A NEW METHOD TO ASSESS WIND FARM PERFORMANCE AND QUANTIFY MODEL UNCERTAINTY

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AWEA WIND RESOURCE ASSESSMENT WORKSHOP 2018

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How can we evaluate the performance of a wind farm?

Stages of Wind Farm Development

Identify Prospective Project Area

Collect on-site met data (met towers, remote sensing)

Develop model, predict wind farm energy production

Build wind farm and install permanent met towers

Begin wind farm operation. Take down pre-construction mets

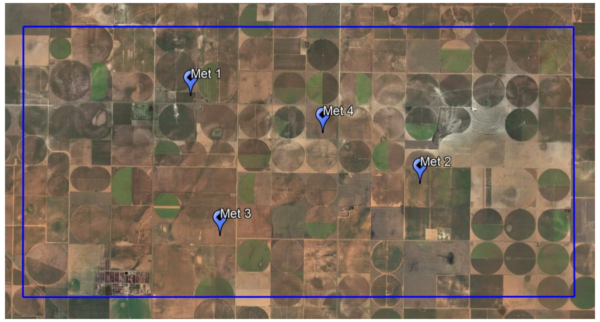
How can we evaluate wind farm performance? How can we compare actual production to predictions?

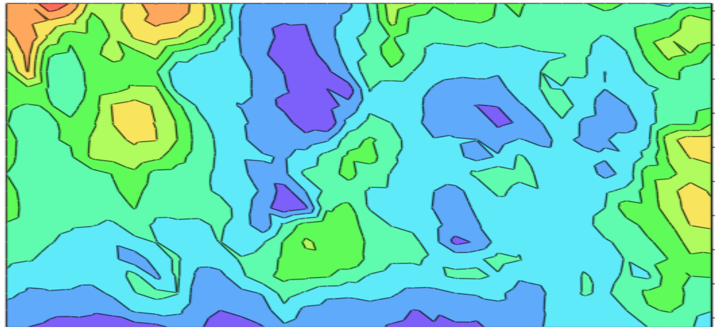
1) **Use nacelle anemometer data**
  - Higher measurement uncertainty. Transfer functions estimate wind speed in front of rotor
  - Does not allow separation of wake loss and wind flow variations

2) **Use wind flow model, wake loss model and permanent met (PMet) data to predict energy production**
  - Introduces wind flow and wake loss model uncertainty but eliminates need for nacelle anemometers.
  - Separates wake loss and wind flow variations so wake losses can be quantified

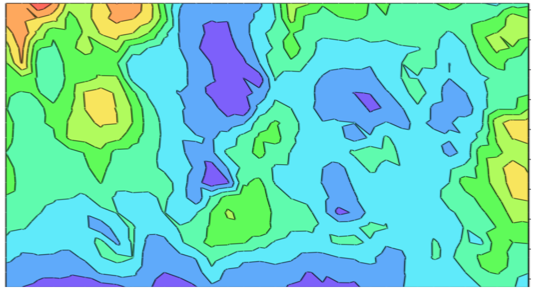
Summary of Methodology: Three Phases

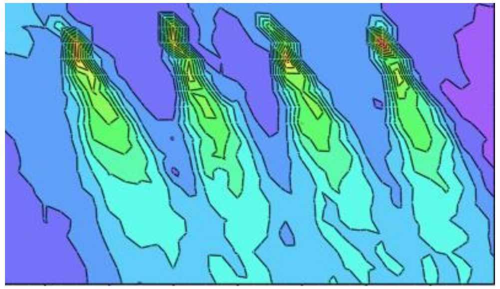
- **Phase 1**: Build model using pre-construction met data

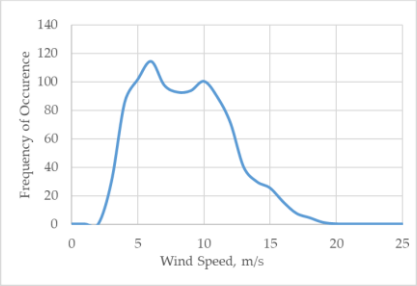




- **Phase 2**: Estimate energy production using wind flow model, wake loss model, and PMet data

