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Continuous Reliability Enhancement for Wind

Visualizing Wind Farm Wake Losses using SCADA Data

Sandia National Laboratories

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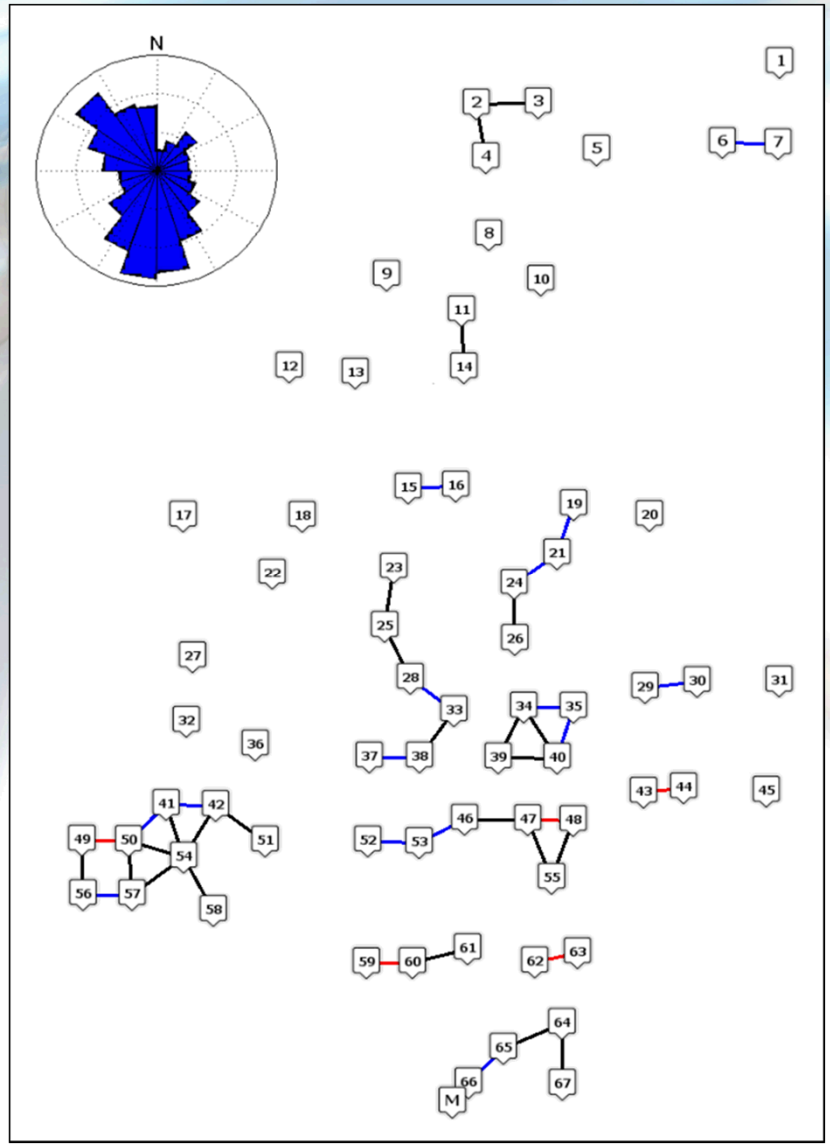
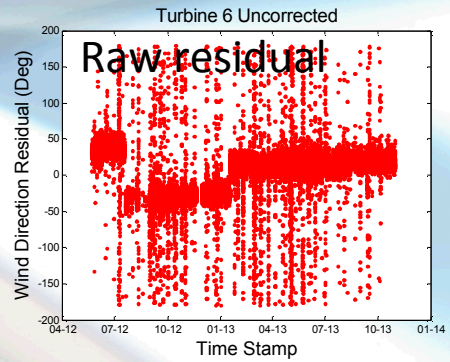
Data

