Alexander Abboud
Jake Gentle
Jacob Lehmer
Tyler Phillips
Brandon Starks

Using Dynamic Line Ratings for Wind Farm Gen-Tie Line Considerations

Clean Power 2021 Virtual Event
June 7-10, 2021

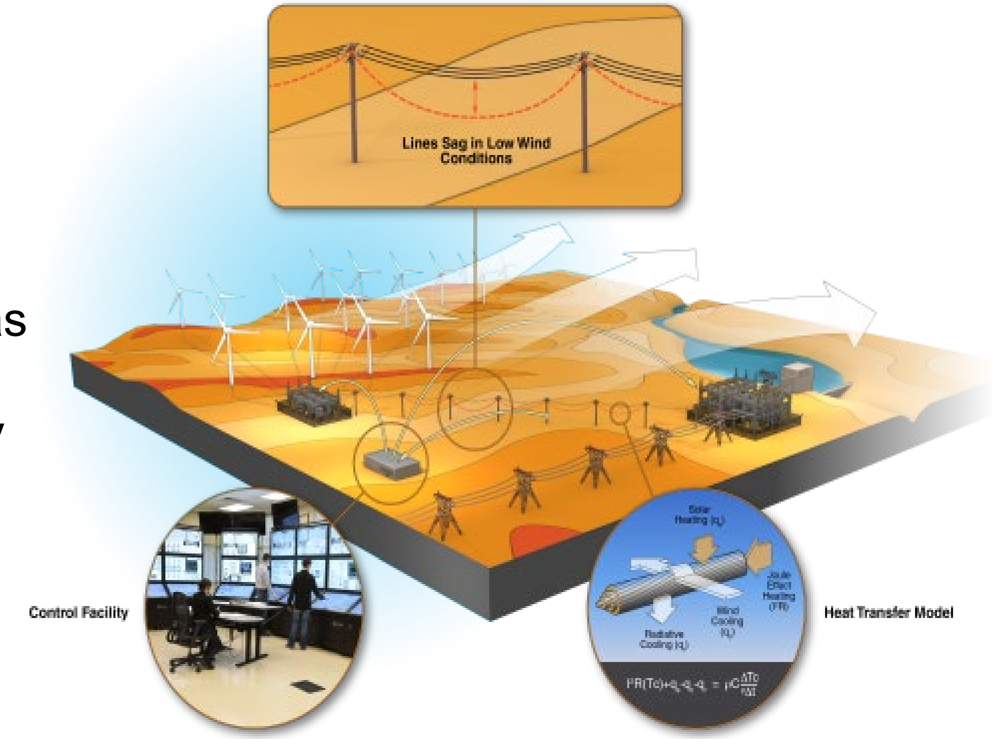
Idaho National Laboratory

Background

- IEEE/CIGRE standards provide a base for overhead transmission line ratings
  - Steady State Ampacity industry standard for Static Ratings using conservative environmental assumptions
- Measurement of many types of sensors provide a possibility to provide more capacity as a time varying capability
  - Direct sensors of line temperature, tension, or sag provide critical, location specific information.
  - Require complex transformation to determine line ampacity rating
  - Are direct measurements sensors placed at key location(s)?
  - Testing and careful calibration of sensors required
- Wide Area Weather-based DLR can provide a calculation of the moment-to-moment steady state rating
  - Definition of weather station proximity to spans is critical – One weather-station based calculation can not approximate a long line or a line with complex terrain.

State of the Industry

- The US produces 4.1 trillion Kilowatt-hours of electricity per year
- Distributed by 500 Power Companies
- 160,000 Miles (~260,000Km) of High Voltage (>100kV) transmission lines in the U.S. known as ”the grid.”
- Challenge is getting it to cities, factories, military bases in the right amounts when needed
- Power utilities operate transmission lines based on **static ratings**, which set a conservative limit on the amount of current the lines can safely carry without overheating
- **Dynamic line ratings** can allow for additional capacity on existing lines

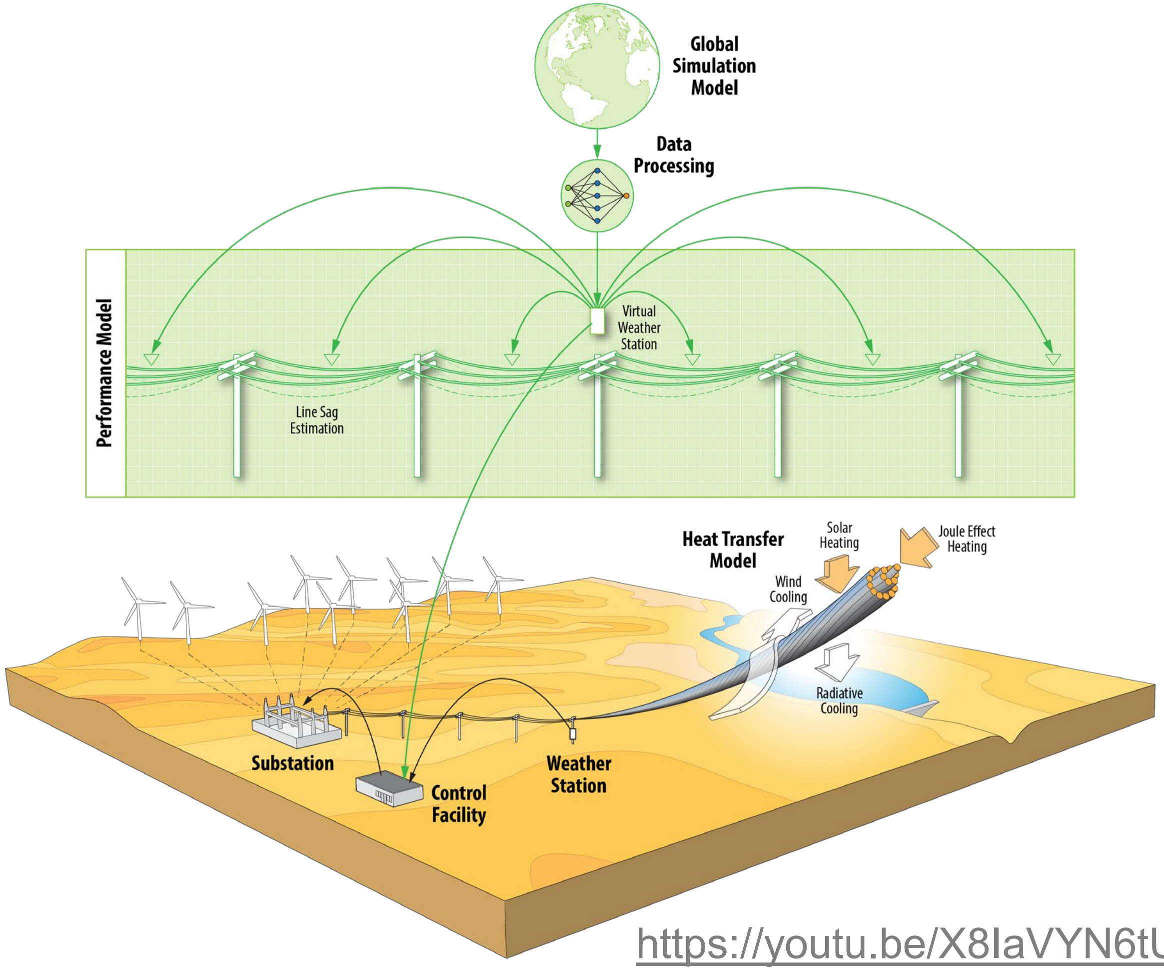


Without accurately measuring the environmental conditions and their effects, lines can be critically underutilized.

Without conservative and accurate forecasts of capacity utilities can NOT plan and effectively use the capacity.

