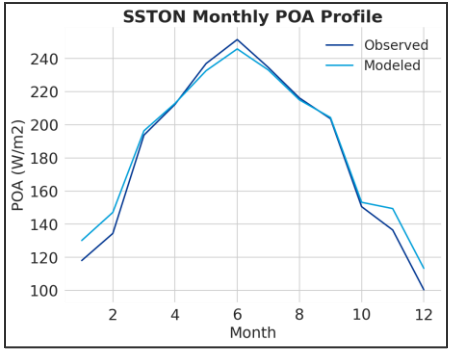
Plane of Array Irradiance (POA)

- 30-degree panel tilt
- Over estimation during winter months
  - Follows GHI
- Average bias of 4%
- MAPE: 16%
  - Within expectations given measurement uncertainty

Table 3-8 Average error in modeled POA at 30° tilt

Station	MBE (%)	MAPE (%)	nRMSE (%)
SSTON	1.9	11.9	18.8
SBUFF	6.8	16.7	25.8
SBRON	2.6	14.0	20.5
SBELL	5.6	17.4	27.5
SWEST	4.1	16.8	26.0
SLOUI	4.2	16.1	24.4
SBELM	3.5	17.2	26.2
SRUSH	4.6	16.5	26.1
SBSPA	7.9	17.0	24.9
SOTIS	1.4	14.5	22.7
SBING	1.1	16.7	25.8





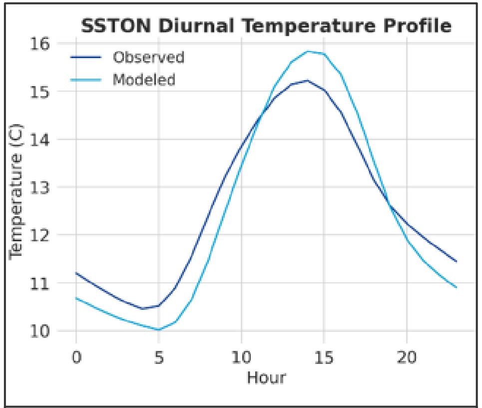
Temperature

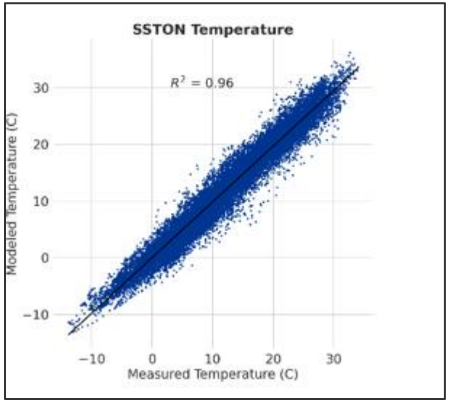
- Within 1°C of measurements at 2 m
- Slight timing shift
  - Measurements are based on averaged 15-minute records
  - Modeled data are instantaneous
  - Model may not be resolving station specific surface temperature fluxes

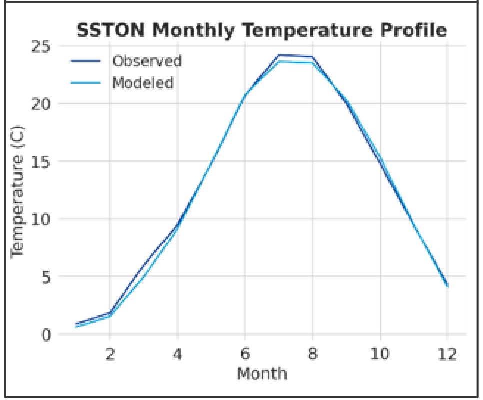
- Monthly profiles in good agreement
- R-squared: 0.95

Table 3-9 Average modeled temperature error

Station	MBE (°C)	MAE (°C)	RMSE (°C)
SSTON	-0.2	1.5	1.9
SBUFF	-0.3	1.7	2.2
SBRON	-0.9	2.0	2.6
SBELL	-0.7	1.8	2.3
SWEST	-0.2	1.9	2.5
SLOUI	-0.3	2.3	3.1
SBELM	-1.0	1.9	2.5
SRUSH	-0.1	1.8	2.3
SBSPA	-0.2	2.0	2.6
SOTIS	-0.8	1.9	2.4
SBING	-0.4	1.9	2.4





