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Deep Array Wake Loss in Large Onshore Wind Farms (A Model Validation)

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Collaborators…

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Background…

- Wake losses higher than modeled have been observed at large offshore wind farms. (i.e., Horns Rev & Nysted)
- Question: Is the same thing happening at large onshore wind farms?
- E.ON provided turbine data from one large wind farm (>100MW) sited on relatively flat terrain.
- Each participant used a different model to compare with the observed data.

Configuration…

- Four models
  - o WindFarmer v4.1 – Eddy viscosity wake model with Large Wind Farm Correction turned on
  - o WindPro v2.7 – N.O. Jensen-EMD wake model (Park), wake decay coefficient – 0.04 (offshore value)
  - o RAM wake model
  - o WAsP v9 – Park wake model, wake decay coefficient – 0.04 (offshore value)

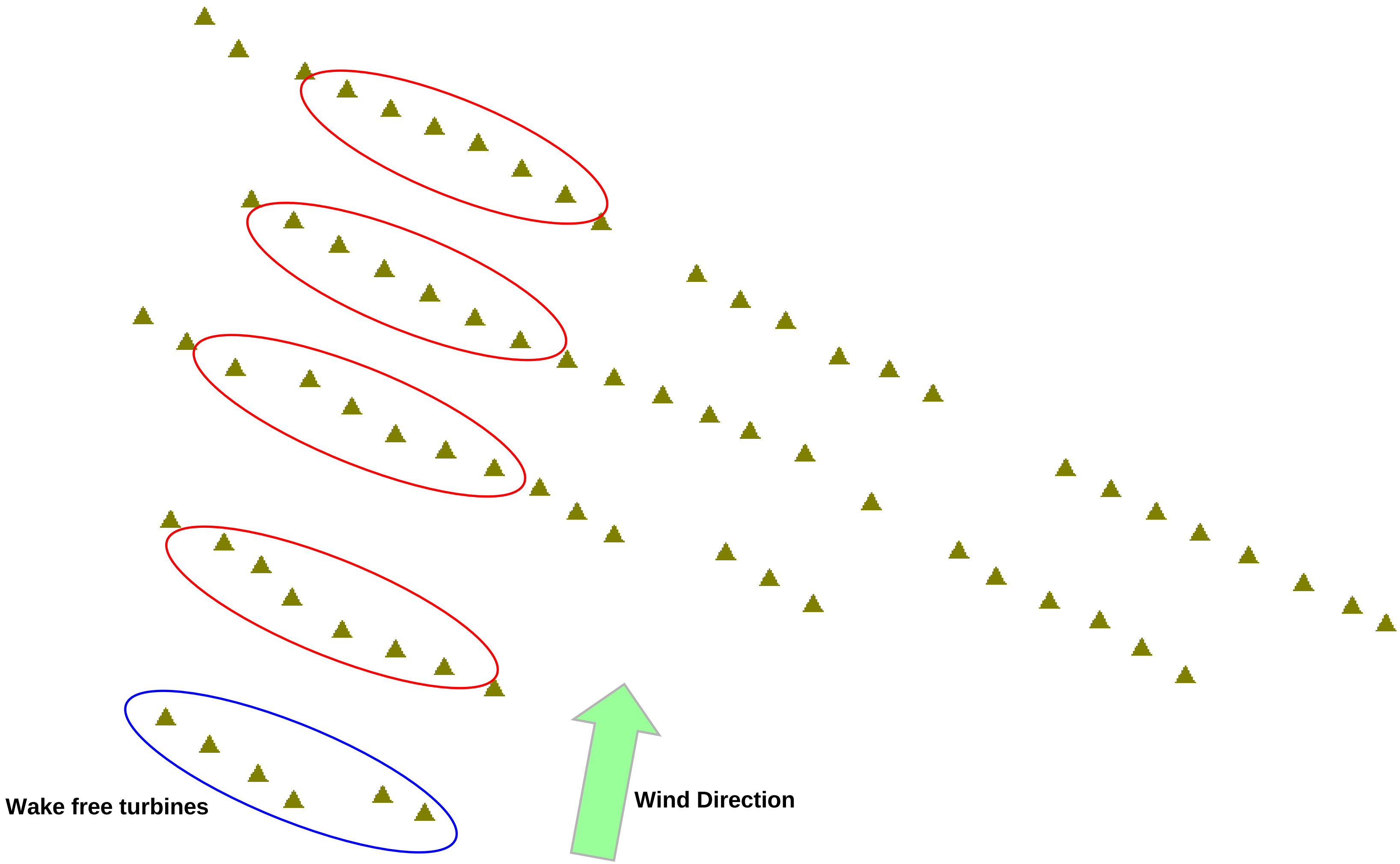
- Four iterations of each model
  - o 7, 8, 9, & 10 m/s
  - o Wind direction: 190° +/- 15°
  - o Flat terrain (i.e., no topography in model)

Configuration…

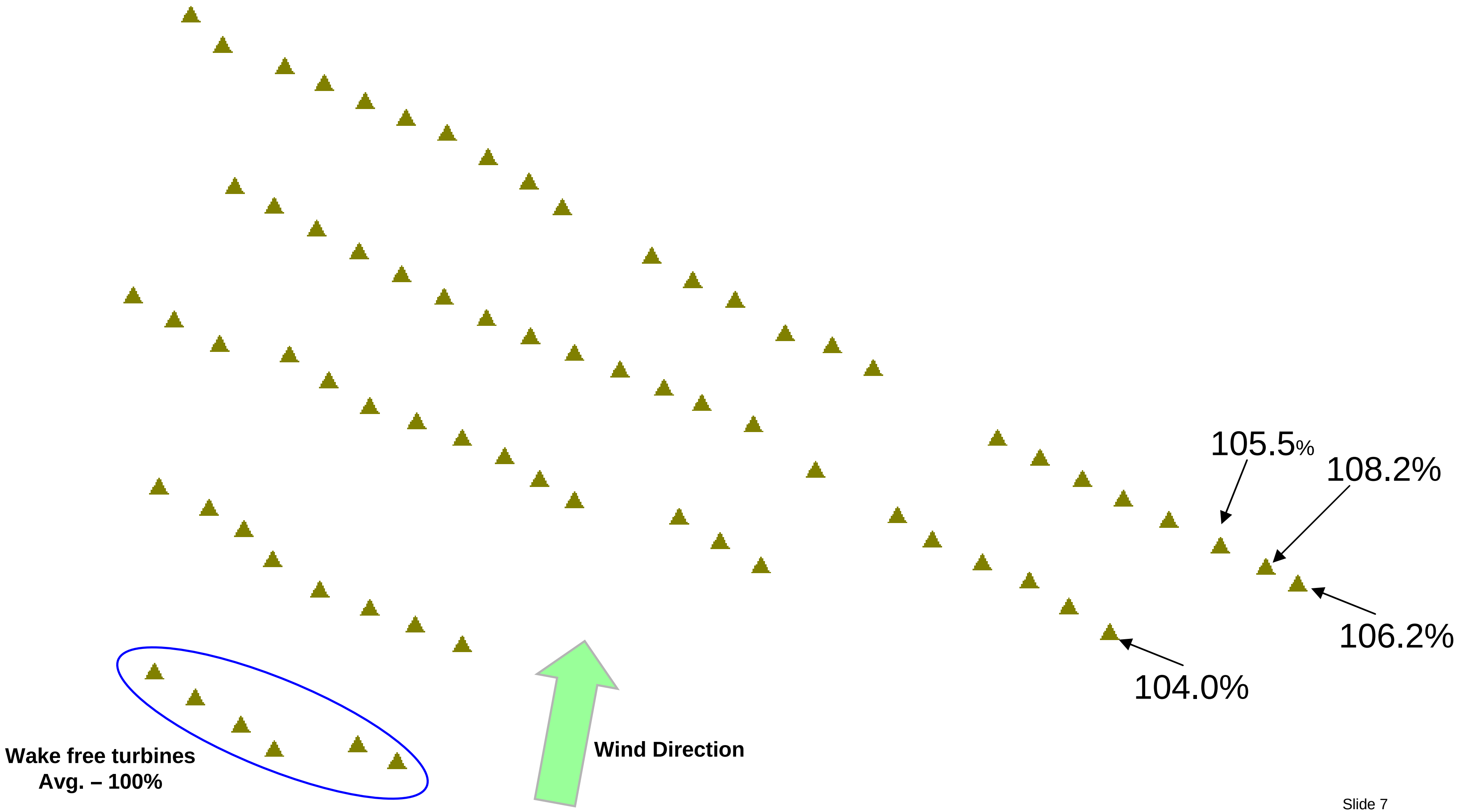
- Data
  - o 1 year of operational data for each turbine
  - o Cleaned power data binned into 4 wind speed bins
  - o Binned power data averaged for each turbine
  - o Power relative to the average of the unwaked turbines

- Terrain
  - o Uniform surface roughness. Cultivated fields, very few trees.