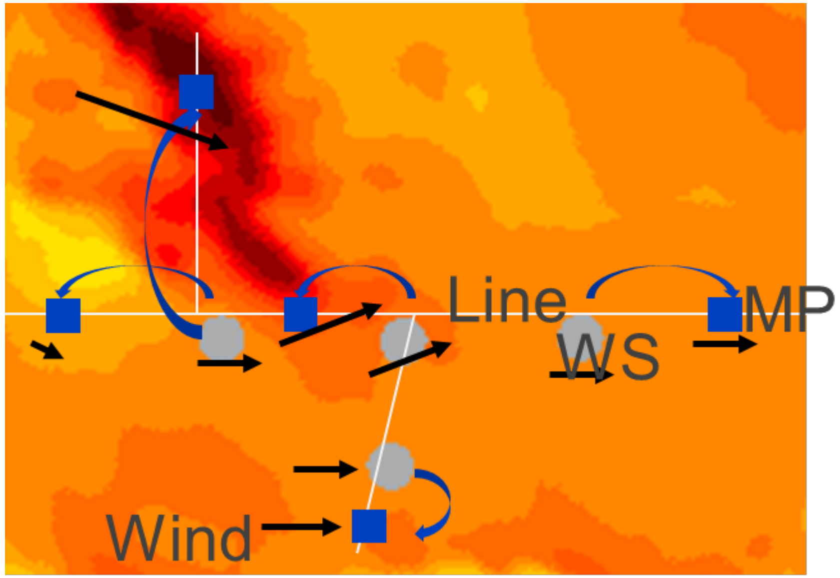
Technical Approach

Computational Fluid Dynamics Informed Weather Based Dynamic Line Rating



https://youtu.be/X8IaVYN6tUw

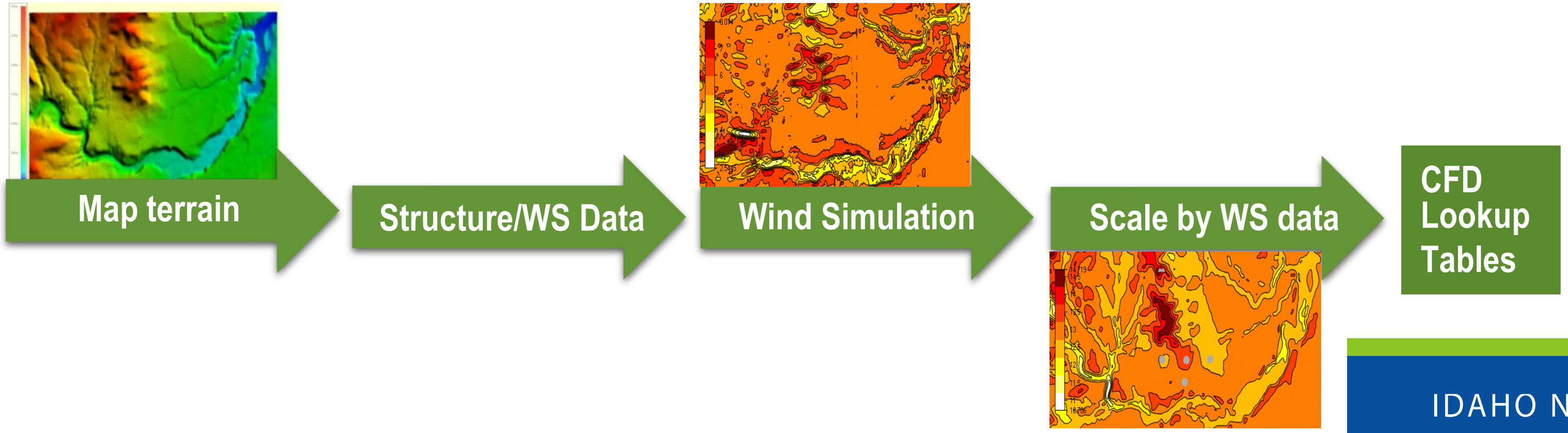
Use CFD to calculate relative speed and direction from measured (or forecasted) locations to spans



CFD Process

For each area:

- Identify bounds for simulation and section divisions based on approximated memory usage
- Create elevation/roughness layer
- Get weather station data/locations and structure midpoints
- Run wind simulations
- Extract data at all midpoint locations
- Create lookup tables scaled on the historical weather station data
  - difference in speed/direction from measured location to transmission lien location
- Lookup tables go into GLASS for historical/real-time/forecasted rating
  - Assume self-similar boundary profiles of wind speed



Line Rating Equations

- Heat balance of convective cooling, radiative heat loss, joule heating solar heating

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_C)}}$$

Where weather enters the equations directly

- In order to solve the steady state equation, we need:

$$T_{film} = \frac{T_s + T_a}{2}$$

$$q_{c1} = K_{angle} \cdot \left[1.01 + 1.35 \cdot N_{Re}^{0.52}\right] \cdot k_f \cdot (T_s - T_a)$$

$$q_{c2} = K_{angle} \cdot 0.754 \cdot N_{Re}^{0.6} \cdot k_f \cdot (T_s - T_a)$$

$$q_{cn} = 3.645 \cdot \rho_f^{0.5} \cdot D_0^{0.75} \cdot (T_s - T_a)^{1.25}$$

$$N_{Re} = \frac{D_0 \cdot \rho_f \cdot V_w}{\mu_f}$$

$$k_f = 2.424 \cdot 10^{-2} + 7.477 \cdot 10^{-5} \cdot T_{film} - 4.407 \cdot 10^{-9} \cdot T_{film}^2$$

$$K_{angle} = 1.194 - \cos(\phi) + 0.194 \cdot \cos(2\phi) + 0.368 \cdot \sin(2\phi)$$

$$\rho_f = \frac{1.293 - 1.525 \cdot 10^{-4} \cdot H_e + 6.379 \cdot 10^{-9} \cdot H_e^2}{1 + 0.00367 \cdot T_{film}}$$

$$\mu_f = \frac{1.458 \cdot 10^{-6} \cdot (T_{film} + 273)^{1.5}}{T_{film} + 383.4}$$

$$q_r = 17.8 \cdot D_0 \cdot \varepsilon \cdot \left[\left(\frac{T_s + 273}{100}\right)^4 - \left(\frac{T_a + 273}{100}\right)^4\right]$$

$$\theta = \arccos\left[\cos(H_c) \cdot \cos(Z_c - Z_1)\right]$$

$$\delta = 23.46 \cdot \sin\left[\frac{284 + N}{365} \cdot 360\right]$$

$$q_s = \alpha \cdot Q_{se} \cdot \sin(\theta) \cdot A'$$

$$H_c = \arcsin\left[\cos(Lat) \cdot \cos(\delta) \cdot \cos(\omega) + \sin(Lat) \cdot \sin(\delta)\right]$$

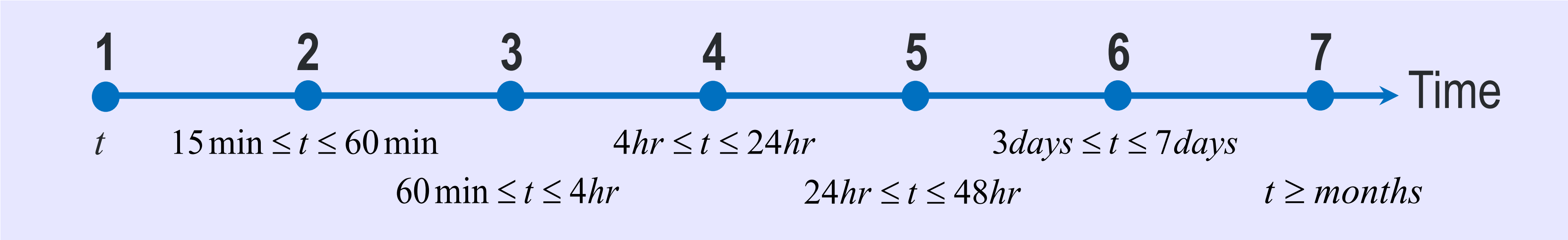
$$Z_c = C + \arctan(\chi)$$

$$R(T_{avg}) = \left[\frac{R(T_{high}) - R(T_{low})}{T_{high} - T_{low}}\right] \cdot (T_{avg} - T_{low}) + R(T_{low})$$

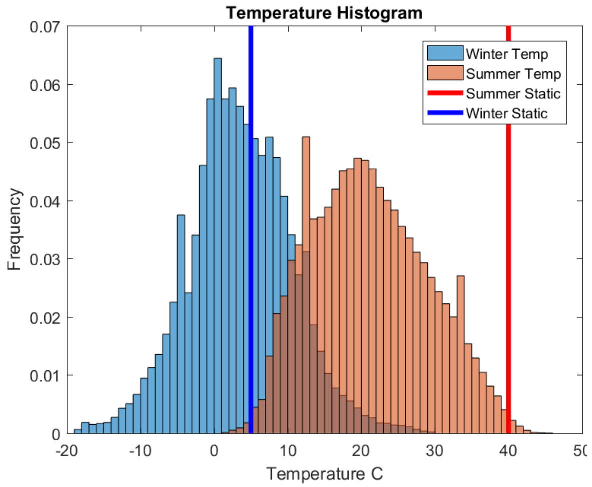
$$\chi = \frac{\sin(\omega)}{\sin(Lat) \cdot \cos(\omega) - \cos(Lat) \cdot \tan(\delta)}$$

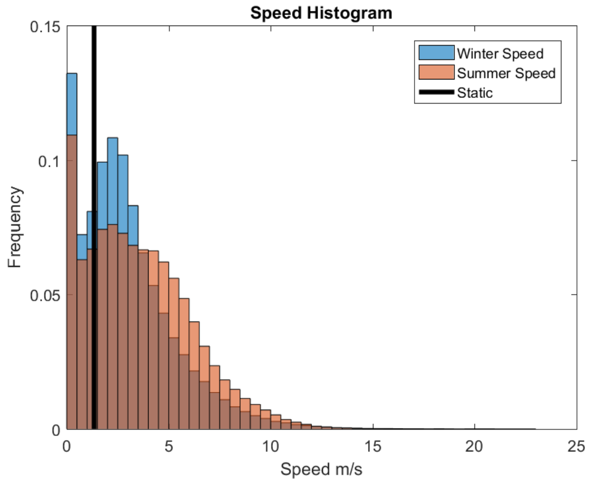
DLR Forecasting Suggested Timeline

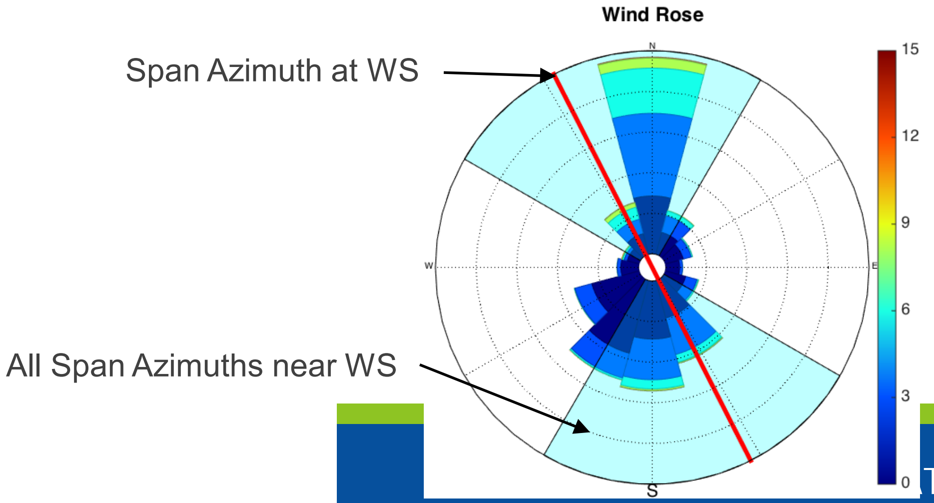
1. Instantaneous
2. Short-term: Thermal Inertia
3. Short-term look ahead
4. Daily Peak Loading, Generation Dispatch
5. Maintenance, Power Marketing
6. Maintenance, Marketing, Construction
7. Construction, Refurbishment, Voltage Upgrades



Visualization: How does weather data compare to static assumptions?
How does prevailing wind compare to transmission line direction?