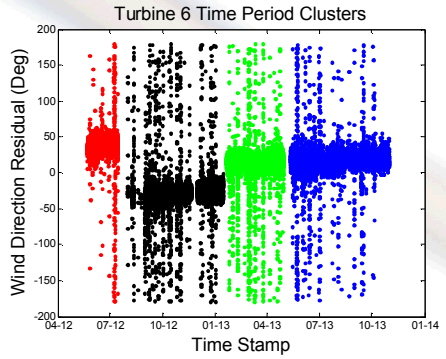
- 1.5 year of SCADA data collected from 67 mid-west MW-class turbines
- Met-mast south of farm {M}
- Flat terrain surrounded by clusters of threes, farm houses and other wind farms
- Data is reduced from 2 sec. resolution to 10 min. value
- Wind rose: NW and S
- Red, blue & black lines show <5D, 5-6D and 6-7D spacing

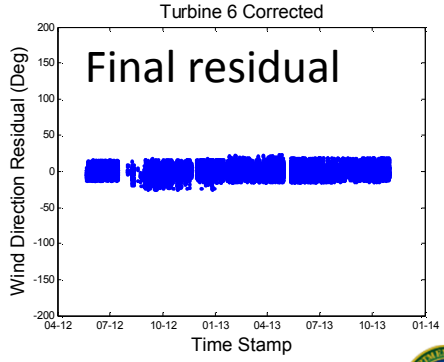


Correcting nacelle position and initial data cleaning

- Only operational data are used for the analysis
- Initial data is 61,000 10 min values per turbines, keeping only data from 4 m/s to 20 m/s, 46,000 10 min values per turbine remain, which agrees with the annual wind speed distribution for the site
- The nacelle position generally serves only little purpose for the turbine control, so often the sensor is un-calibrated and associated with drift and/or offset
- Steps for correction of nacelle position:
  1. Define residual as deviation from average of met-mast and two neighbor turbines
  2. Identify and remove periods with discrete off-set
  3. Remove outliers larger than one std. dev.
- The remaining data is ~34,000 10 min values per turbine







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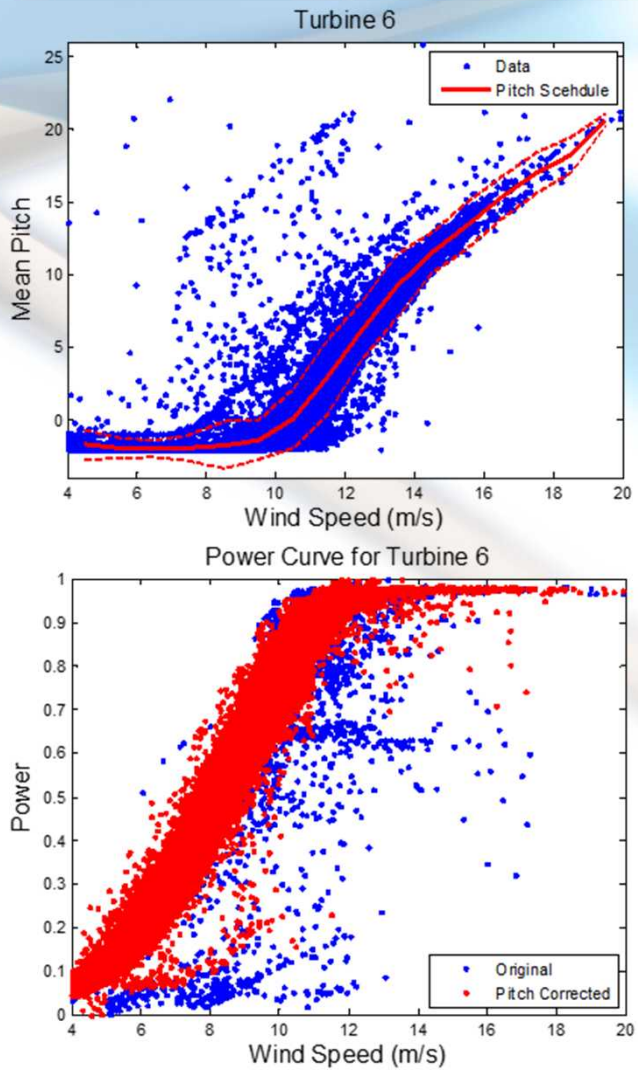
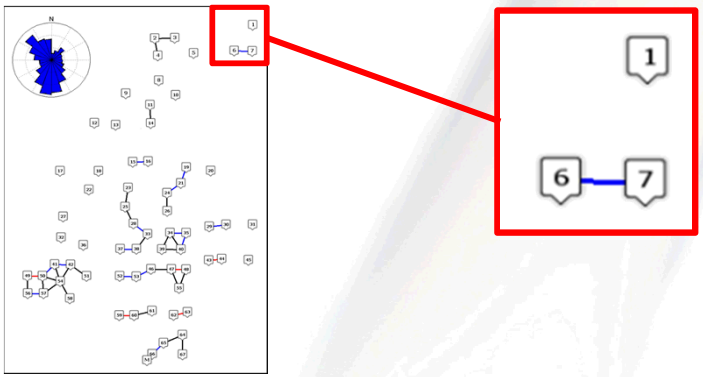
Cleaning power curves