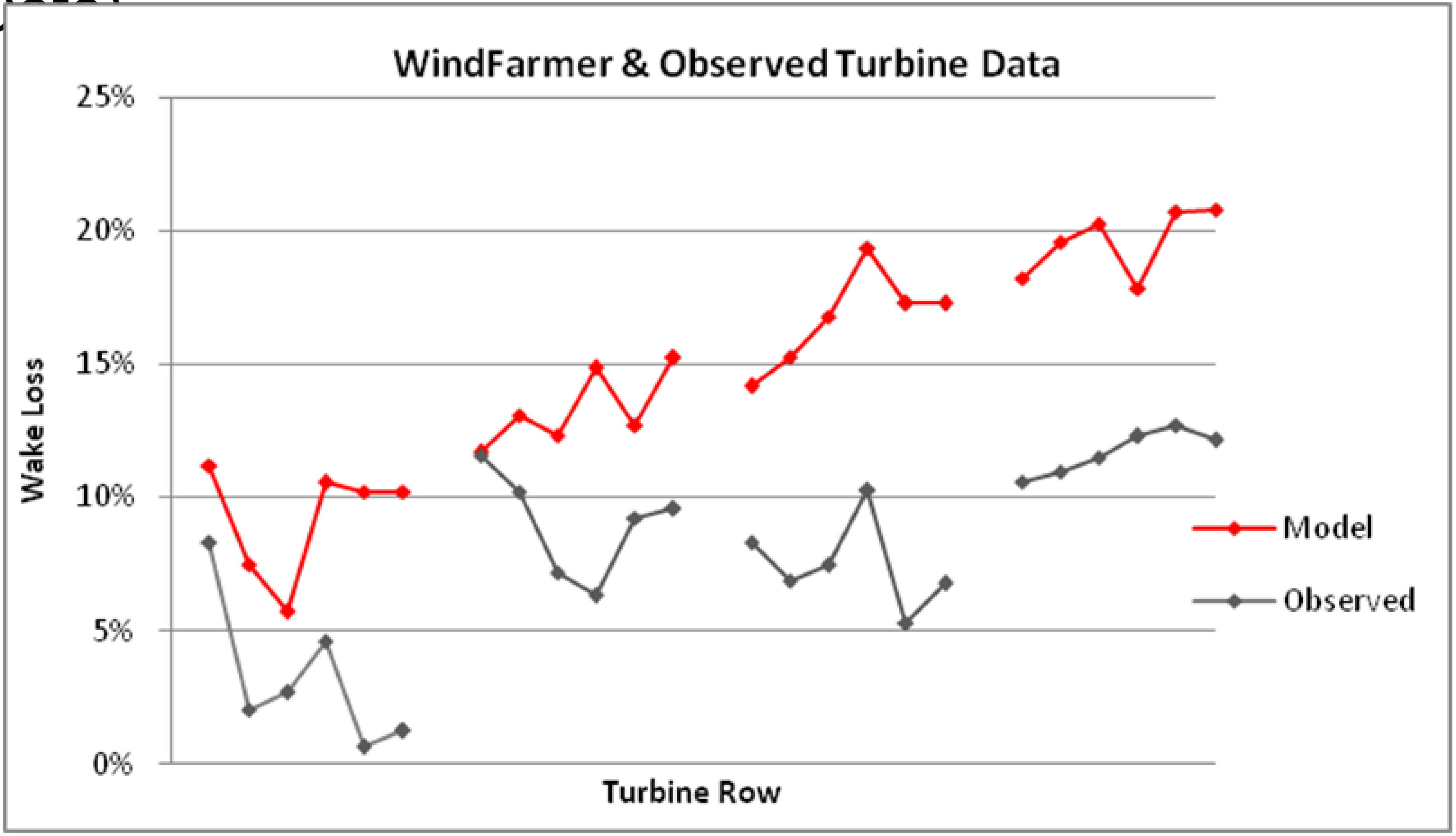
Case 1 – 5 rows deep, 190°wind direction



Wind Speed Variation…



Results – With Wind Speed Variation (i.e., Measured Data)



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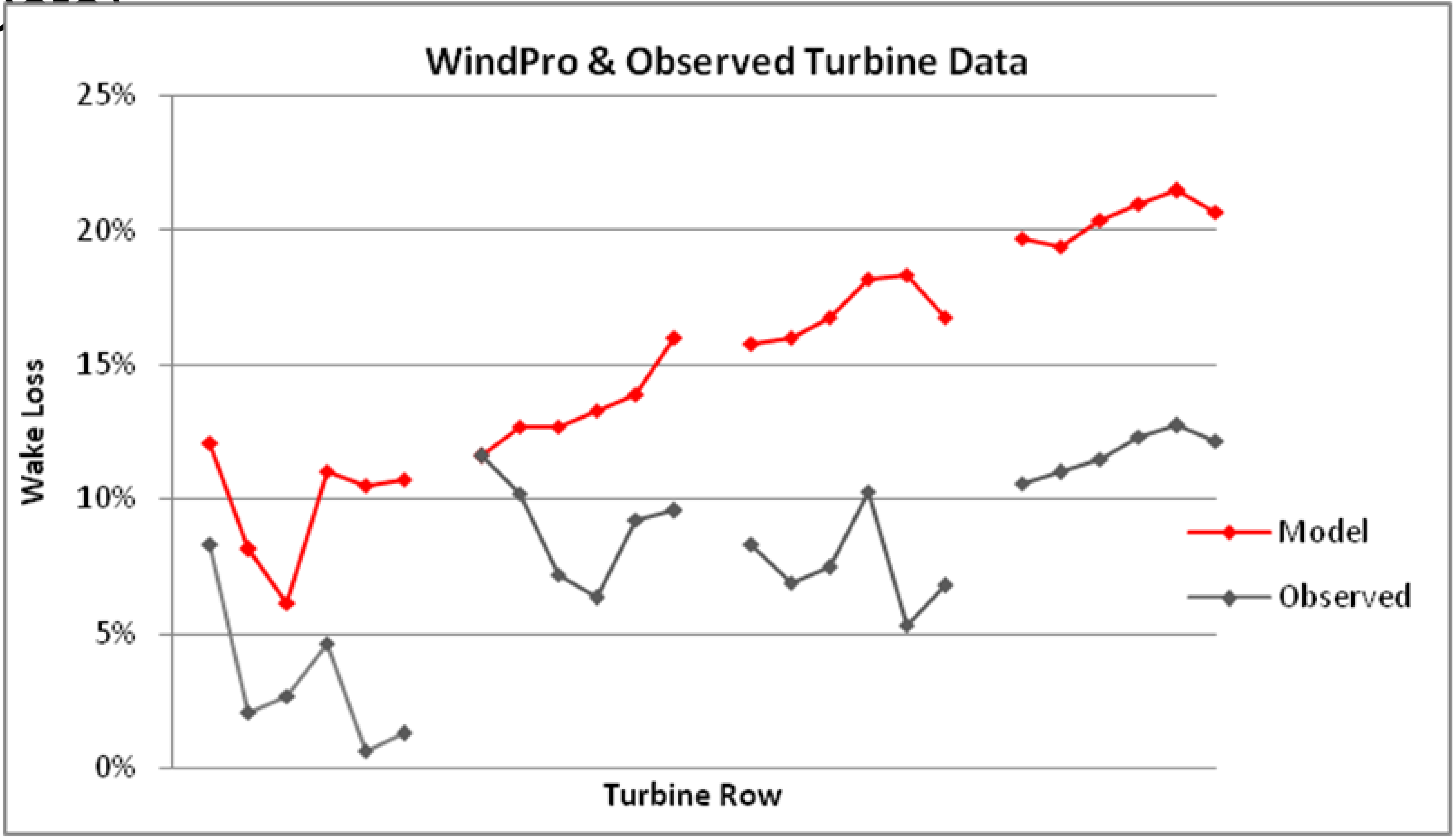

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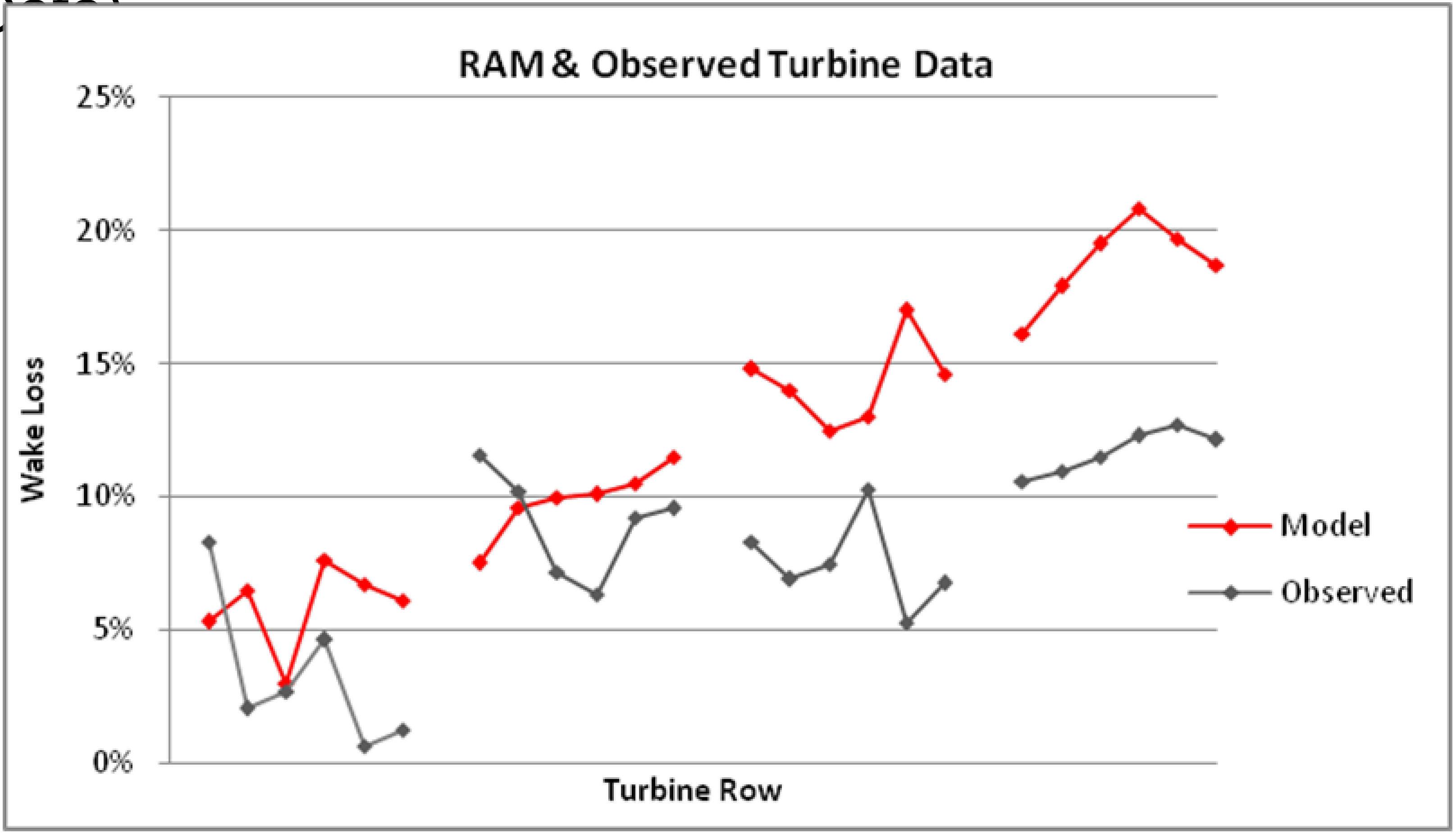