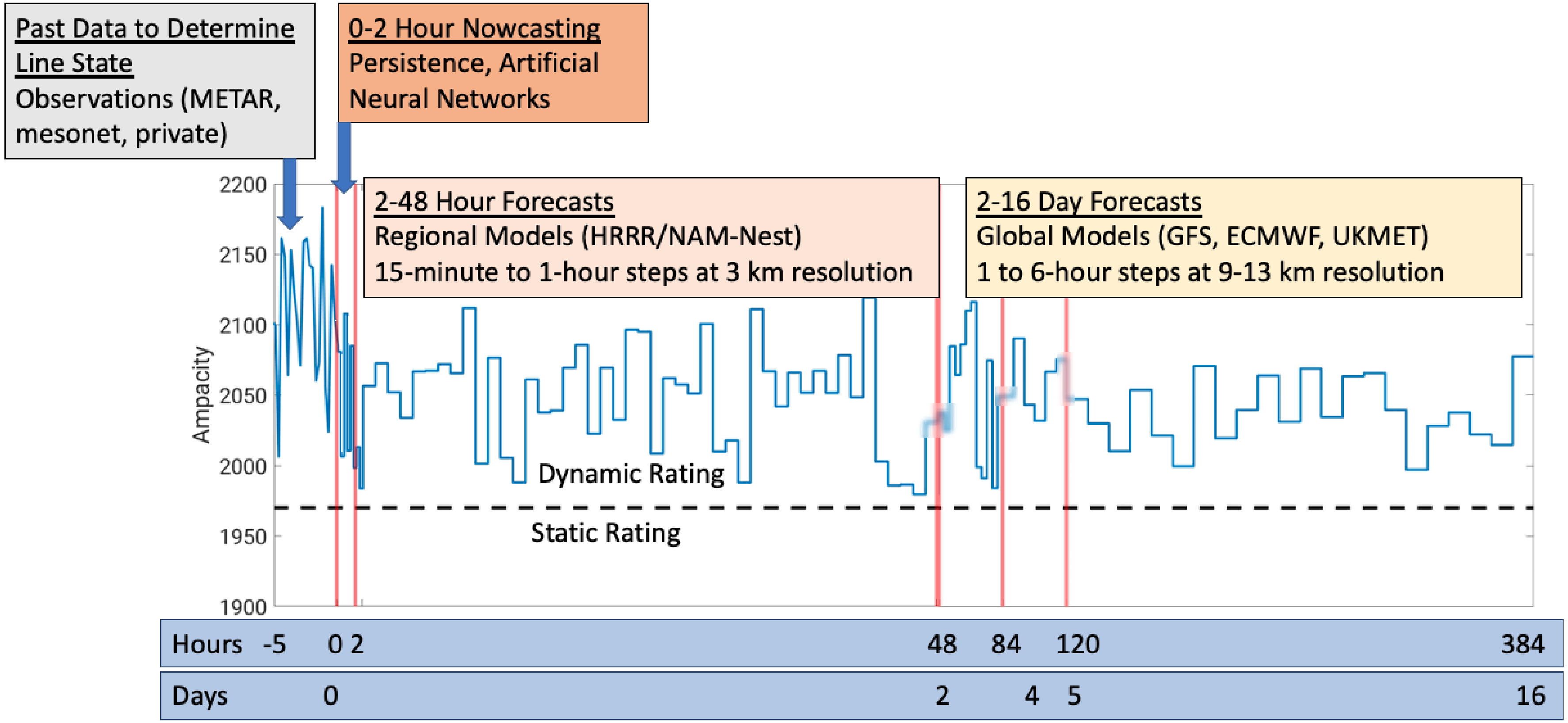






Forecasting Example

- Computation time frame delay occurs with obtaining updated regional forecast results
- Use ANN or persistence in region <2 hours in the future
- Beyond this, use regional forecasts with decreasing temporal updates based on how far in the future the forecast is needed



What is the HRRR?

- NOAA High-Resolution Rapid Refresh Model
  - Data is publicly available from NOMADS, some archived data available publicly

Inputs

Weather observations (temperature, wind, humidity, pressure)

Radar

Satellite

HRRR

Processing:

Partial differential equations

Parameterizations

Numerical approximations

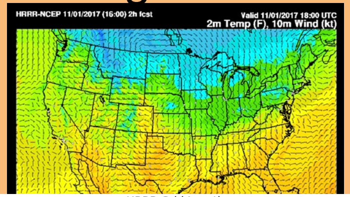
Outputs – Forecasts of:

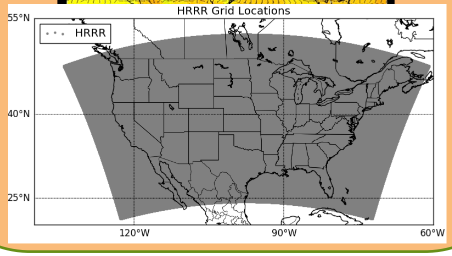
Temperature, Wind

Humidity, Rain, Clouds, etc

15-minute intervals up to 48 hours in HRRRv4

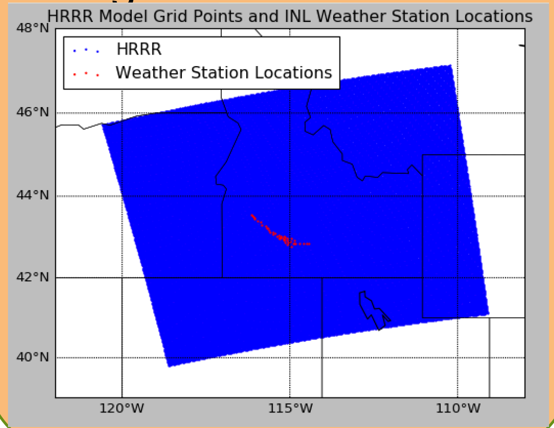
3 km resolution, with 10m height winds





Used in Idaho study

- Extract 3 km grid spacing over Idaho
- Output variables of temperature, wind speed, wind direction, and solar flux at 10 m height at WS locations



http://www.nco.ncep.noaa.gov/pmb/products/hrrr/

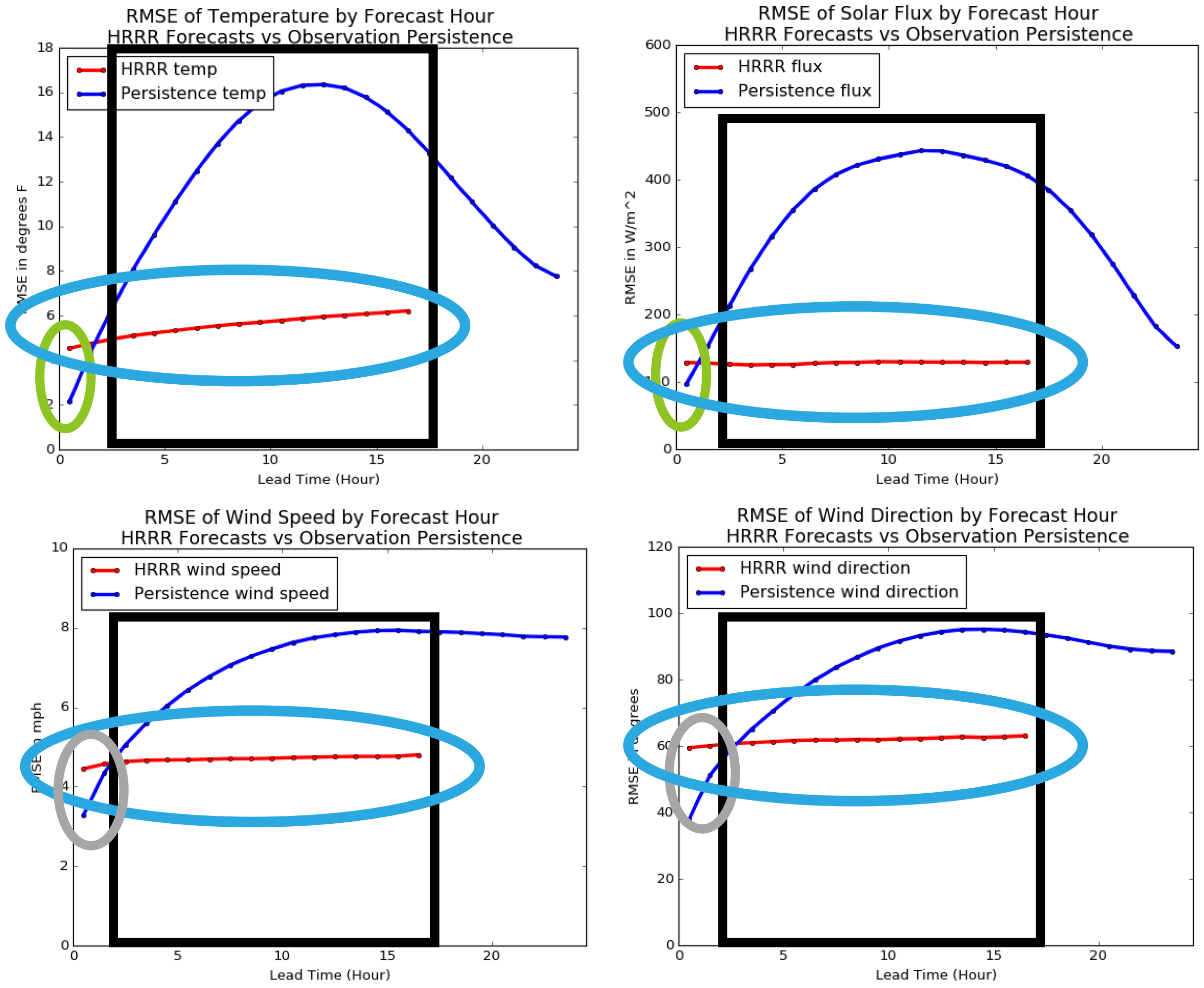
Accuracy with HRRR Forecasts

HRRR forecasts are more accurate than persistence for lead times 2.5 – 16.5 hours