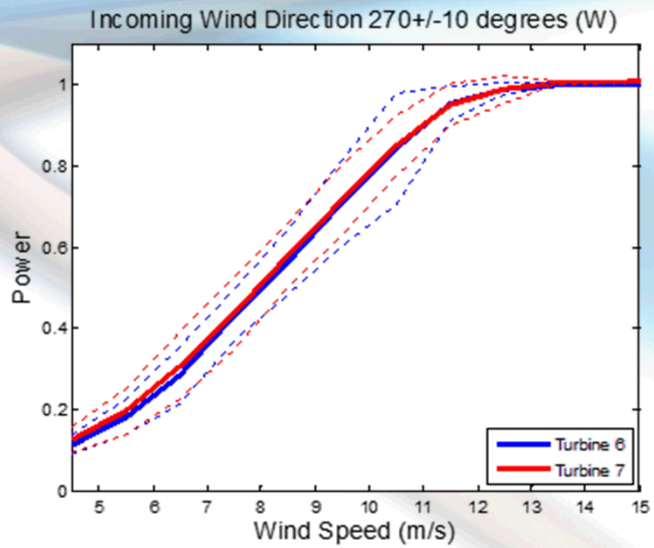
- With the wind range and nacelle position corrected, turbine pitch as a function of nacelle wind is used to filter abnormal power mode operations
- Steps for correction of power curve:
  1. Compute 1 m/s binned pitch curve
  2. Remove outliers larger than one std. dev.
- The method removes:
  - Most severe outliers
  - De-rated power modes
  - Most low wind outliers
- Final number of data available is 32,000 10 min values per turbine or ~ 222 days of operation

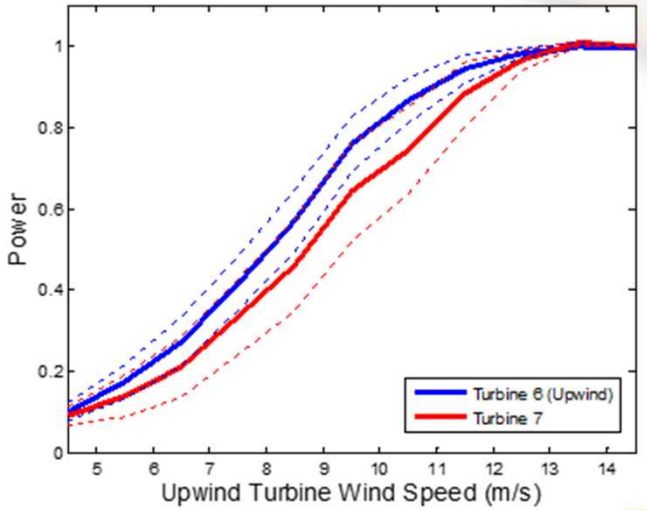


Paired power curve comparison

- Turbine #6 and #7 is 6D apart in NE corner of the wind farm
- Using western wind, mapping turbine #6 and #7 against their own nacelle anemometer, the wake turbine #6 impose on #7 can not be detected
- Mapping both turbines to turbine the upstream nacelle anemometer of #6, turbine #7 (obviously) show a wake deficit in region II of the power curve as expected
- This method can only be used when the upstream turbine is free, which for most complex layouts, never is the case