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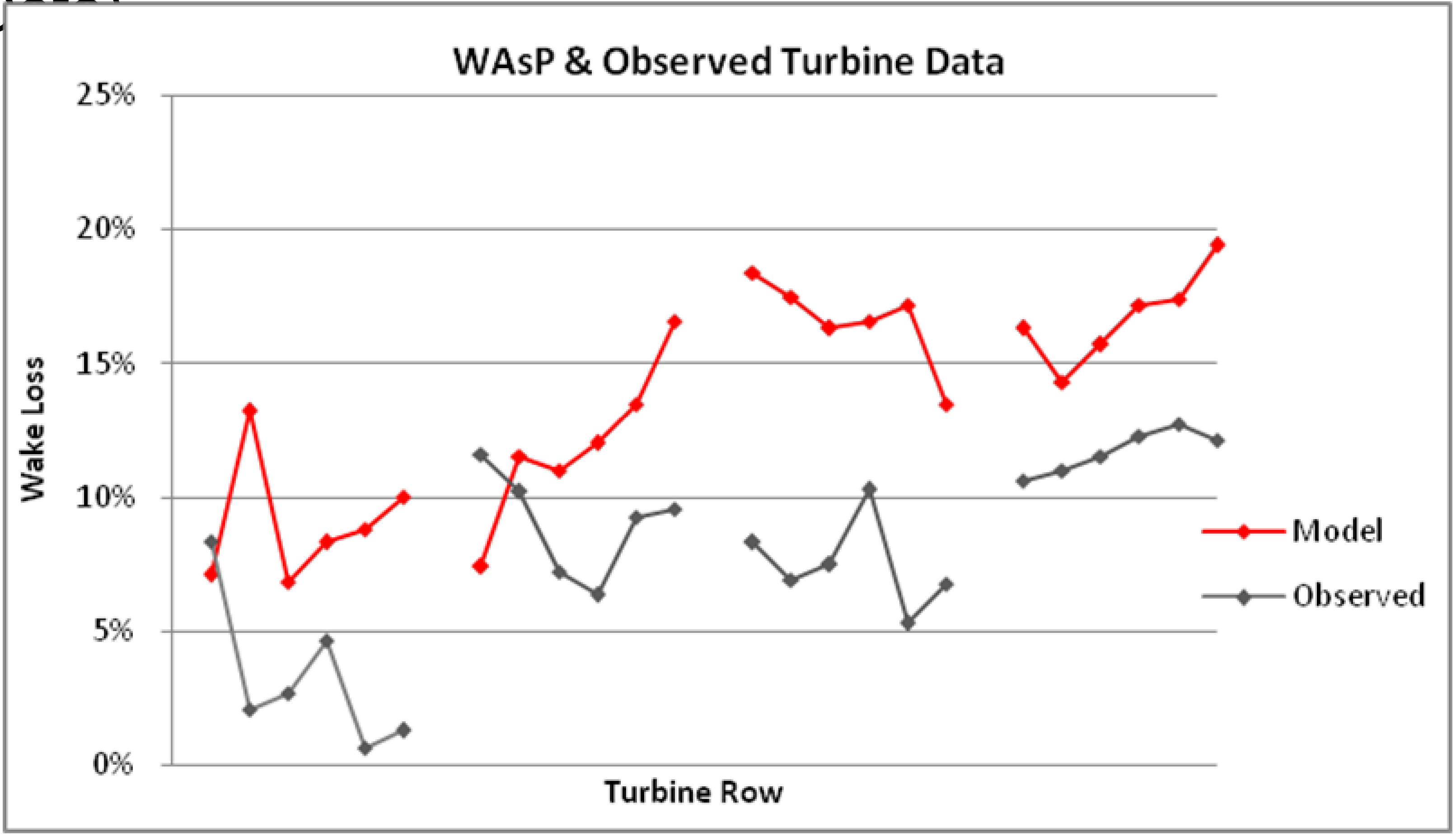

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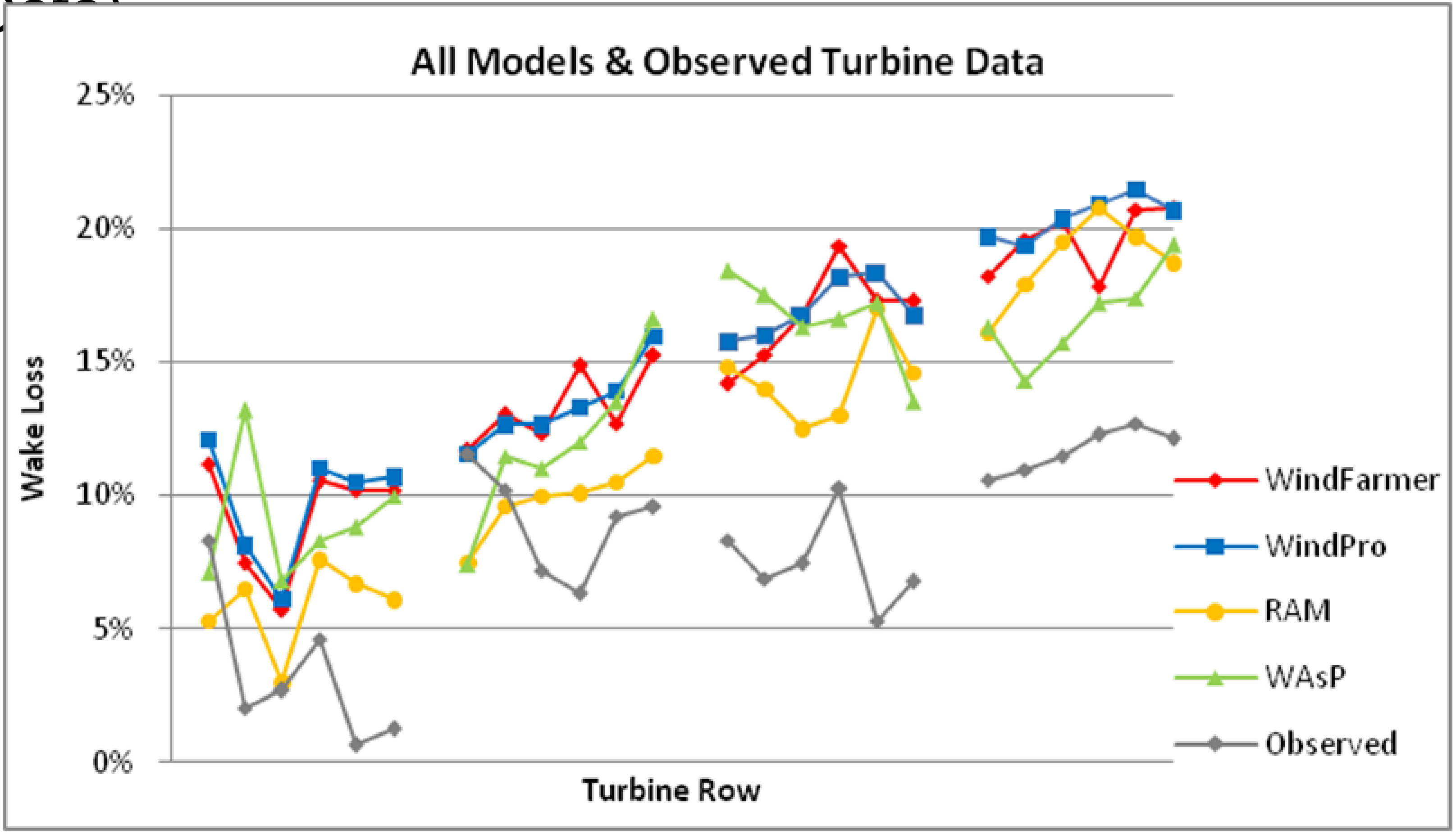

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Removing Wind Speed Variation from Turbine Results

- Calculate wind speed at each turbine using the RAM model and 4 temporary pre-construction met masts.
- Convert wind speed variation to expected power variation using wind speed to power sensitivity.
- Method 1
  - o Calculate average power of unwaked turbines for 6, 7, 8, 9, 10, & 11 m/s bins.
  - o Sensitivity ratio is the percent change in power across each bin divided by the percent change in wind speed across each bin.
  - o Apply sensitivity ratio to wind speed ratio to create a power ratio.
  - o Relative power / power ratio = normalized power