Persistence is better than the HRRR at the 30-minute lead time

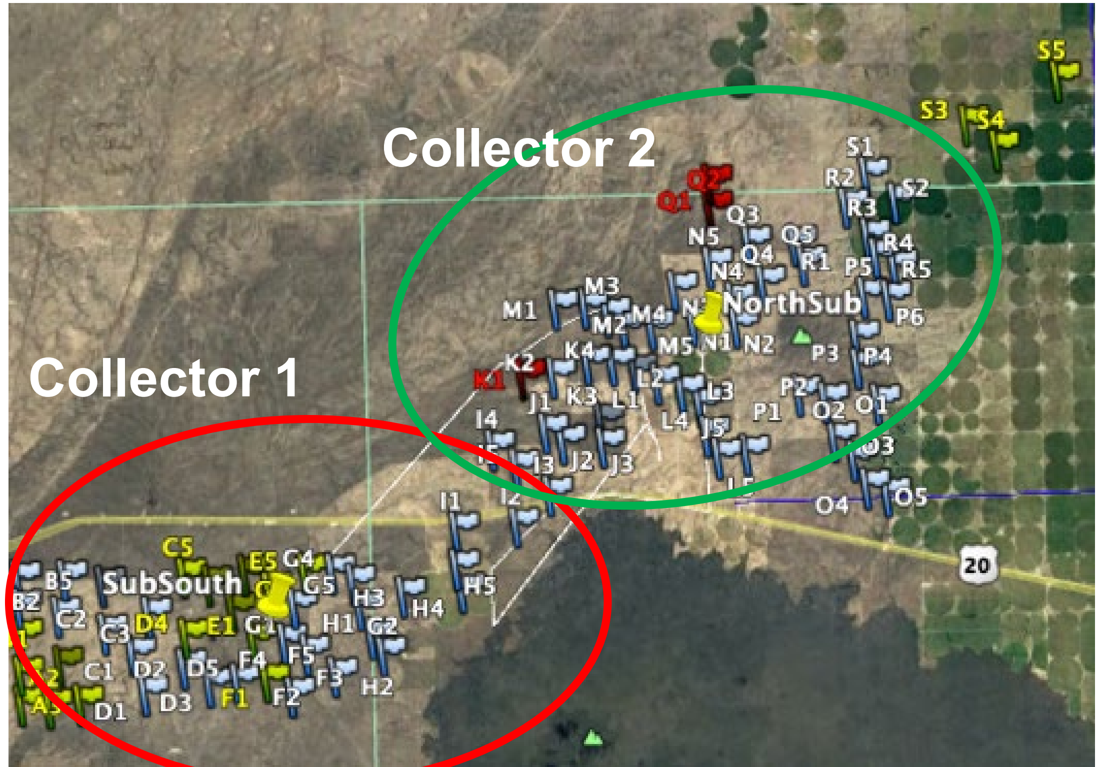
Similar errors at 1.5 hour lead time (except wind direction)

Over time the error of the HRRR does not significantly increase – similar accuracy in ampacity should be expected whether using HRRR for 3 hours in future or 18 hours in future



Wind Farm near Idaho Falls

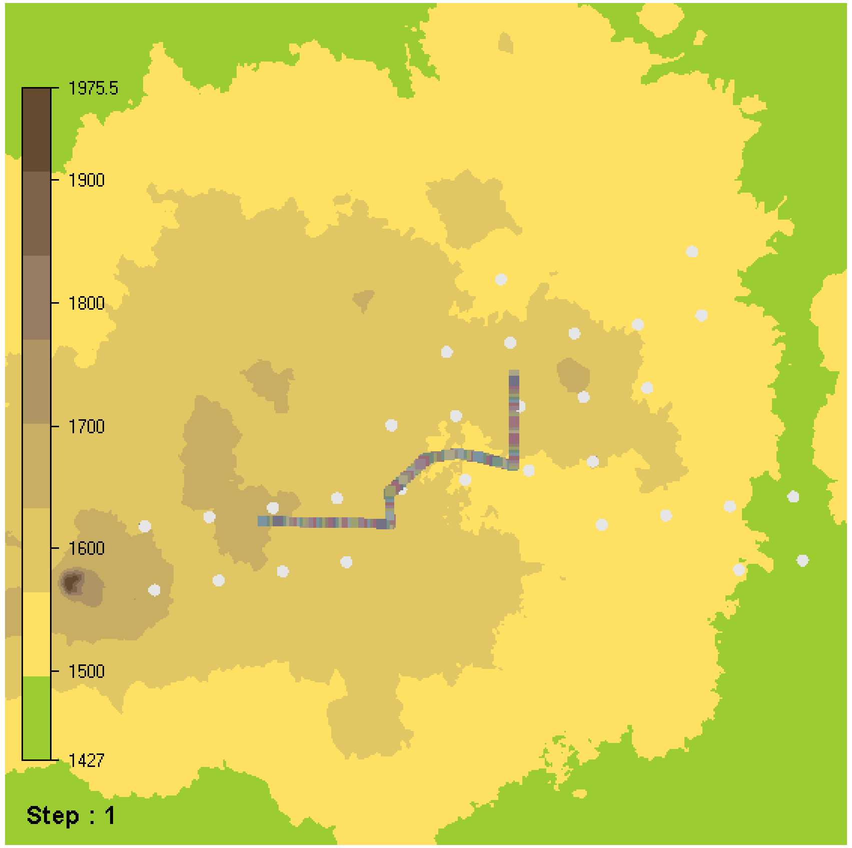
- 78 Turbines total turbines
  - Collector 1: Turbines 1-38,
  - Collector 2: Turbines 39-78
- 115 m hub height, 170 m blade, 5.8 MW max
- 225 MW from collector to collector and 450 MW collector to transmission



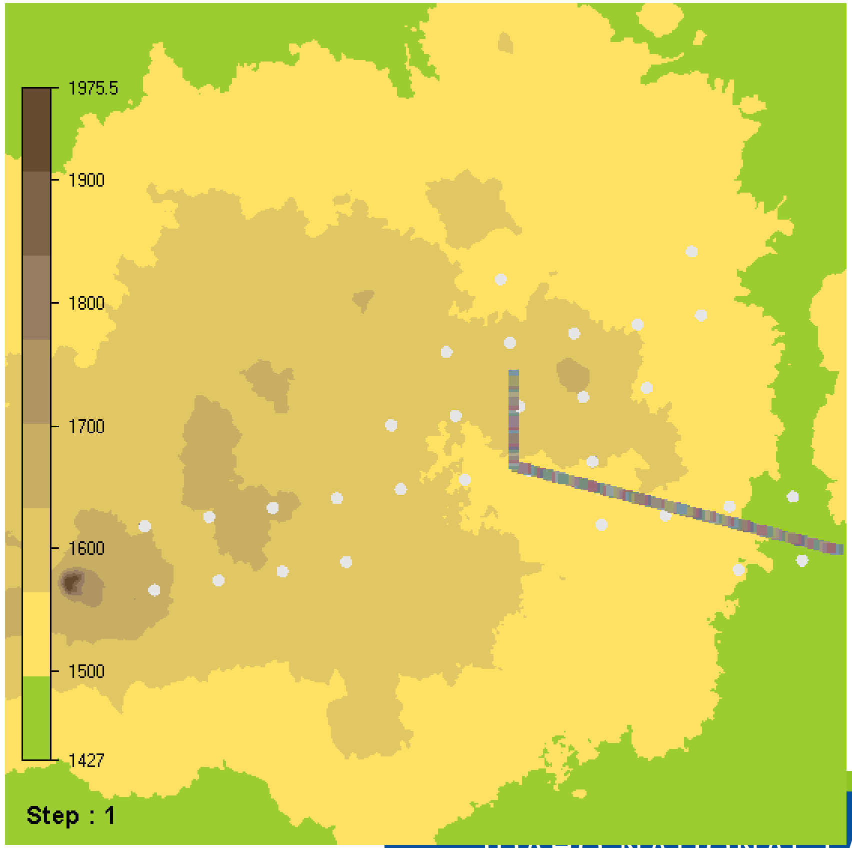
Gen Tie Lines

- Squares show midpoints, circles show HRRR locations

Collector 1-to-collector 2
225 MW capacity

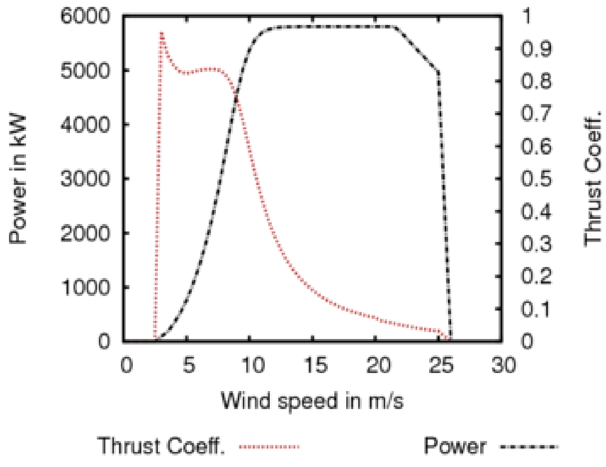


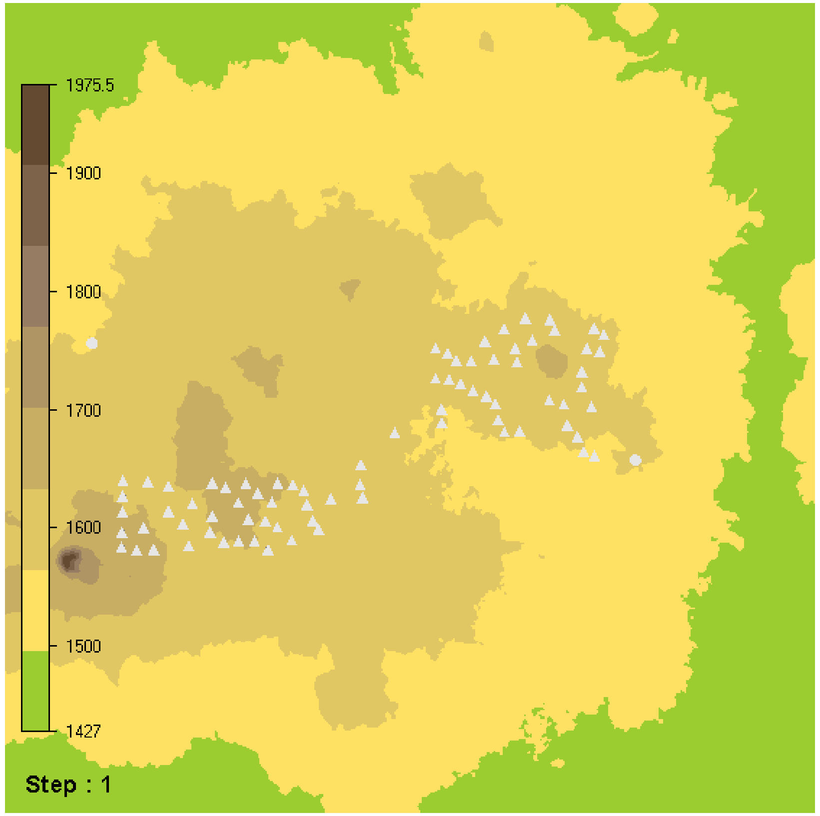
Collector 2-to-transmission
450 MW capacity