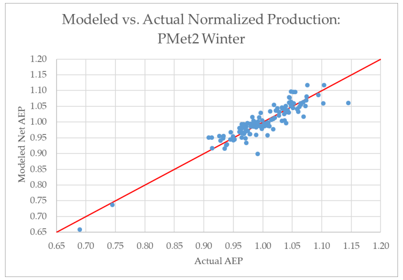


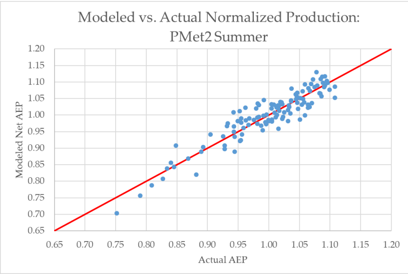


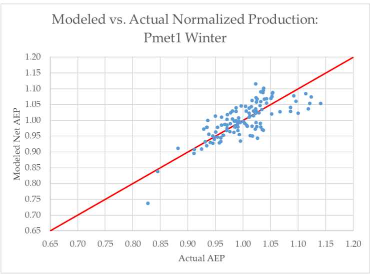


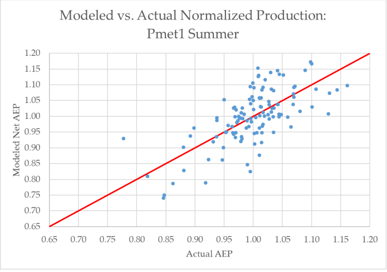
Energy Production Estimates

- **Phase 3**: Compare actual and modeled production. Calculate actual losses.









Phase 1: Building the model with pre-construction Met data

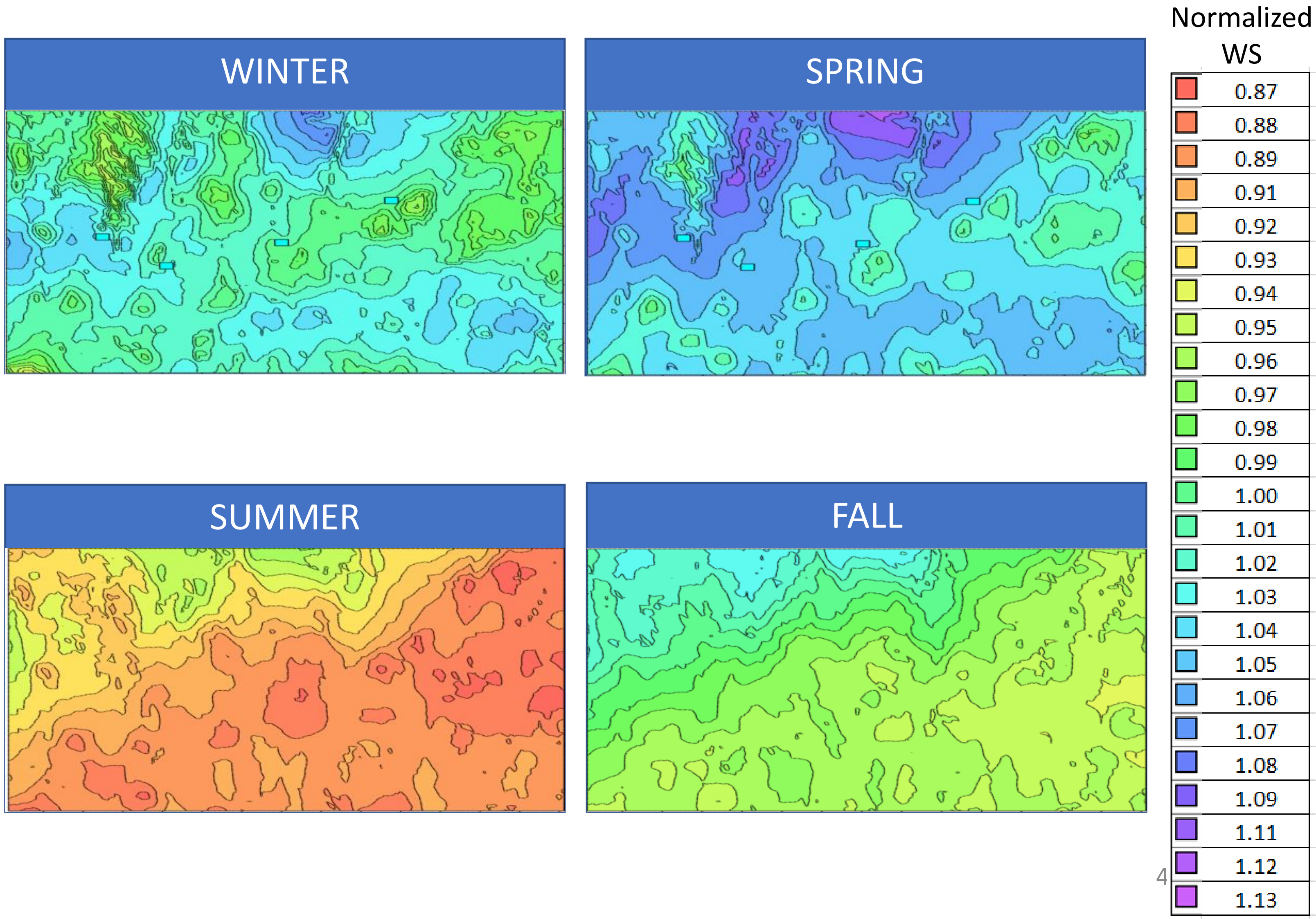
- **Case Study:**
  - 4 – 60 m met masts
  - QC filtered and extrapolated to 80 m
  - Data length: 2.5 – 6 years
  - Used longest met dataset and Measure-Correlate-Predict (MCP) to normalize all met data to same time interval
  - Split data up by season
  - Created Continuum® wind flow model for each season