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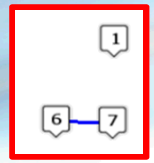
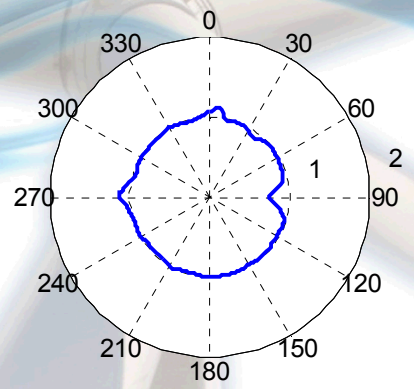
Paired directional comparison

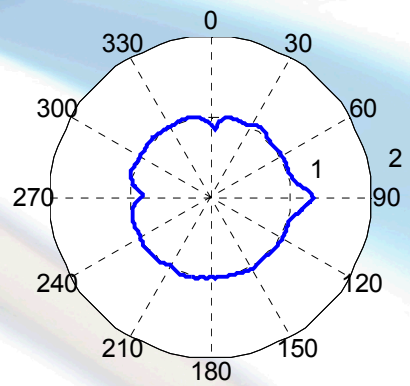


- For each wind direction the average normalized instant power and variability reveals wakes clearly by direction, magnitude and shape
- Neighboring features, for example turbine#1 in NE direction, is also revealed
- For a two turbine situation, the nominator is strongly influenced by the wake. If all the farm is used, this effect becomes negligible