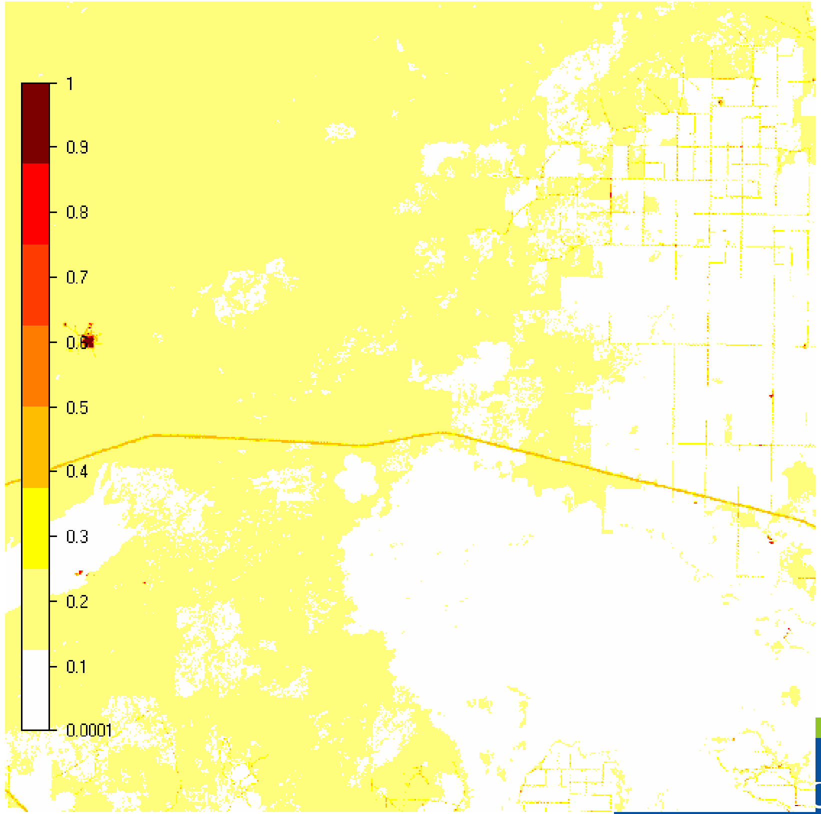


Updated Turbines

- Triangles show Turbines, circles are weather stations
- Use power curve for 5.8 MW turbines, CFD calculates difference in wind speed from measurements to turbines and feeds into power curve







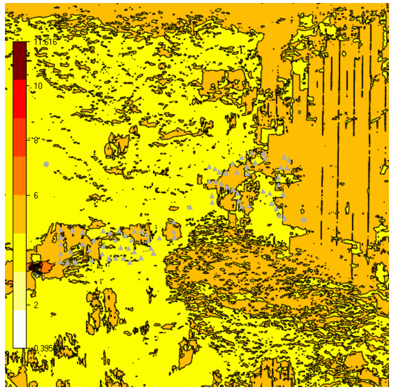
Roughness layer shows major features

Highway
MFC blip
Lava field

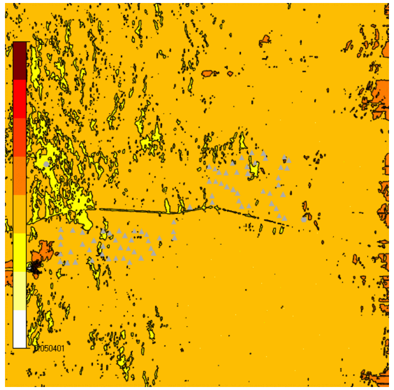
Computational Fluid Dynamics

- Results shown at line height and turbine height

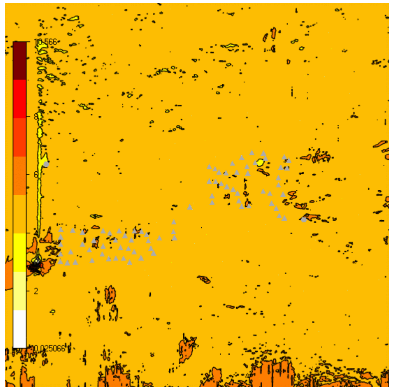
North



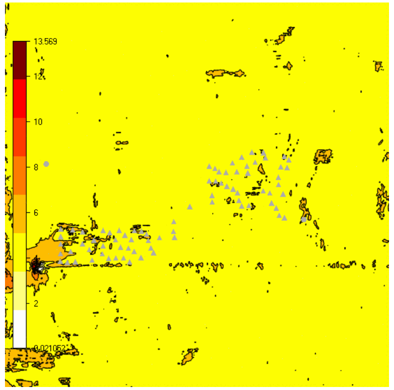
East



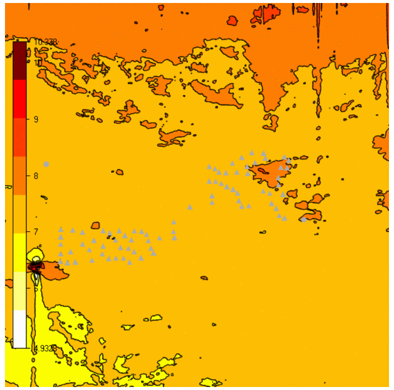
South

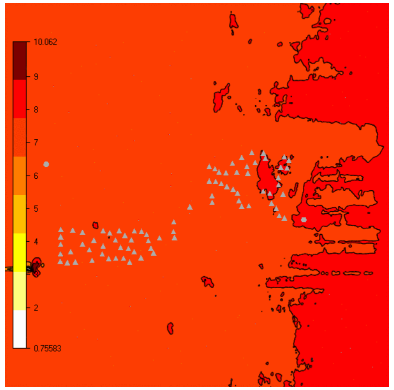


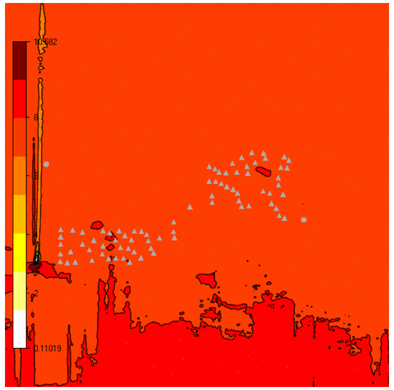
West

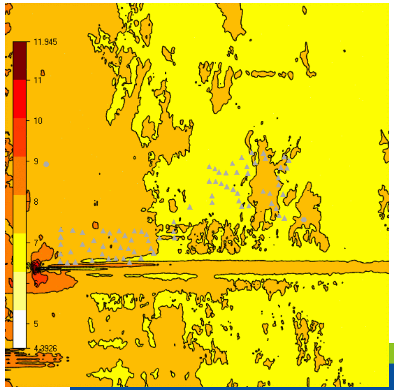


10m ABG







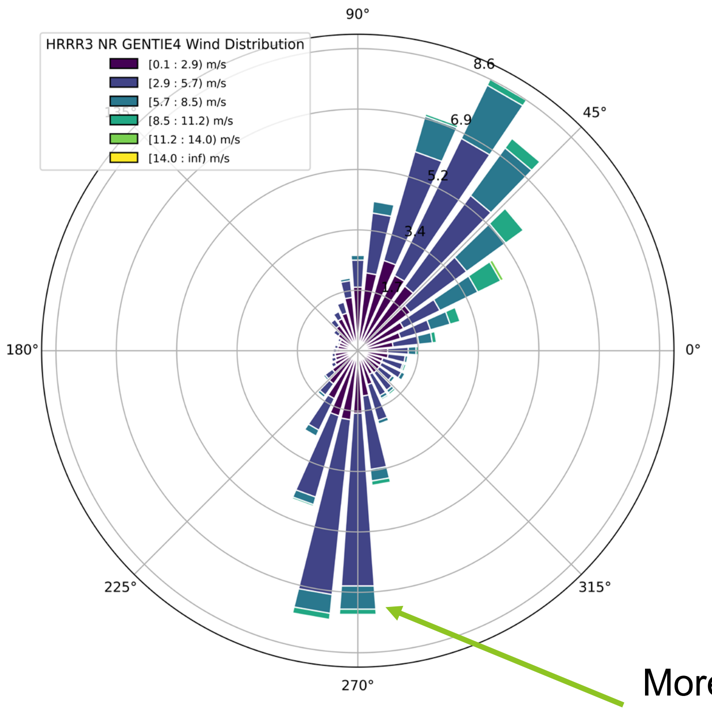


115m ABG

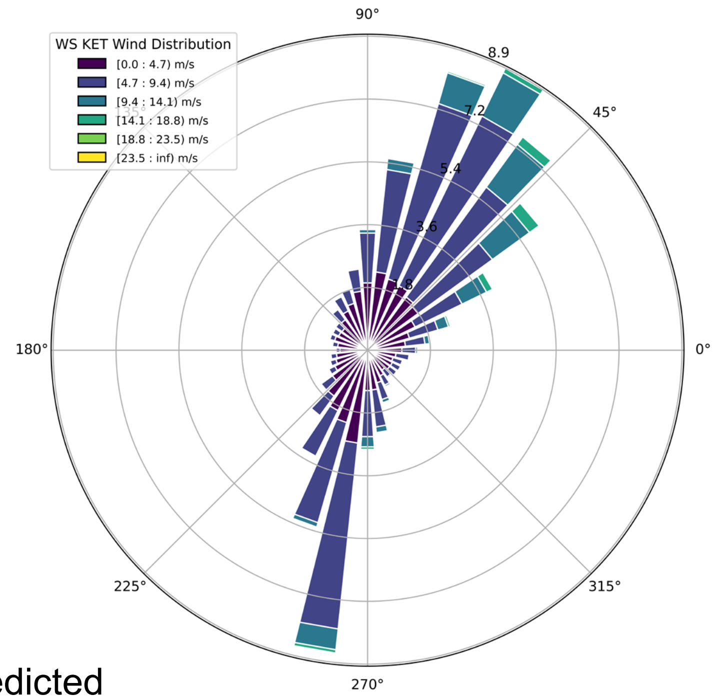
Turbine height mostly unaffected by terrain except from the west due to large butte