Met Cross-Prediction Errors

Season	RMS Error
Winter	1.28%
Spring	1.07%
Summer	1.75%
Fall	1.20%

Round Robin Errors

Season	RMS Error
Winter	2.26%
Spring	0.99%
Summer	1.02%
Fall	0.85%



Phase 2: Filter PMet data and use models to predict energy production

- >100 – 1.8 MW wind turbines in operation for ~2 years
- Two permanent met (PMet) masts
  - One north (PMet1) and one south (PMet2) of wind farm
- Filtered PMet and power production data for:
  - Wakes
  - Availability (> 85% turbines operational)
  - Icing
  - Min/Max WS SD
- Created Continuum® models for each season and using each PMet filtered dataset and site-calibrated models (generated from pre-construction data)
- Used Deep Array Eddy Viscosity (DAWM) wake loss model
- Found 'other' losses

PMet	Season	Data Count (Days)	Normalized Mean WS
1	Winter	47	1.01
1	Spring	34	0.98
1	Summer	9	0.76
1	Fall	25	1.00
2	Winter	64	1.06
2	Spring	80	1.12
2	Summer	108	1.02
2	Fall	98	1.04

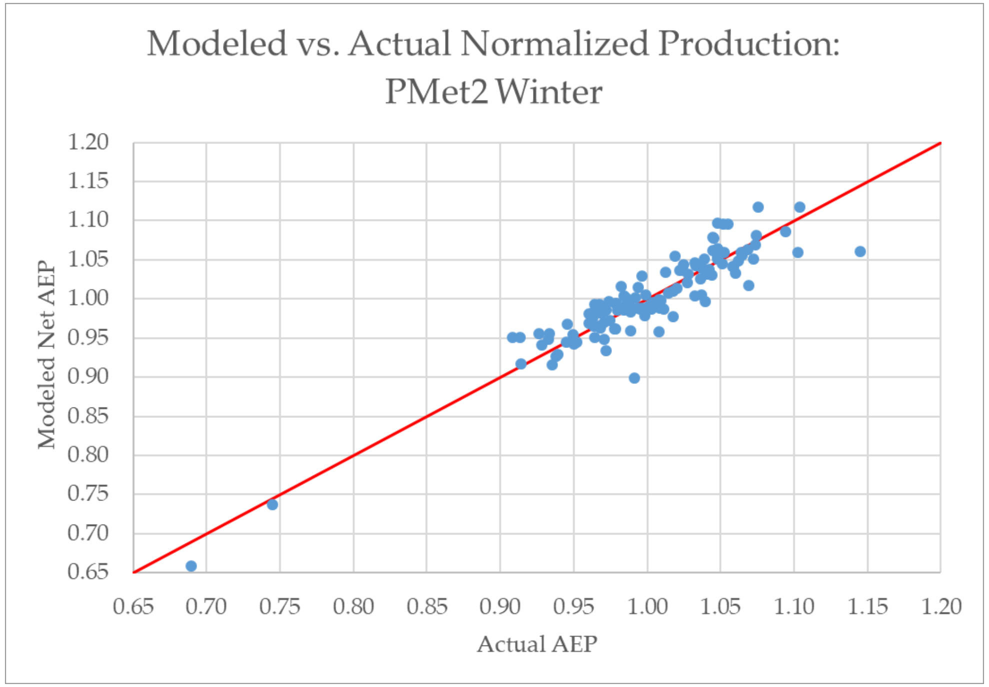
$$Other\ Losses = \sum (Gross\ Energy\ - Wake\ Loss) - \sum Actual\ Energy$$

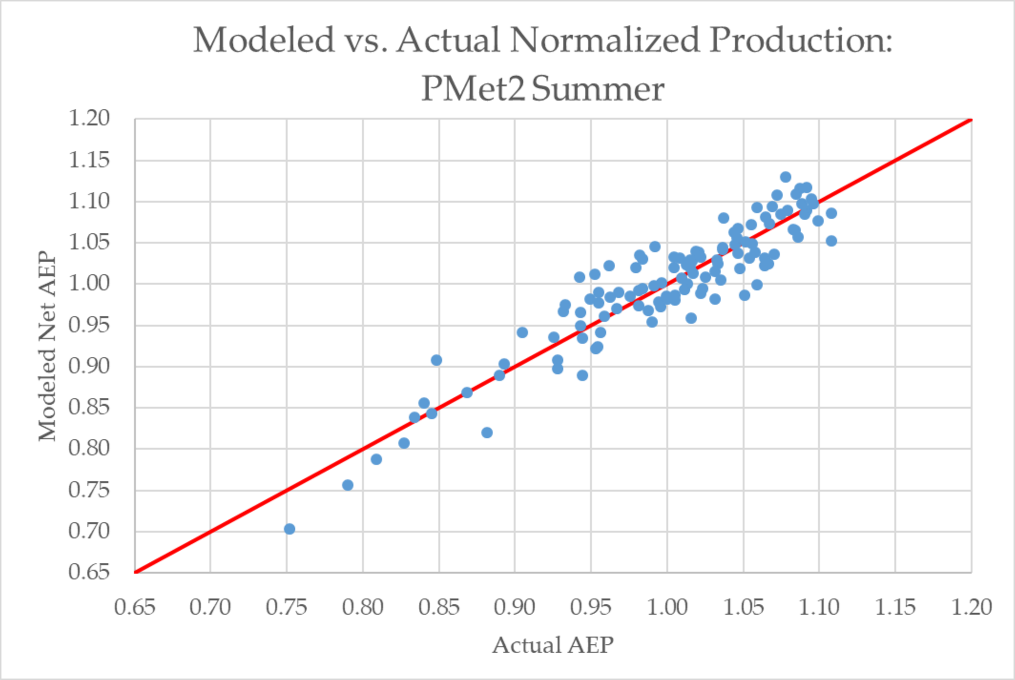
Using PMet data & Wind Flow Model

Deep Array EV Wake Loss Model

Phase 3: Compare Actual vs. Estimated Energy Production

- For each season and for each PMet, compare actual versus modeled energy production. Calculate:
  - Modeled vs. Actual error and correlation coefficient, R
  - Avg. Wake loss
  - Other losses