Example:

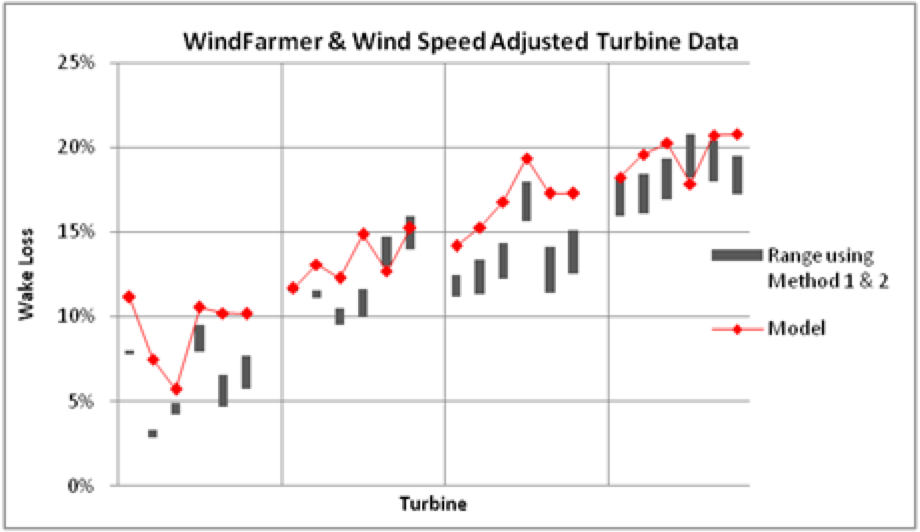
$$SR(7mps) = \frac{\frac{(P(8) - P(6))}{P(7)}}{\left(\frac{8-6}{7}\right)}$$

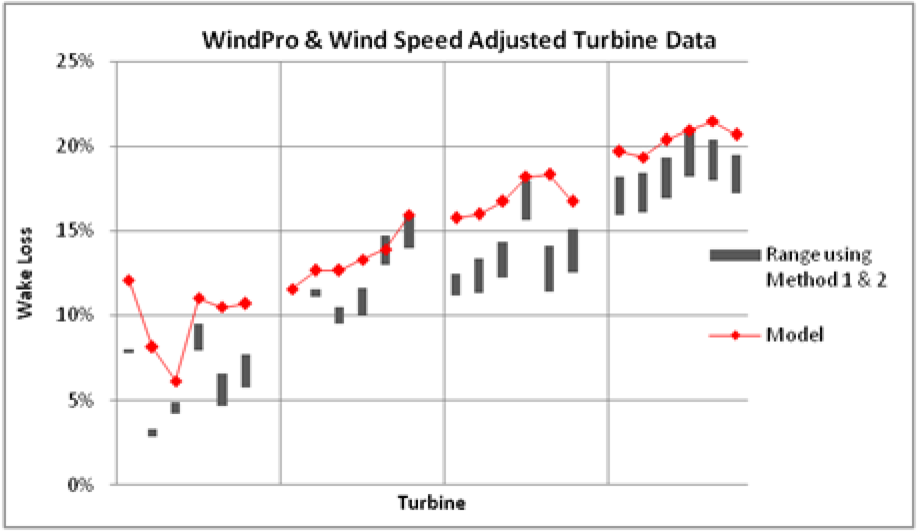
Removing Wind Speed Variation from Turbine Results…

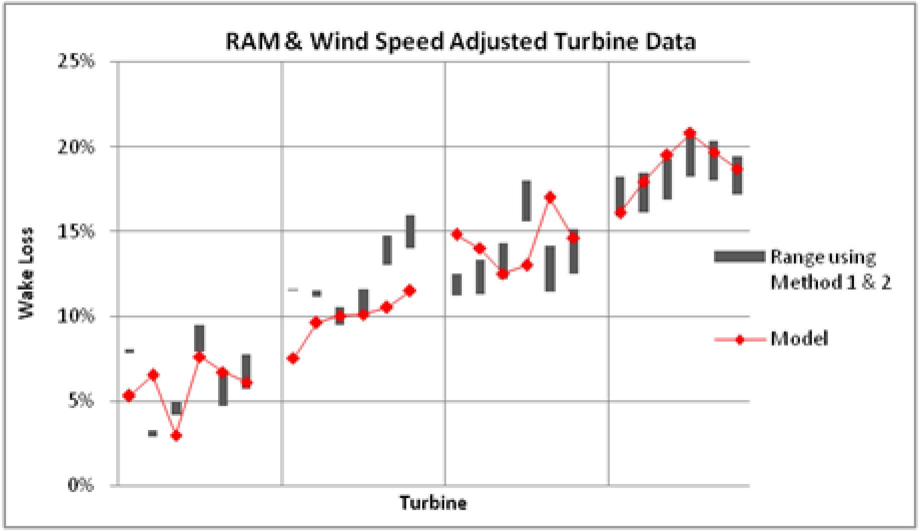
- Method 2
  - Calculate linear regression of wind speed ratio and relative power for each unwaked turbine.
  - Apply transfer function from linear regression to wind speed ratio to create a power ratio.
  - Relative power / power ratio = normalized power

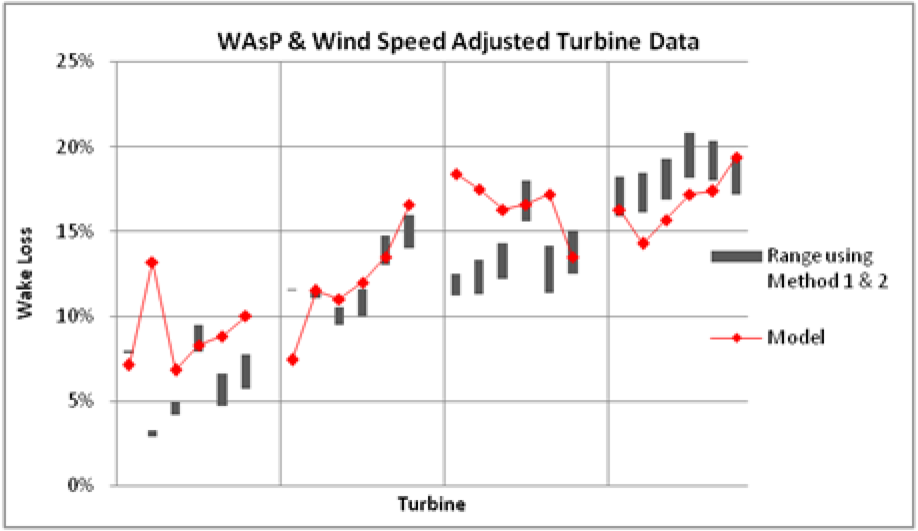
- For comparison to the models the results using both methods are shown as a range.