Weather Station Data / Wind

HRRR Forecast



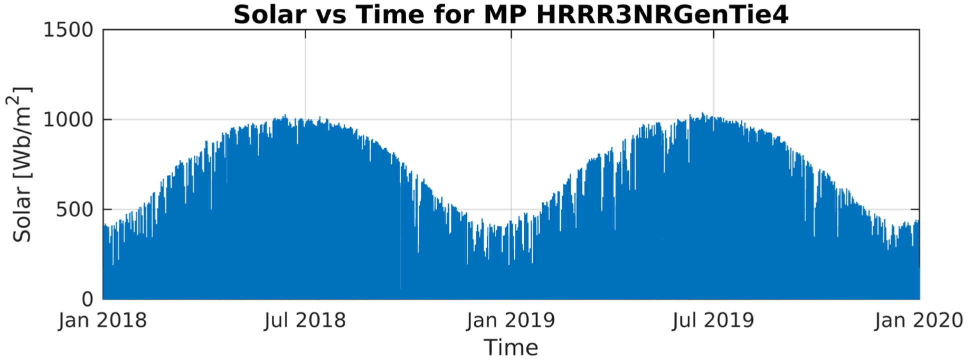
Observational

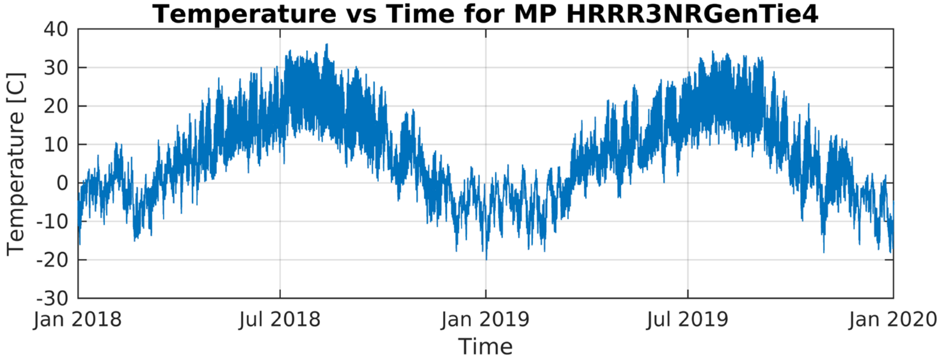


More south-bound winds predicted than observed.

Weather Station Data / Solar and Temperature

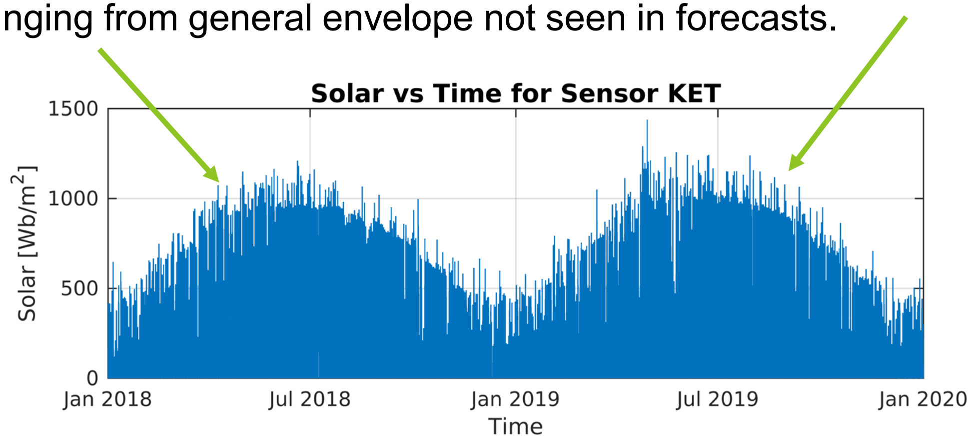
HRRR Forecast

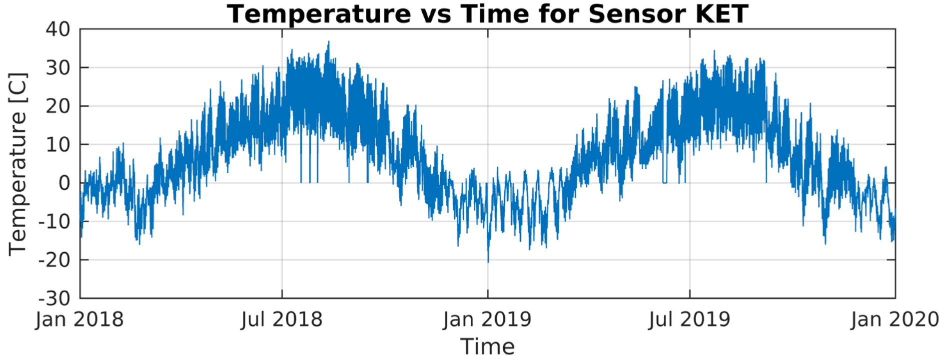




Observational

Fringing from general envelope not seen in forecasts.





Weather Station Data / QA Tests

- QA Tests
  - Wind speeds greater than 75 m/s.
  - Wind speed changes less than 0.5 m/s per hour.
  - Constant wind directions with changing speeds.
  - Wind speed changes greater than 20 m/s.
  - Temperature changes greater than 8ºC per hour.

- Crop out “bad” weather data from analysis

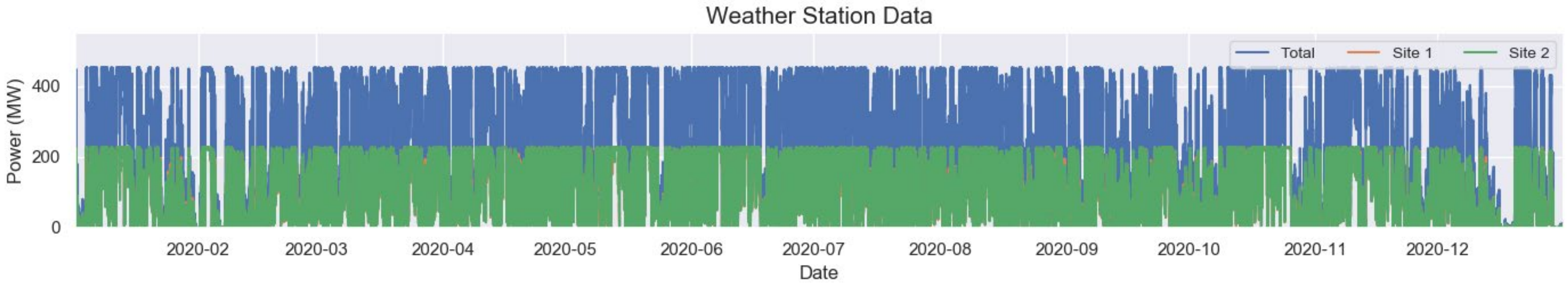
QA Test Error

	Percent Discrepancy				
Test #	1	2	3	4	5
HRRR3	0.00%	dismiss	0.00%	0.00%	0.00%
WS	0.00%	6.20%	0.74%	0.00%	0.11%

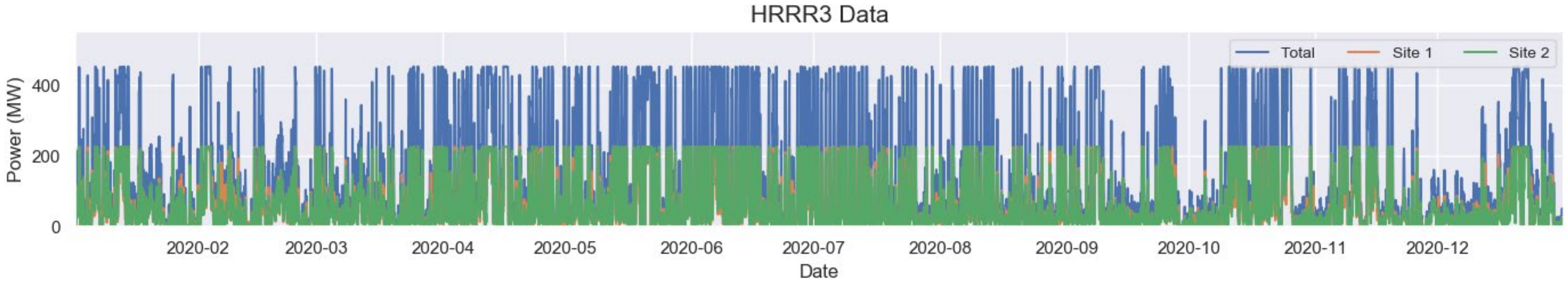
Most likely due to long periods of low wind currents.