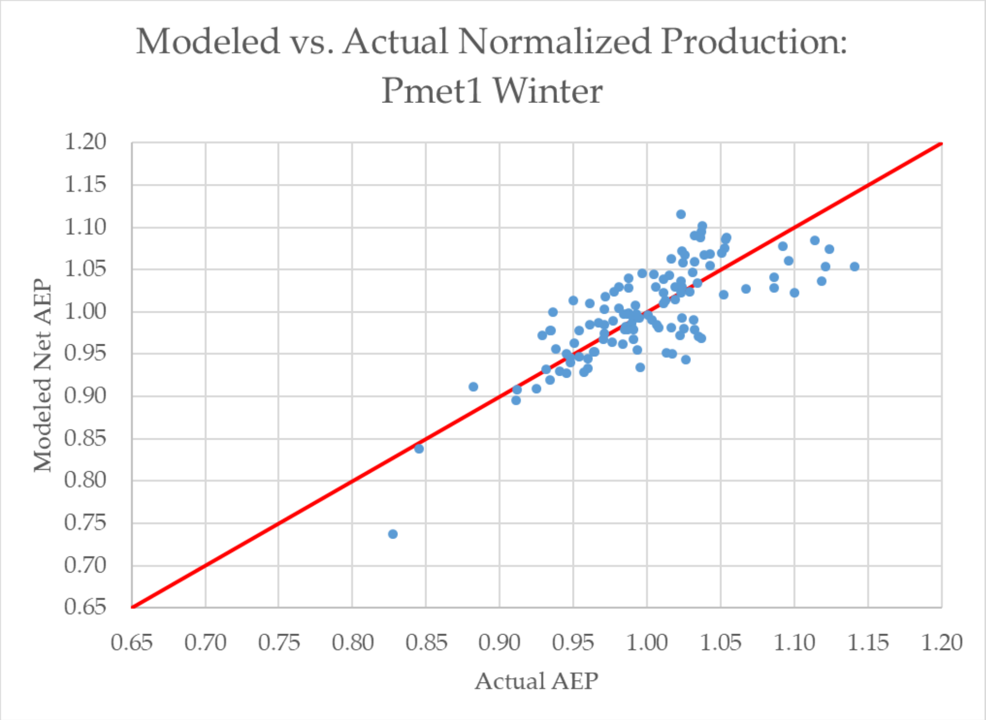
R = 0.92
Avg Error = 0.13%
St. Dev Error = 2.4%

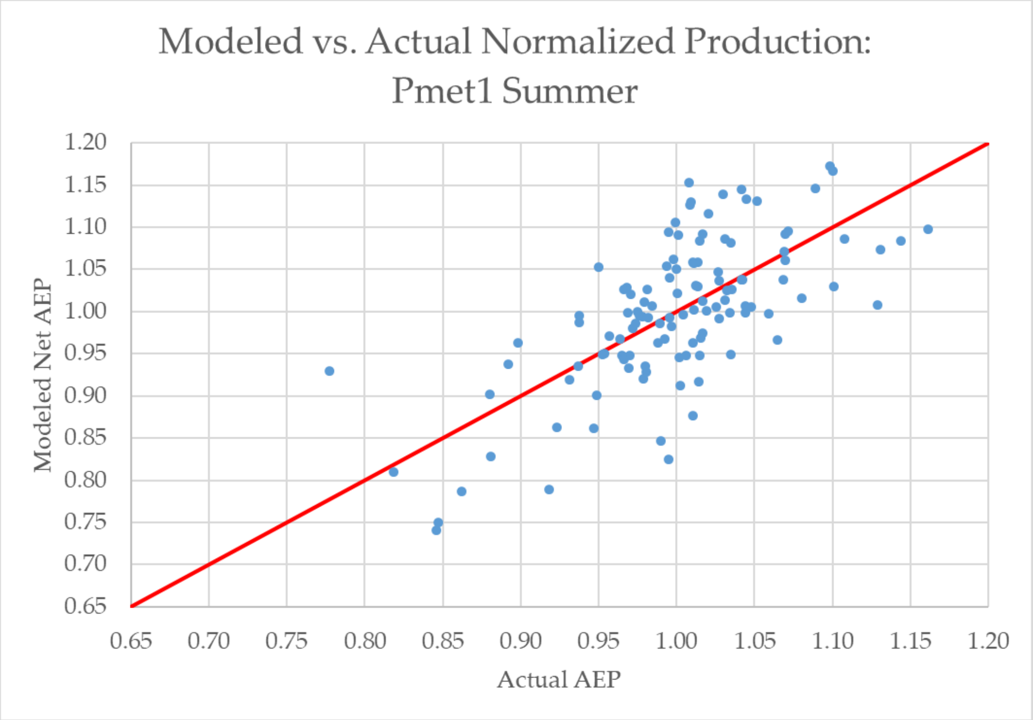
Avg Wake Loss = 6.4 %
Other Losses = 0 %