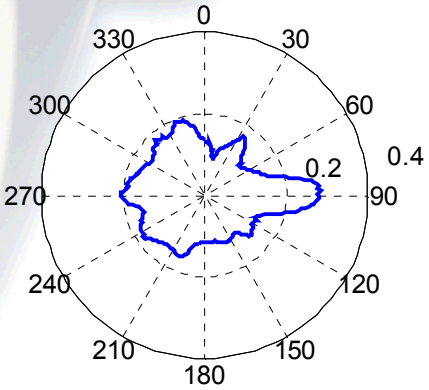
$$P_N(t) = 2P_6(t)/(P_6(t) + P_7(t)).$$



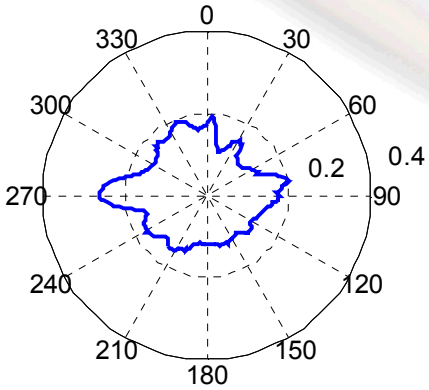
Normalized Instant Power Turbine 6



Normalized Instant Power Turbine 7

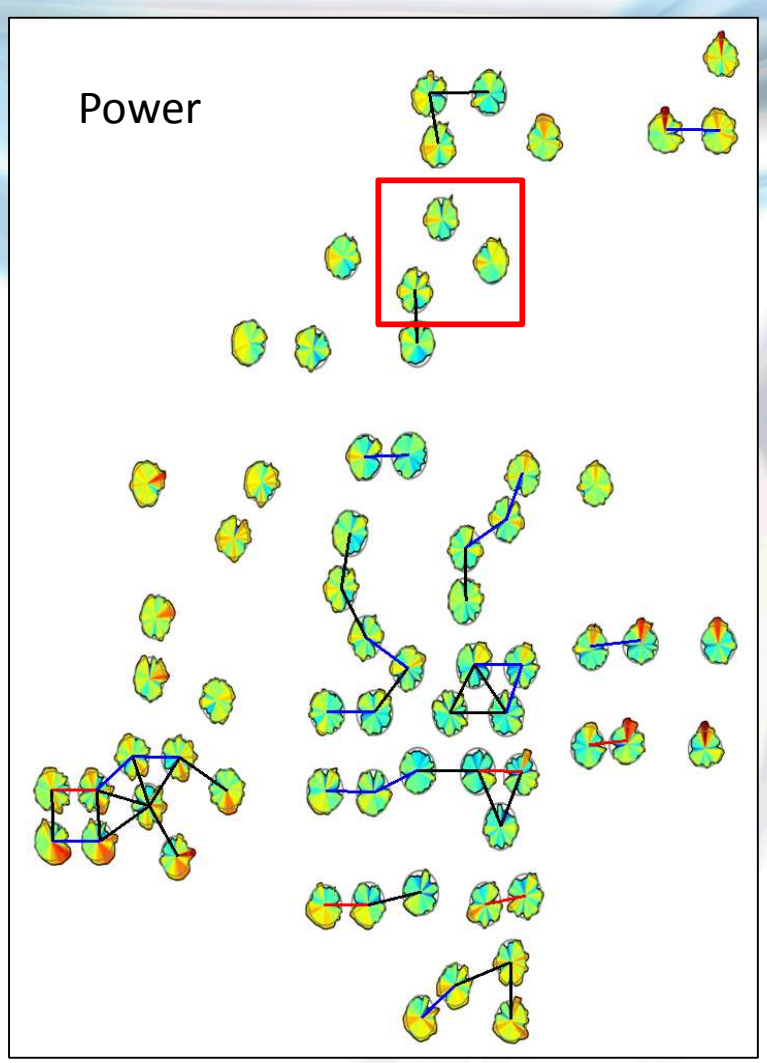


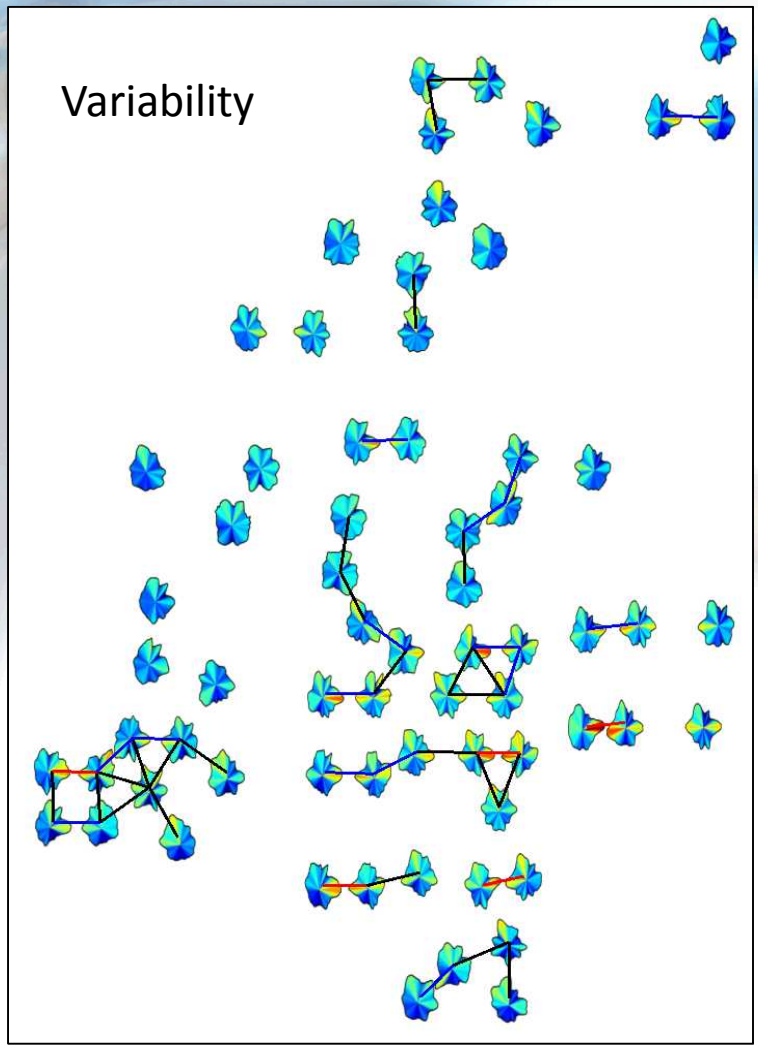