Wind Power Generation Data for 2020

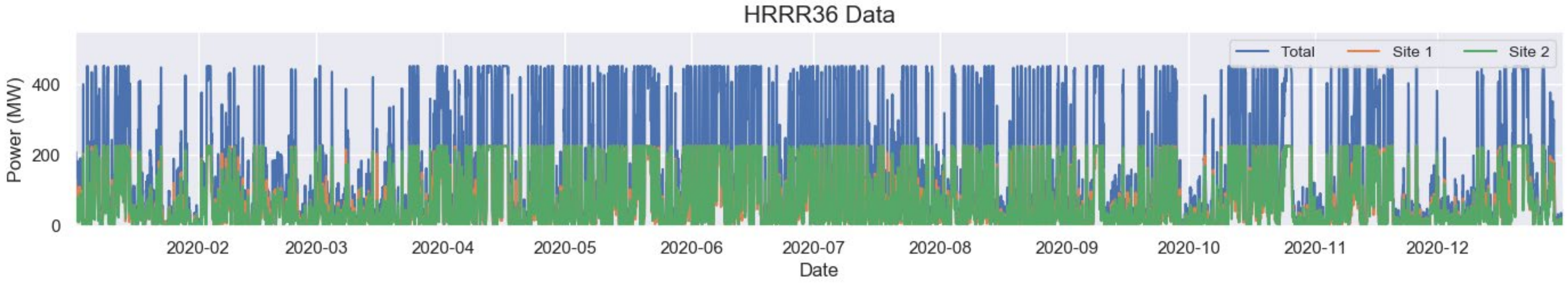
Weather Observation



Near-term Forecasts

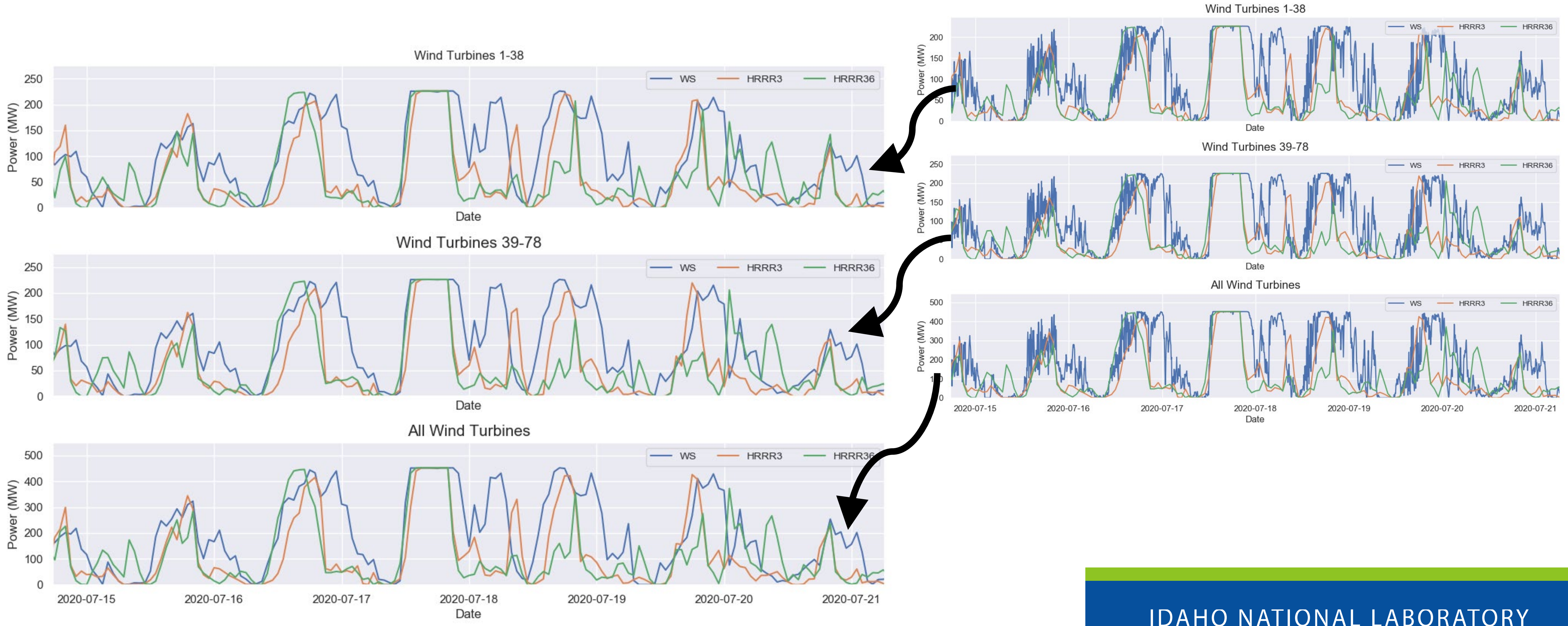


Day-ahead Forecasts



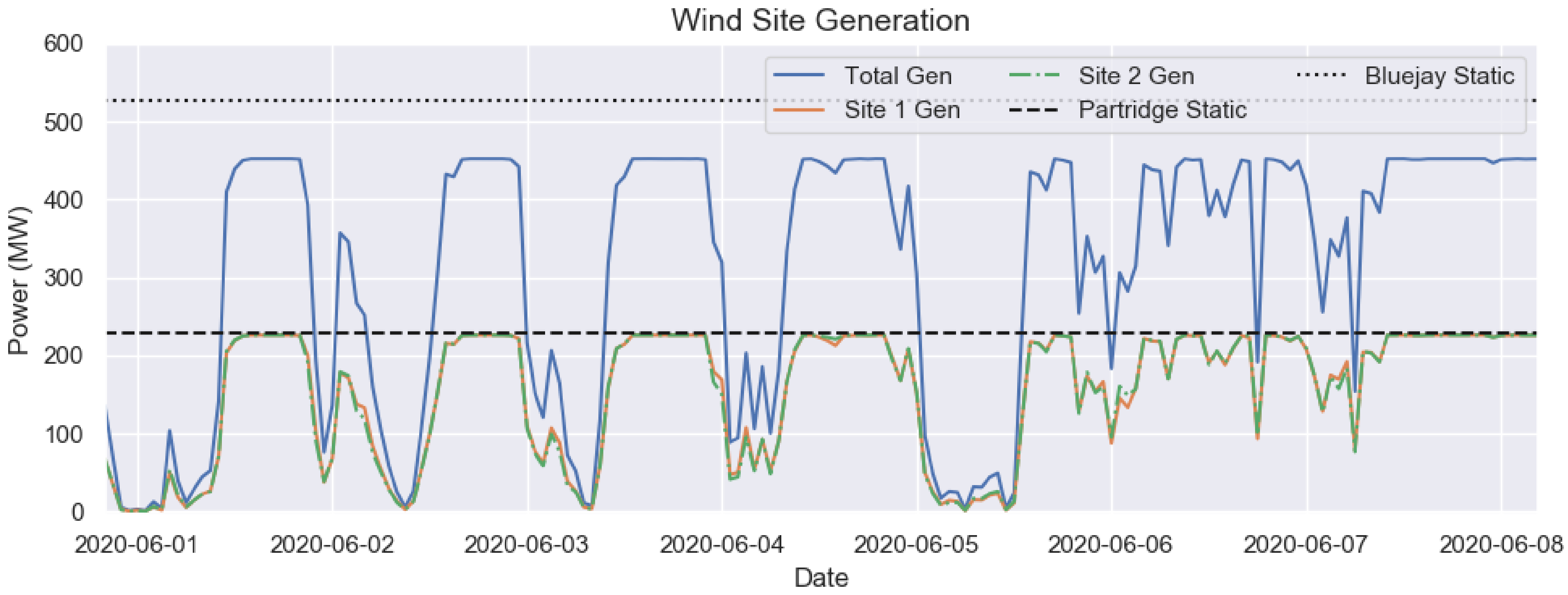
Wind Generation Data

- Resample weather station data for analysis to match HRRR frequency
  - 5min to 1hr (archival data not 15min)



Wind Generation Data

- Gen-tie line conductor
  - Baseline selection of Bluejay and Partridge ACSR for 450/225MW
  - Selected so that generation does not exceed static rating