Results – Wind Speed Adjusted Turbine Data…









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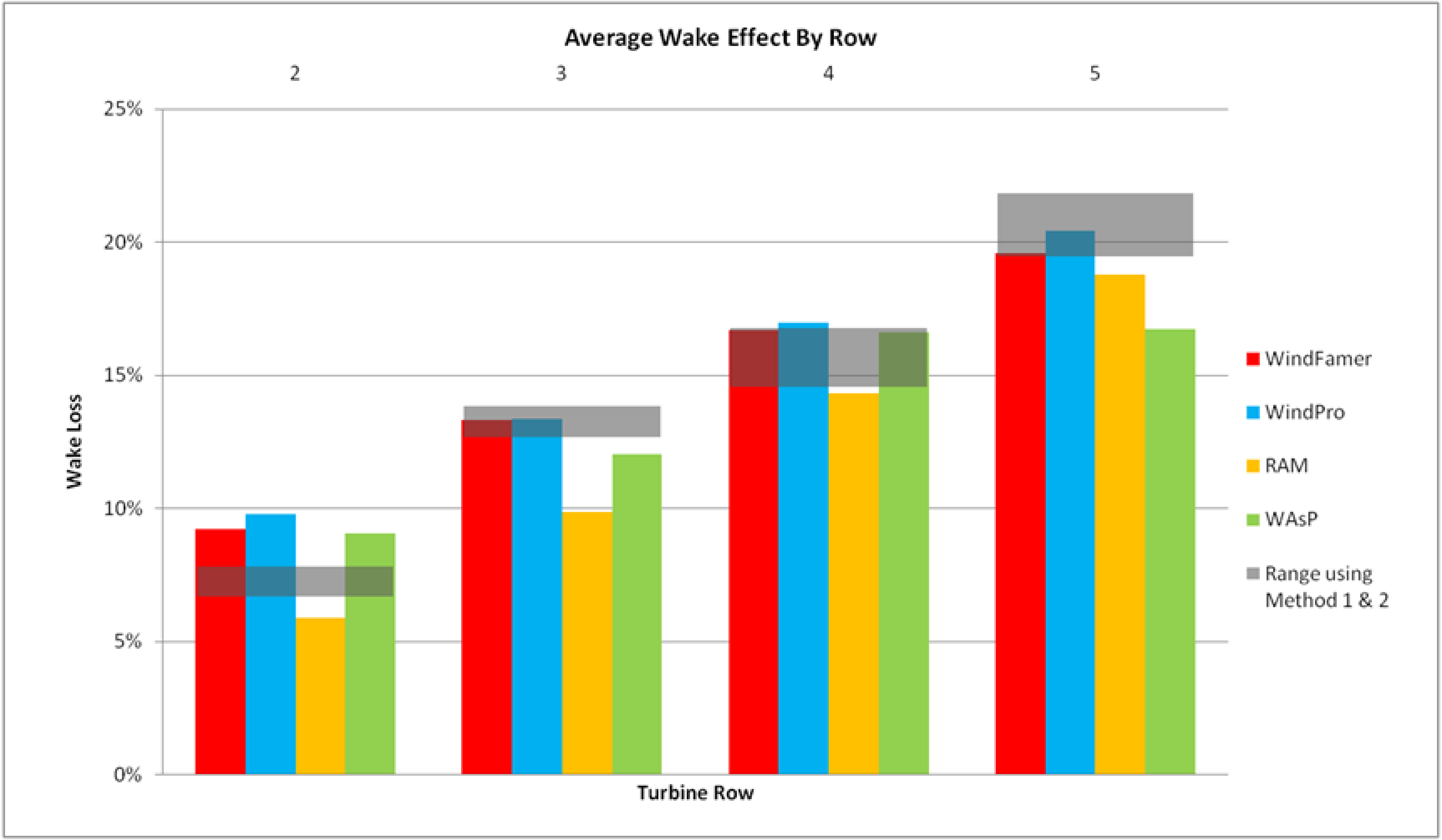
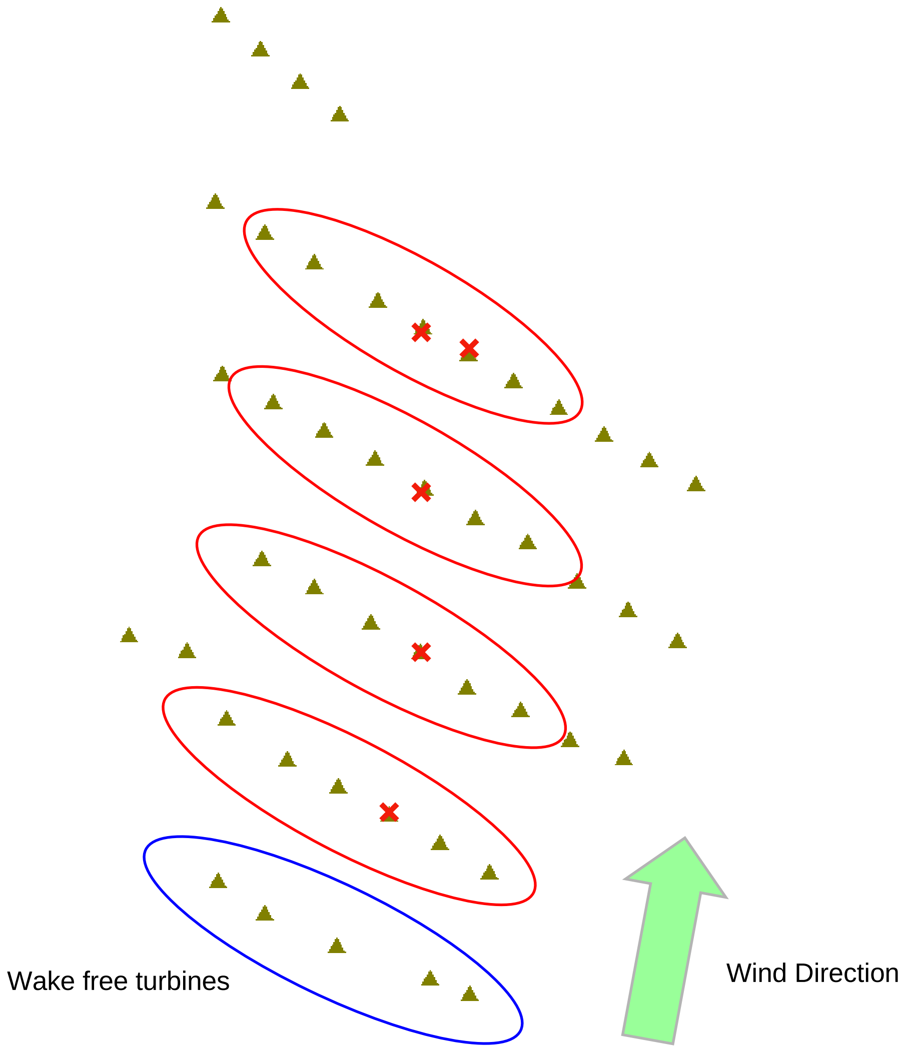


Case 2 – 5 rows deep, 190°wind direction



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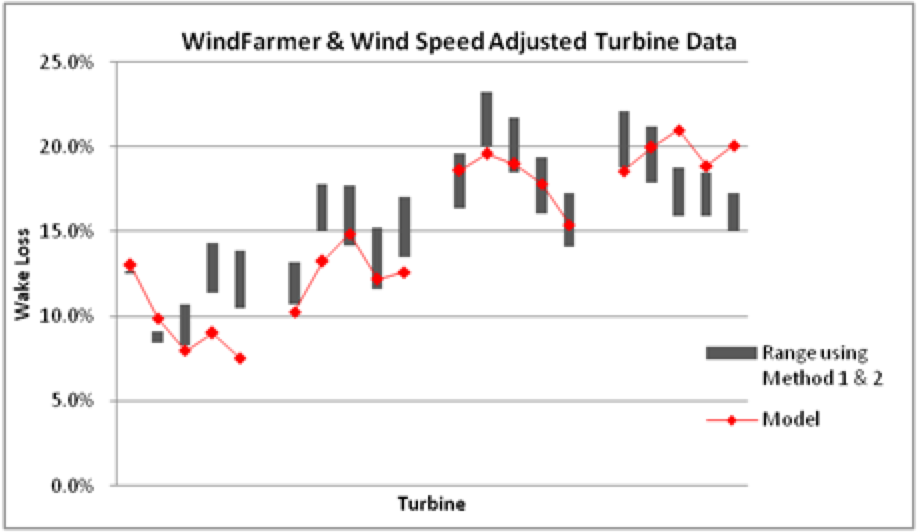
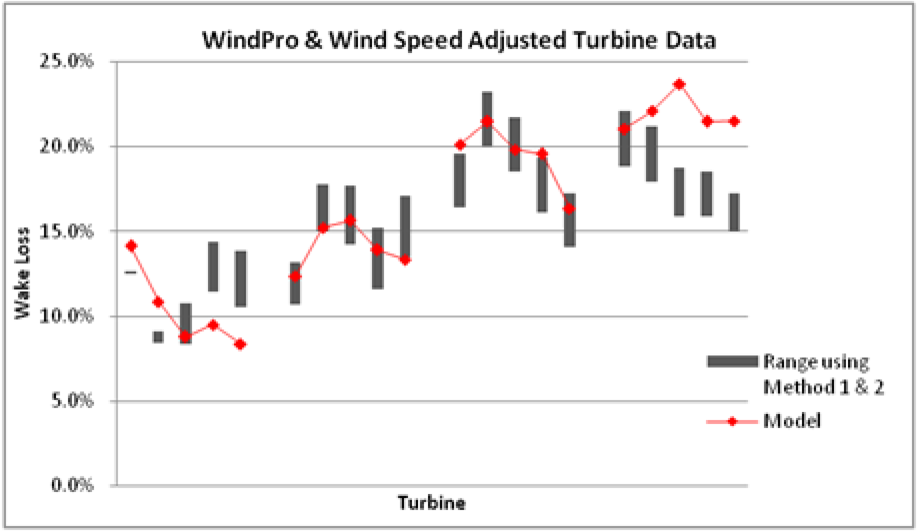
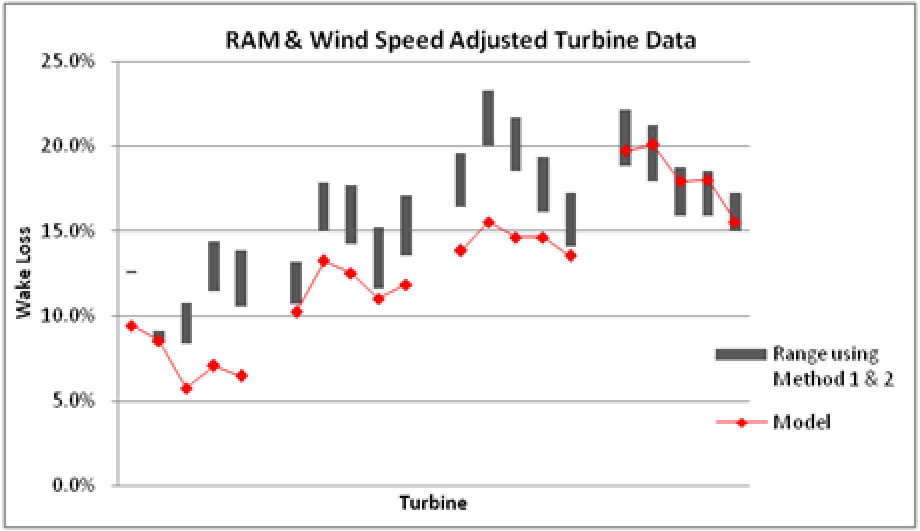
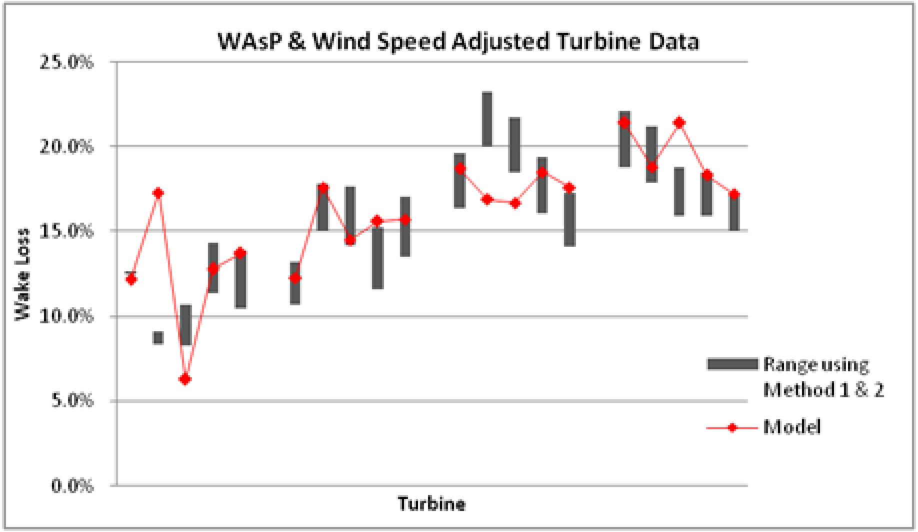
Results – Wind Speed Adjusted Turbine Data…