R = 0.93
Avg Error = 0.11%
St. Dev Error = 3.0%

Avg Wake Loss = 6.6 %
Other Losses = 14%

Phase 3: Compare Actual vs. Estimated Energy Production cont'd





R = 0.77
Avg Error = 0.3%
St. Dev Error = 3.7%

Avg Wake Loss = 4.5 %
Other Losses = -3.0%

R = 0.68
Avg Error = -0.65%
St. Dev Error = 6.5%

Avg Wake Loss = 5.6 %
Other Losses = 0%

Phase 3: Compare Modeled vs. Actual

- Good model agreement (R = 60 – 93%)
  - Better agreement with PMet2 (South).
- Low model uncertainty, σ
  - Min σ = 2.3% (PMet2 Fall). Max σ = 6.5% (PMet1 Summer)
  - Includes wind flow model, wake loss model, and data measurement uncertainty
- Wake losses higher during southerly winds
  - Avg. Wake Loss = 5.3% (north) vs. 6.8% (south)
- Other “losses” can be positive or negative
  - Negative Loss (Gain)
    - Based on PMet data and wind flow model, turbines produced more than estimated.
  - Affected by:
    - Density
    - Wind conditions (shear, turbulence, stability)
    - Blockage effects
      - PMet wind speed affected by wind farm and therefore not truly free-stream

PMet	Wind Direction	Season	Normalized Mean WS	Data Count (days)	Correlation Coefficient	Avg % Diff	SD % Diff	Wake Loss	Other Gains/Losses
1	North	Winter	1.01	47	77%	0.3%	3.7%	4.5%	3.0%
1	North	Spring	0.98	34	60%	0.0%	6.0%	6.7%	1.5%
1	North	Summer	0.76	9	68%	-0.7%	6.5%	5.6%	0.0%
1	North	Fall	1.00	25	80%	-0.5%	3.8%	4.5%	0.0%
2	South	Winter	1.06	64	92%	0.1%	2.4%	6.4%	0.0%
2	South	Spring	1.12	80	65%	0.5%	4.3%	7.7%	-4.6%
2	South	Summer	1.02	108	93%	0.1%	3.0%	6.6%	-14.0%
2	South	Fall	1.04	98	92%	0.7%	2.3%	6.3%	-8.0%

Key take-aways and Further Considerations

- Using PMet data and wind flow model allows for separation of wake loss and wind flow variability
  - Quantify actual wake losses
- Found good model agreement and low model uncertainty.
  - Model uncertainty varied from 2.3% to 6.5% (energy)
    - Includes wind flow model, wake loss model, and measurement uncertainty
- "Other" losses can be positive or negative
  - Likely associated with blockage effects (More on this during wind flow modeling session)
- Conducting this exercise on a yearly basis will show trends in the wind farm performance
  - Blade soiling / degradation
  - Performance boosting technologies