Power Variablity Turbine 6



Power Variabilty Turbine 7

Directional analysis – full wind farm





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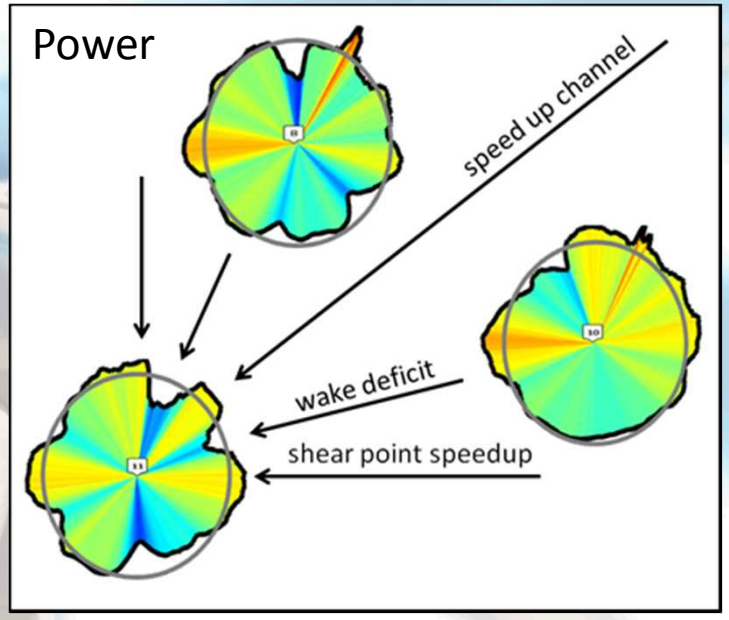
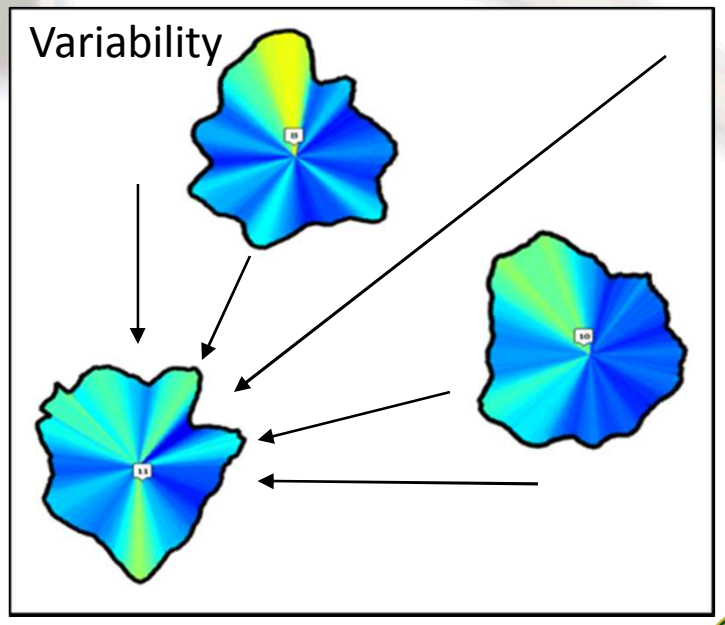
New observations