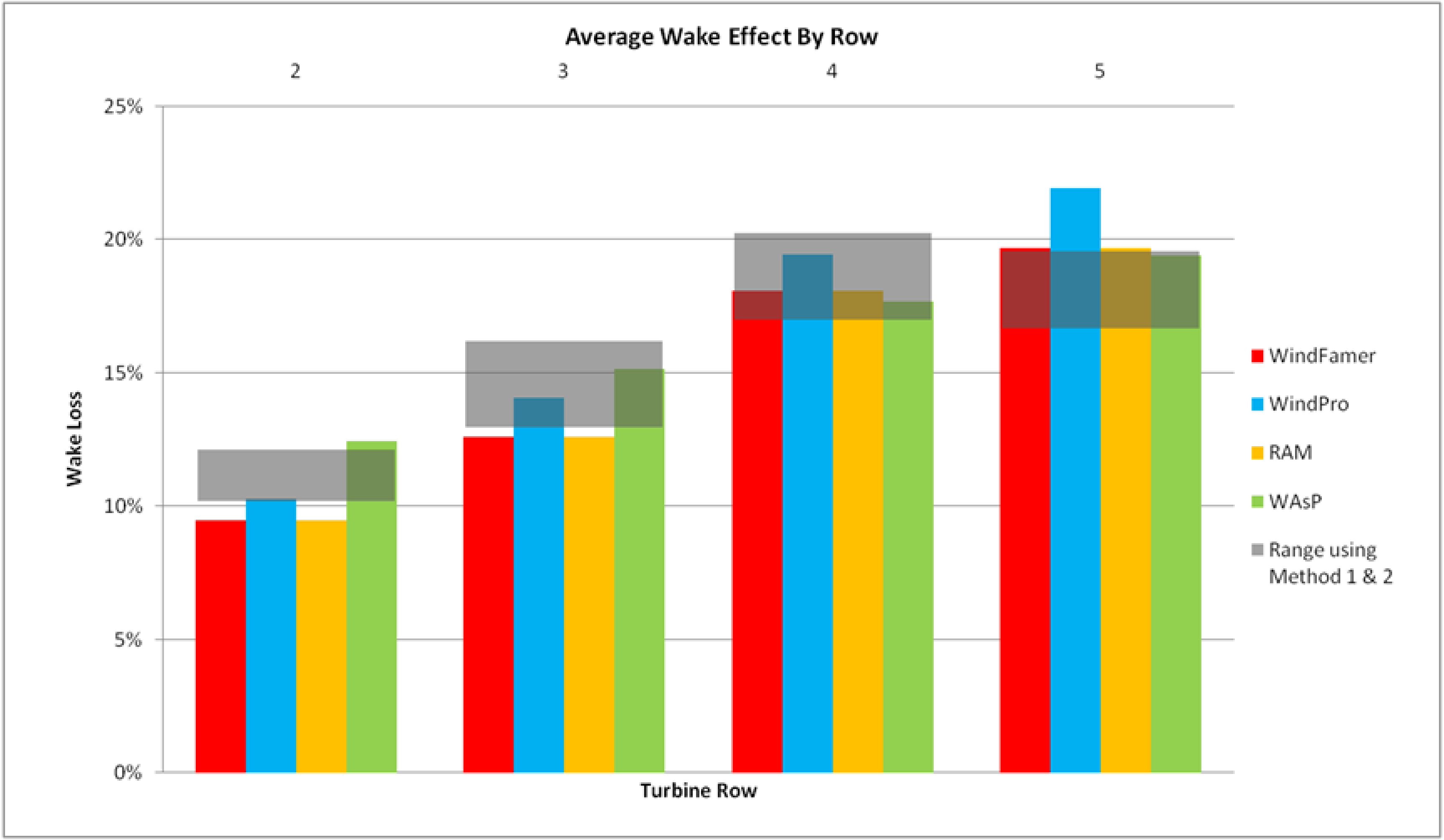








Results – Wind Speed Adjusted Turbine Data…



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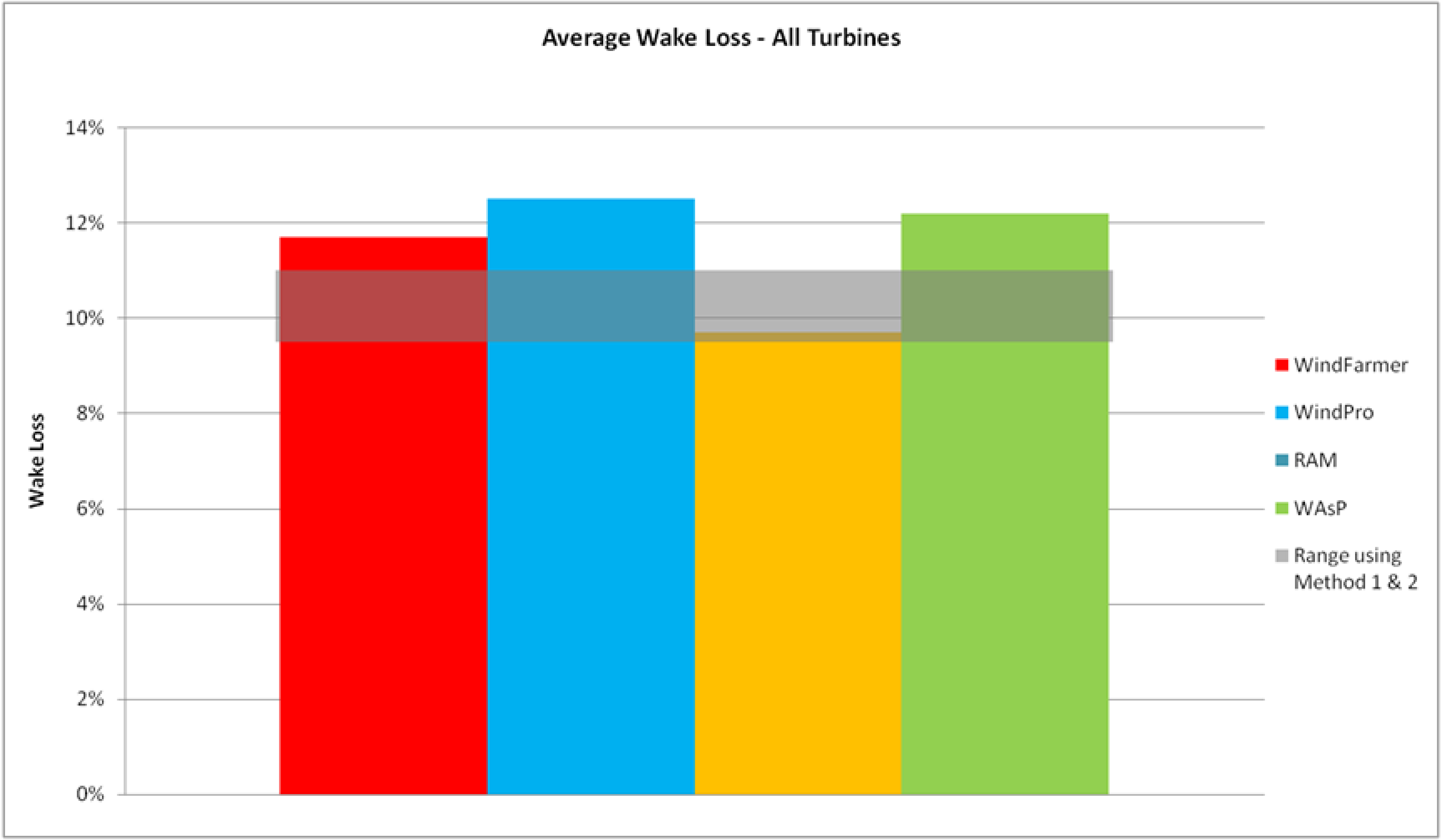
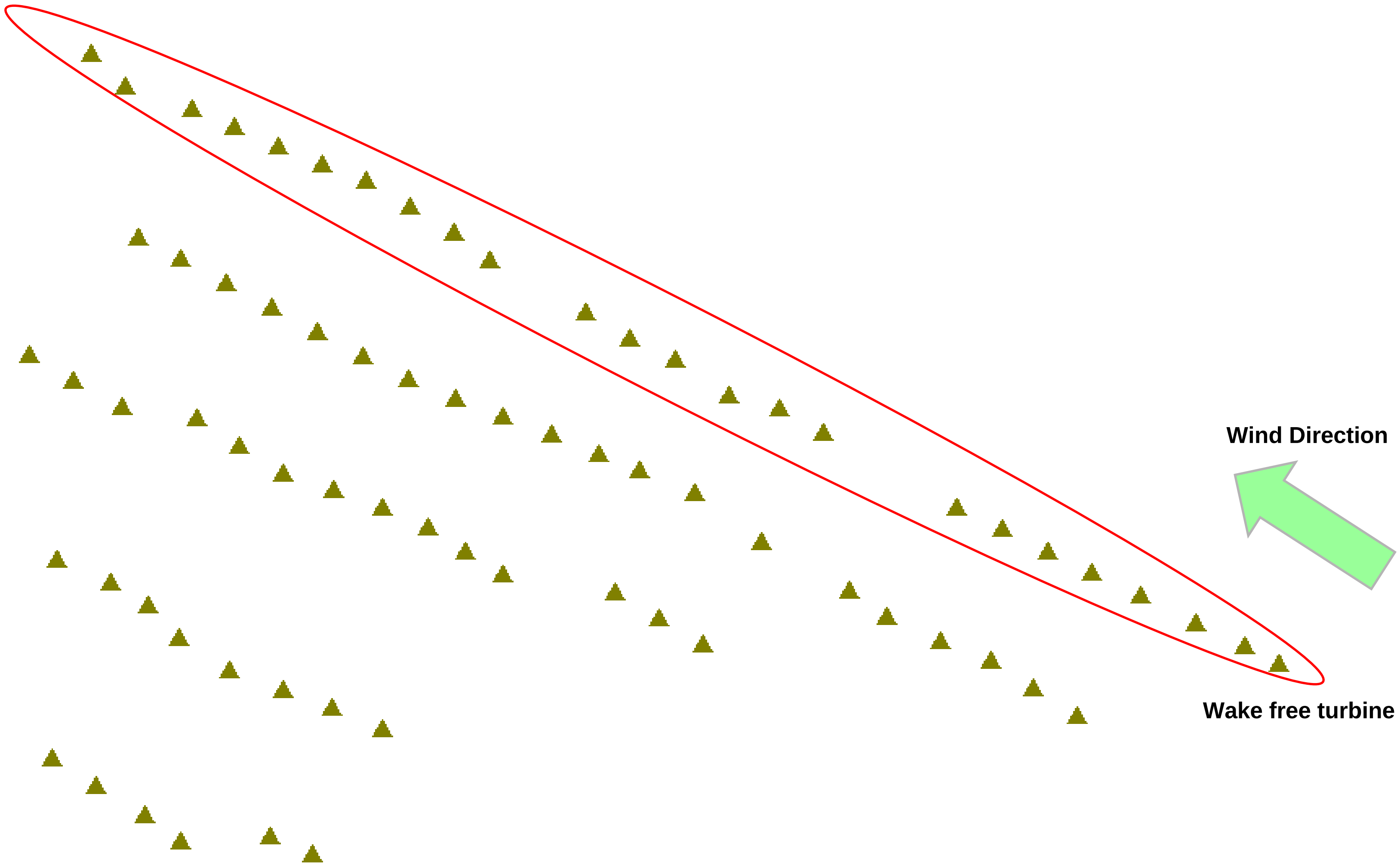
Results – Wind Speed Adjusted Turbine Data (118