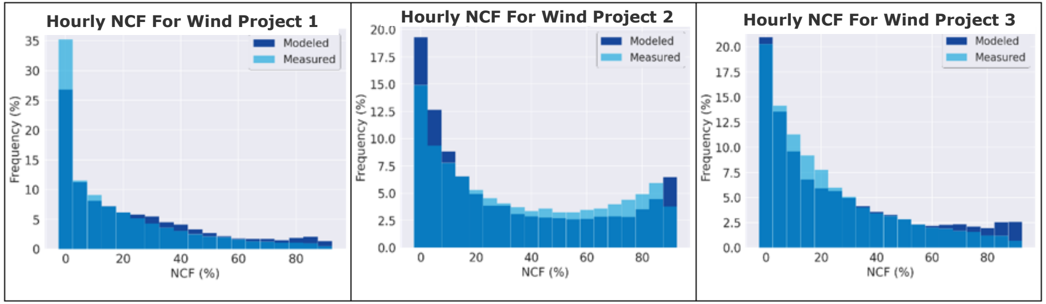


Energy Distributions

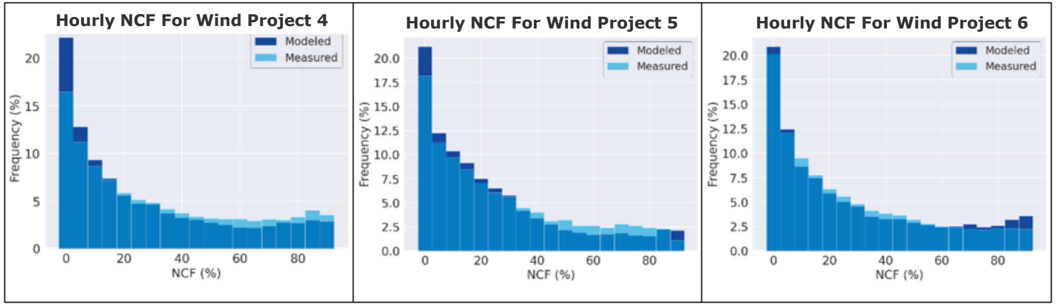
- Hourly operational data inclusive of availability, curtailment and performance losses.
- Class 2 turbine power curve
  - ➢ Not actual turbine model
- Modeled NCF uptick on right due to turbine being at rated power

- Discrepancies may be caused by:
  - – Differences in underlying wind resource data
  - – Turbine power curve shape and cut-in wind speed.

Measured vs Modeled Hourly Production Distribution at Wind Projects 1, 2 and 3



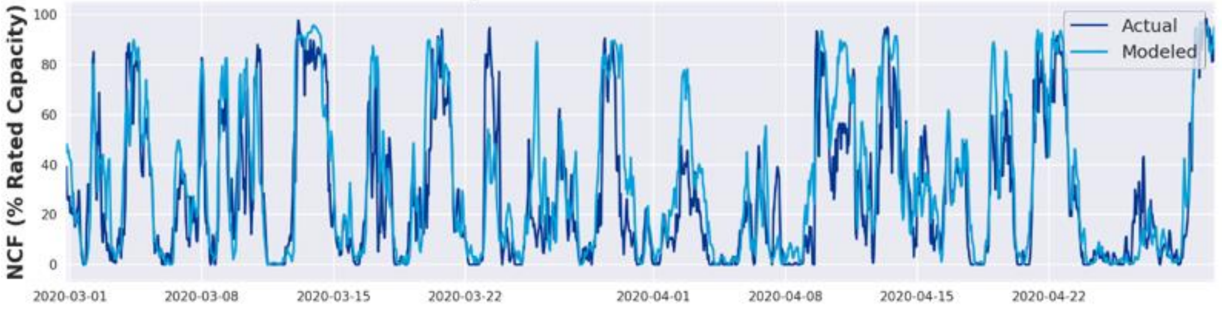
Measured vs Modeled Hourly Production Distribution at Wind Projects 4, 5, 6



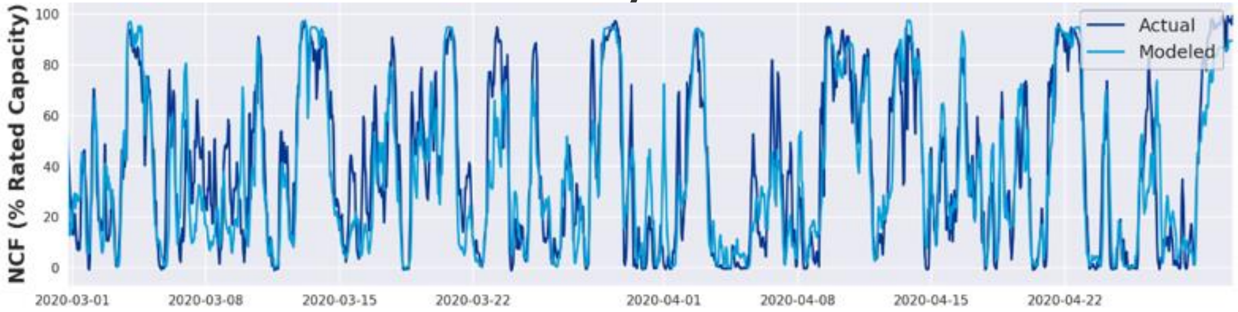
Modeled and Measured Power

- Good agreement
- Weather systems appear to be captured in modeled data
- Measured power data **not** used to inform modeled dataset

Measured vs Modeled Hourly Production at Wind Farm 1



Measured vs Modeled Hourly Production at Wind Farm 2



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Solar Energy Distributions

- In general, good agreement
  - ➢ Greater frequency of low production
- Discrepancies driven by:
  - ➢ Differences in solar resource
  - ➢ System technology and configuration
- Daytime hours only
- Single-axis tracker

Measured vs Modeled Hourly Production Distribution at Solar Projects 1, 2 and 3