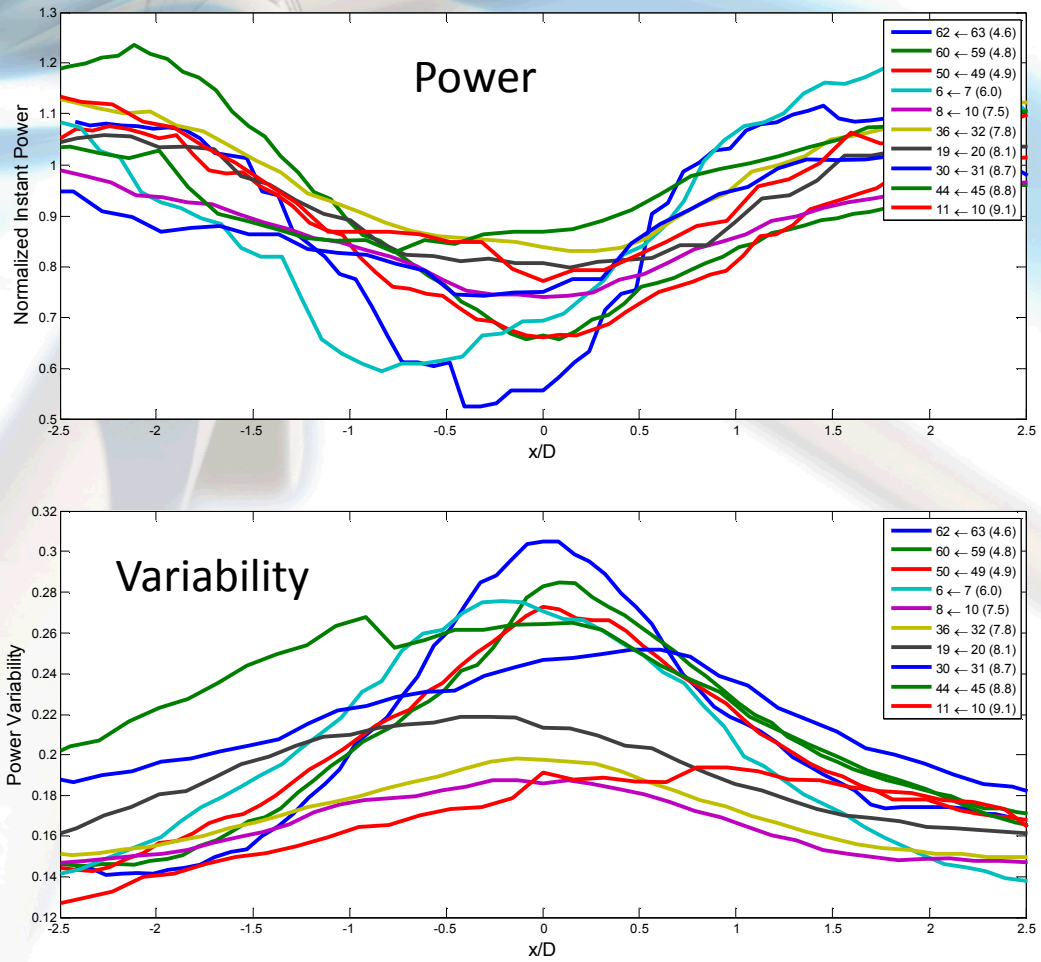
- Four effects have been identified:
  - Wake deficit
  - Speedup channels from two upstream turbines
  - Shear point speedup from one upstream turbine
  - Shear point speedup from multiple upstream turbines or an upstream wind farm
- The three speedup effects are new, generally not considered in wind farm modeling





Wake deficits

- Wakes can be identified in profiles of power deficit at expected bearings within a few degrees of accuracy
- Wake width, plotted in x/D using bearing and turbine distance
- Power variability is a strong and consistent indicator of wake
- The site contains almost no clean inflow situations due to landscape, upstream farms and upstream turbines, which skews profiles