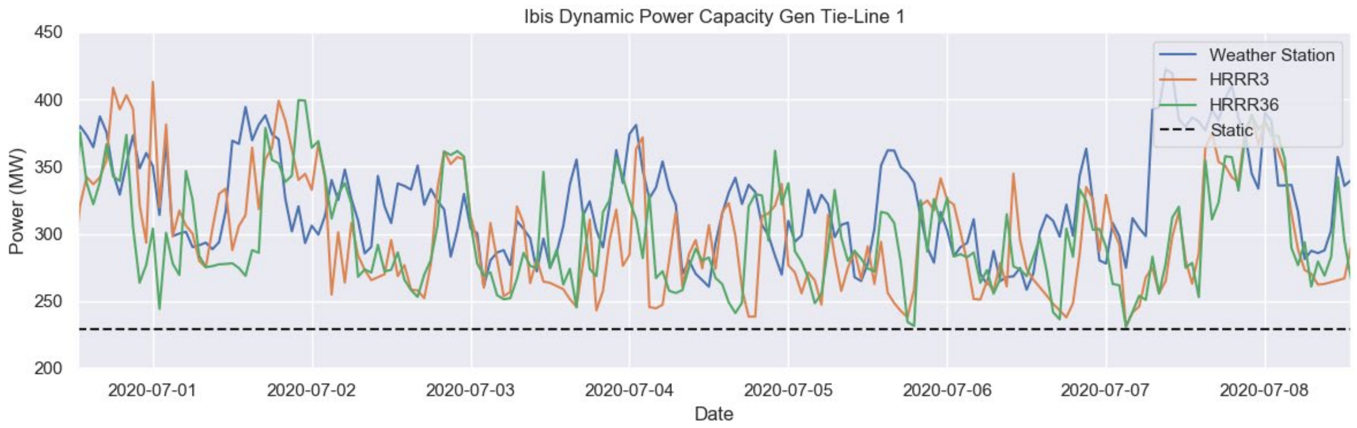


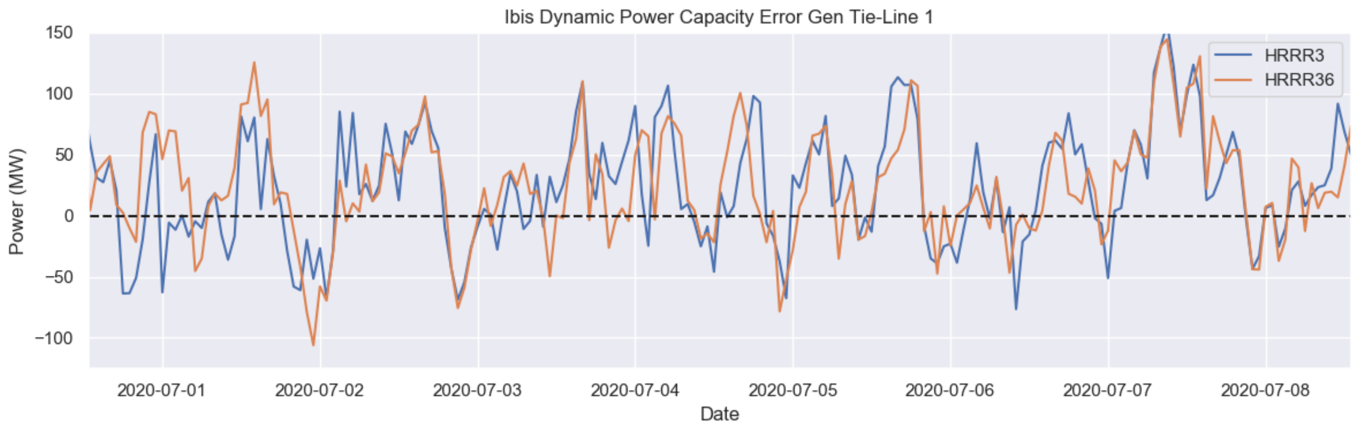
Gen Tie-line Dynamic Power Capacity and Error

- Dynamic power capacity of baseline conductors
- RMSE between models

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_{HRRR} - P_{WS})^2}{N}}$$

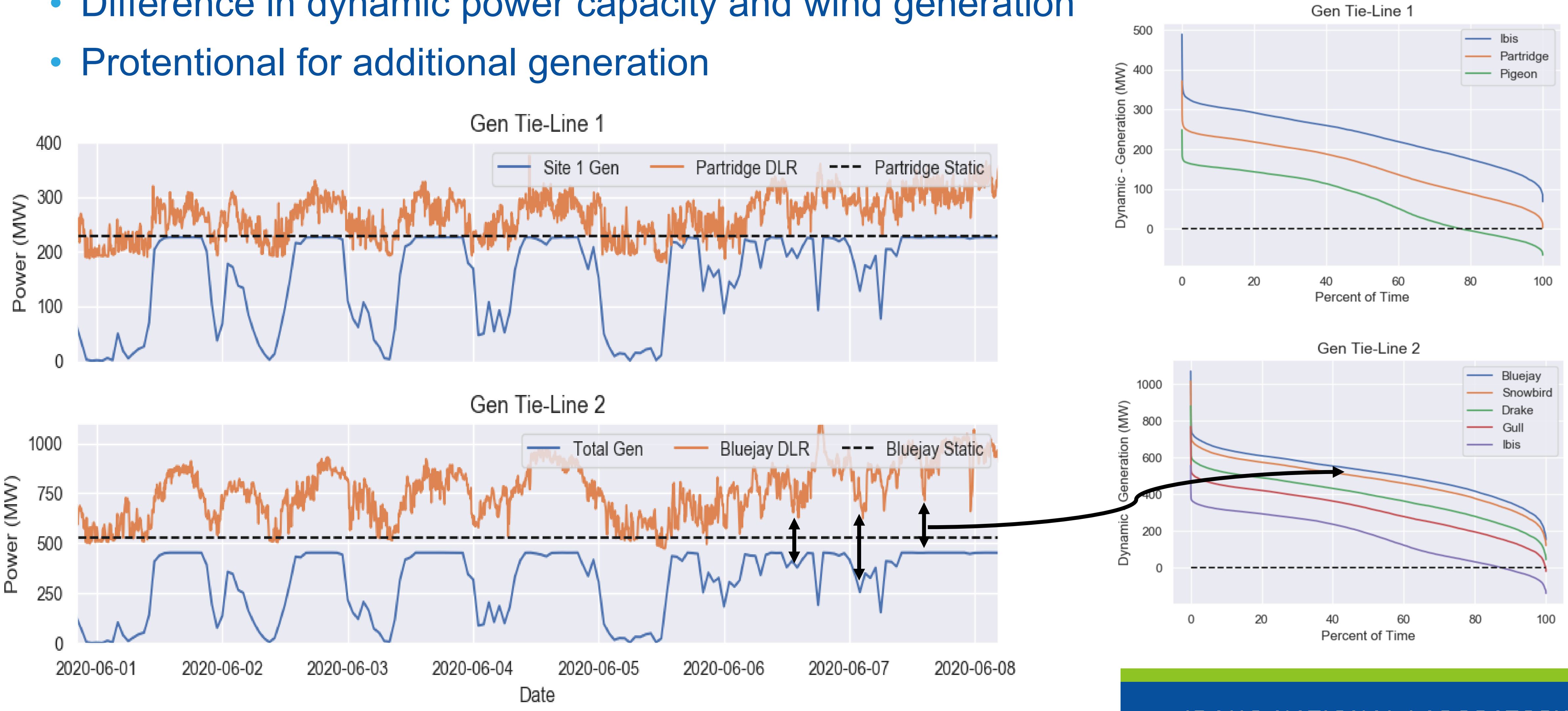
	Conductor	HRRR3		HRRR36	
		RSME	%RSME	RSME	%RSME
Gen Tie Line 1	Ibis	55.0	15.2	55.0	15.4
	Partridge	54.2	15.6	43.2	15.8
	Pigeon	30.4	16.1	30.5	16.3
Gen Tie Line 2	Bluejay	153.0	19.1	151.8	19.3
	Snowbird	145.8	19.2	144.7	19.4
	Drake	127.4	19.4	126.5	19.6
	Gull	112.1	19.6	111.3	19.8
	Ibis	82.9	20.0	82.4	20.2





Concurrent Cooling

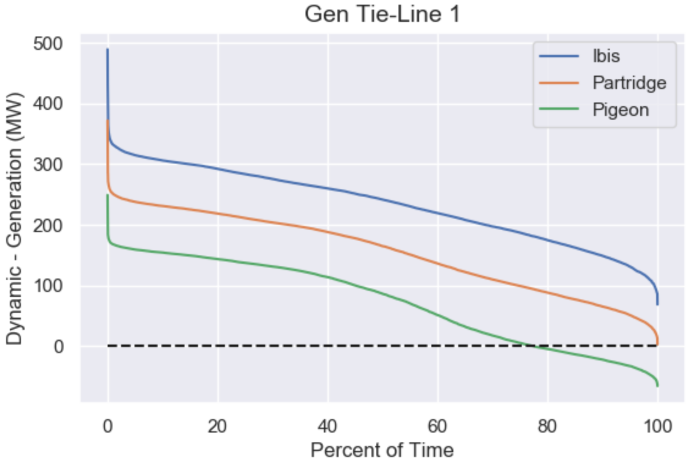
- Difference in dynamic power capacity and wind generation
- Protentional for additional generation

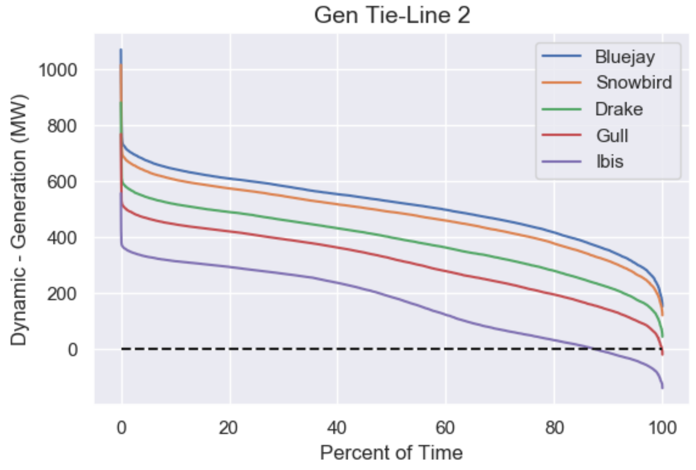


Concurrent Cooling Results

- Partridge has additional 31 MW capacity 99% of the time
- Bluejay has additional 233 MW capacity 99% of the time
  - Drake has 116 MW capacity 99% of the time
  - Gull has 48 MW capacity 99% but goes below base generation requiring small curtailment

	Conductor	Percent of Time				
		80%	90 %	95%	99%	100%
Gen Tie Line 1	Ibis	175	149	131	105	68
	Partridge	89	66	51	31	3
	Pigeon	-4	-21	-32	-49	-65
Gen Tie-Line 2	Bluejay	417	354	307	233	153
	Snowbird	377	316	270	199	122
	Drake	280	221	180	116	45
	Gull	196	141	104	48	-19
	Ibis	32	-12	-40	-83	-138





Summary

- DLR was used to rate a gen-tie line for a proposed wind farm
- This approach showed ~50%+ additional capacity available on gen-tie line using DLR
  - Or line can be downsized for capital cost reduction

- When considering forecasting, some accounting for error needs to occur
  - Day ahead and near-term forecasts have very similar error
  - In this particular region 15-20% of ampacity

Acknowledgements

- This research was performed by Idaho National Laboratory with support from NorthRenew Energy and funding from the U.S. Department of Energy Wind Energy Technologies Office. INL is operated by Battelle Energy Alliance under contract No. DE-AC07-05ID14517.


INL
Idaho National Laboratory
WIND INTEGRATION R&D
Concurrent Cooling, Dynamic Line Rating
Jake P. Gentle – jake.gentle@inl.gov

ABORATORY