Case 3 – 24 rows deep, 120°wind direction



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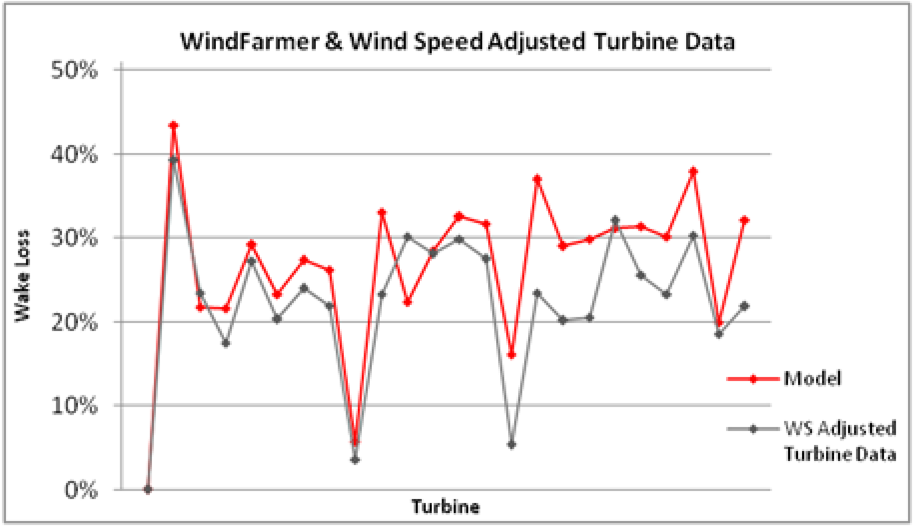
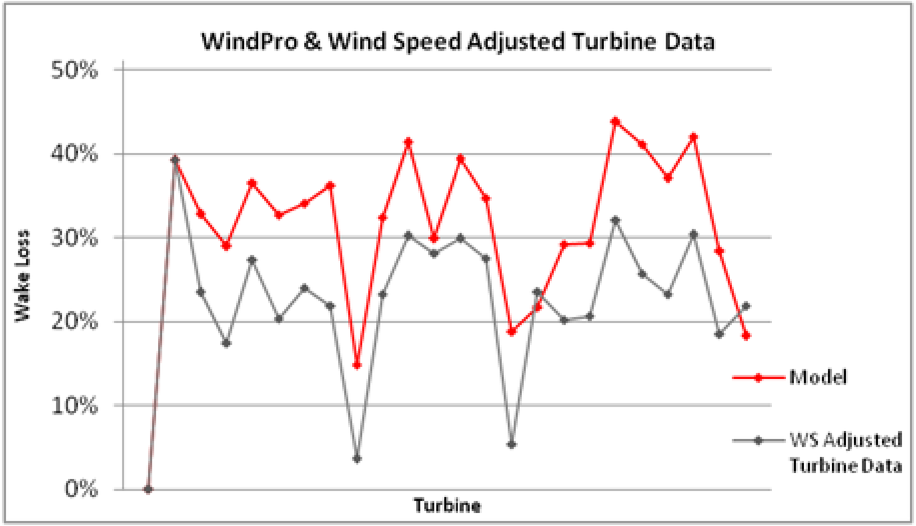
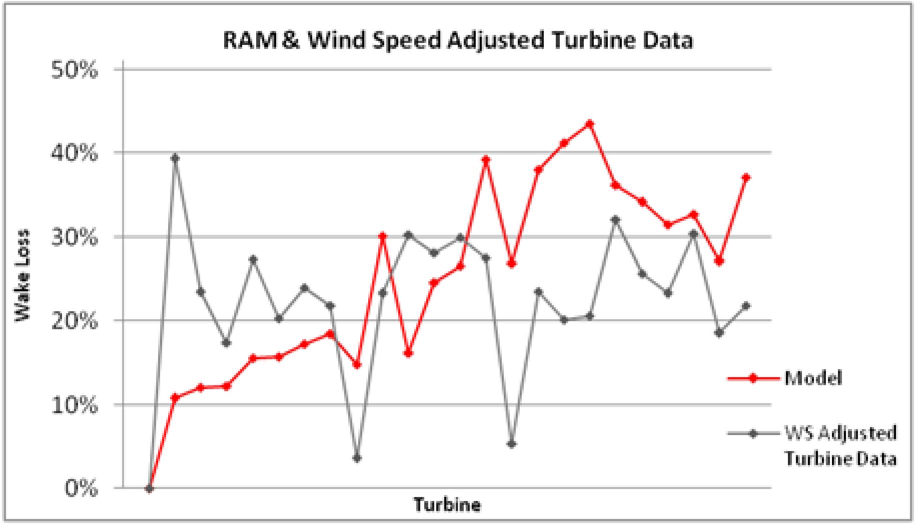
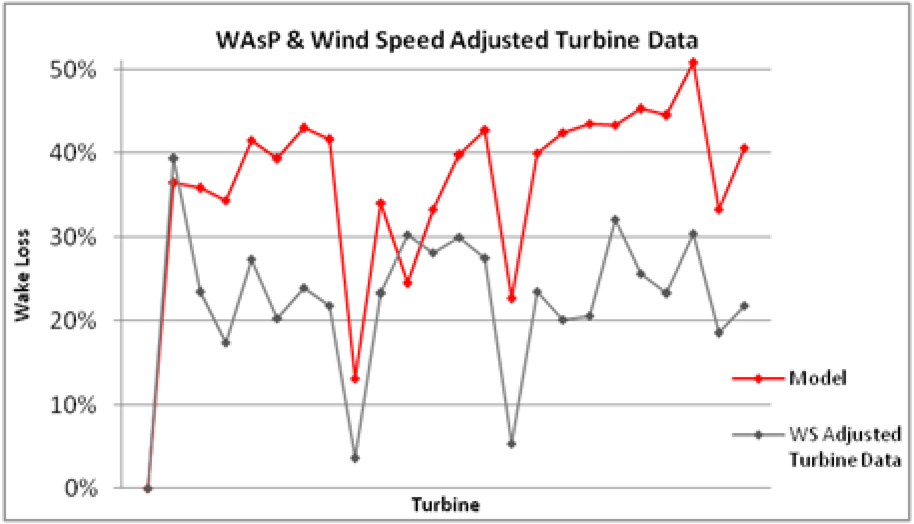
Results – Wind Speed Adjusted Turbine Data…



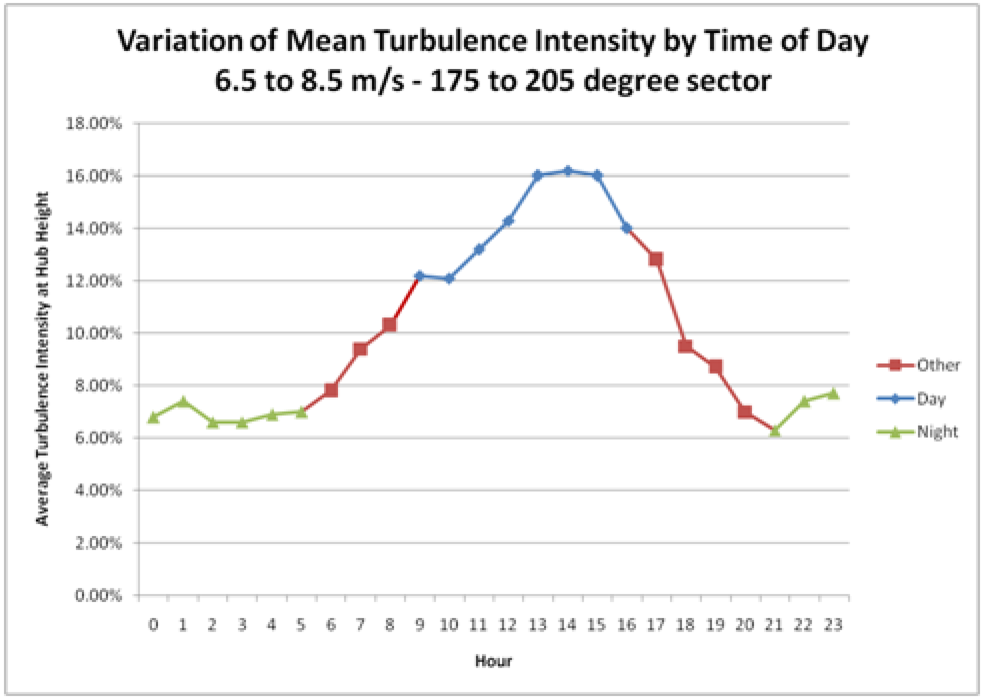






Stability & Turbulence Intensity

- Turbulence intensity (TI) was used as a proxy for stability. Assumption: High TI = Low stability
- Clear indications of higher TI during the day than night for wind speed and directions of interest.



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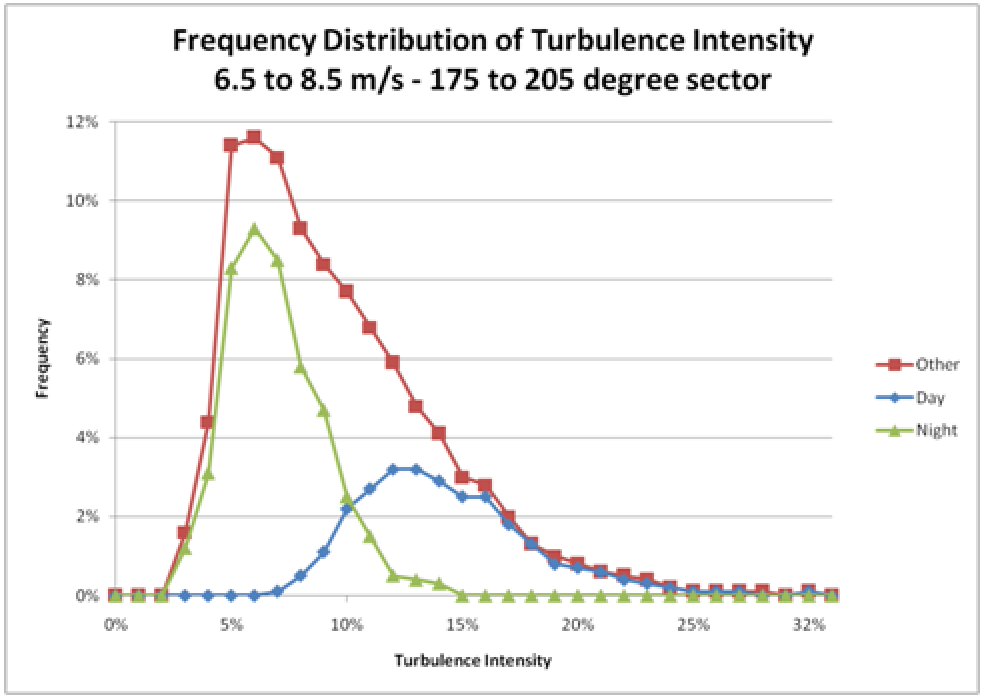
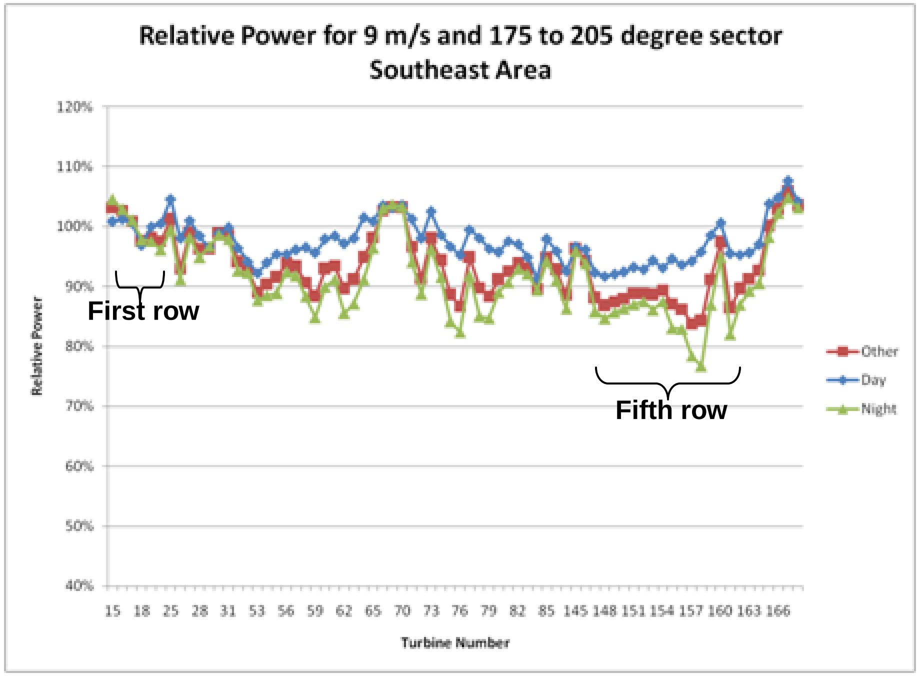
Turbulence Intensity Frequency Distribution

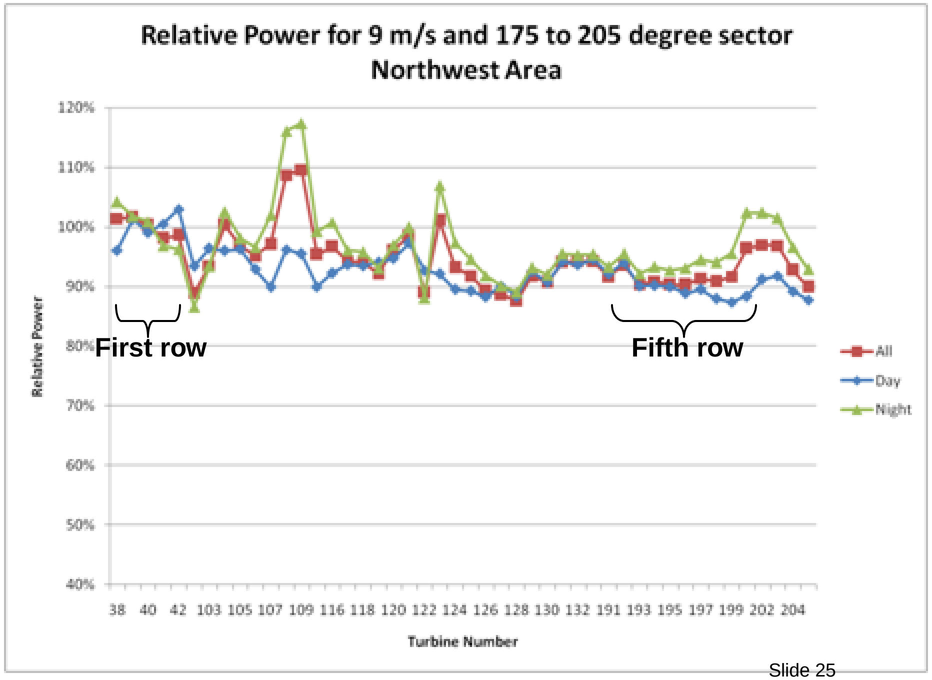
- Day – 1000 to 1700 local time
- Night – 2200 to 0500 local time
- Mean TI – Day = 14.2%
- Mean TI – Night = 6.9%



Turbulence Intensity & Wake Loss

- Hypothesis: Increased wake loss during low TI / high stability (night).
- Note: Wind speed variation across project has not been removed from results.





Conclusion…

- Accounting for uncertainty in the turbine results, commonly used wake models are capturing the wake effects within large onshore wind farms reasonably well.
- As stability changes, changes in wind flow may have a greater impact on power output than changes in wake

Cautions…

- The frequency distribution within the 30° direction sectors varies, affecting the turbine results.

- Normalizing power output across an onshore project, even a very flat site, is difficult, due to small wind speed variations.
    - The method for adjusting relative power based on wind speed variations lacks consensus.

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Next Steps…

- Remove wind speed variation from turbulence intensity results.
- Investigate wake model sensitivity to wind direction.
- Model vs. actual wake effect of one large wind farm on another large wind farm.
- With caution, use a properly configured model to provide good estimates of wake loss for large wind farms.