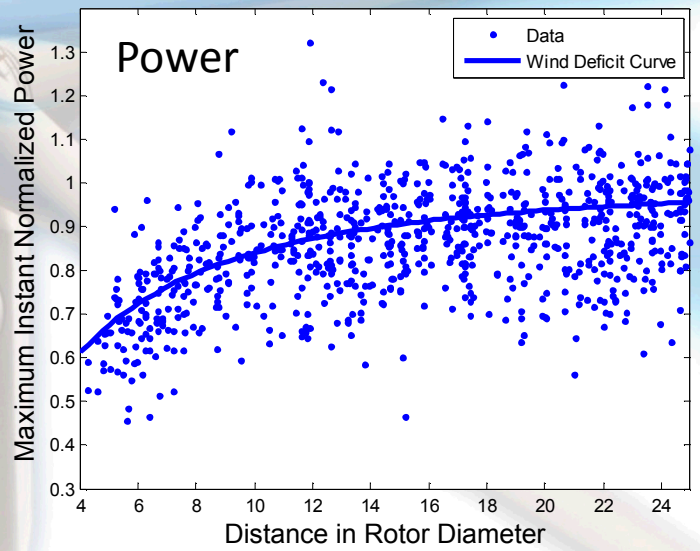
Profiles for 4 to 8D turbine distances

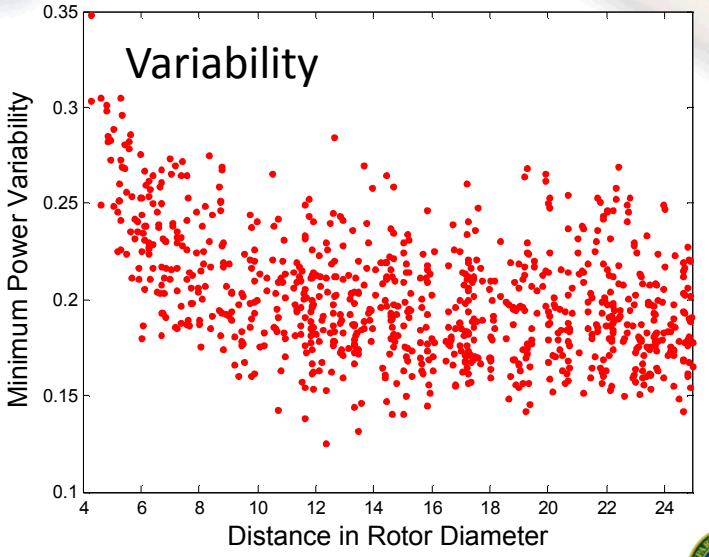
Wake deficit as function of distance

- Data comparing 854 turbine pairs in direct wake of each other
- Power wake deficit follows expected behavior, comparing to classic wake deficit theory:

$$\frac{U_x}{U_0} = 1 - \frac{1-\sqrt{1-C_T}}{1+2k\frac{x}{D}},$$

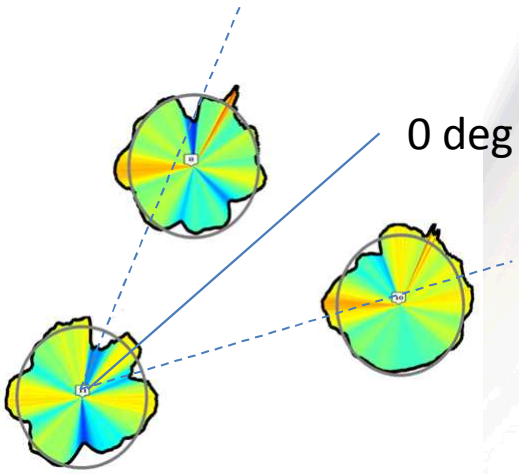
- Variability drops rapidly as some wake models predicts

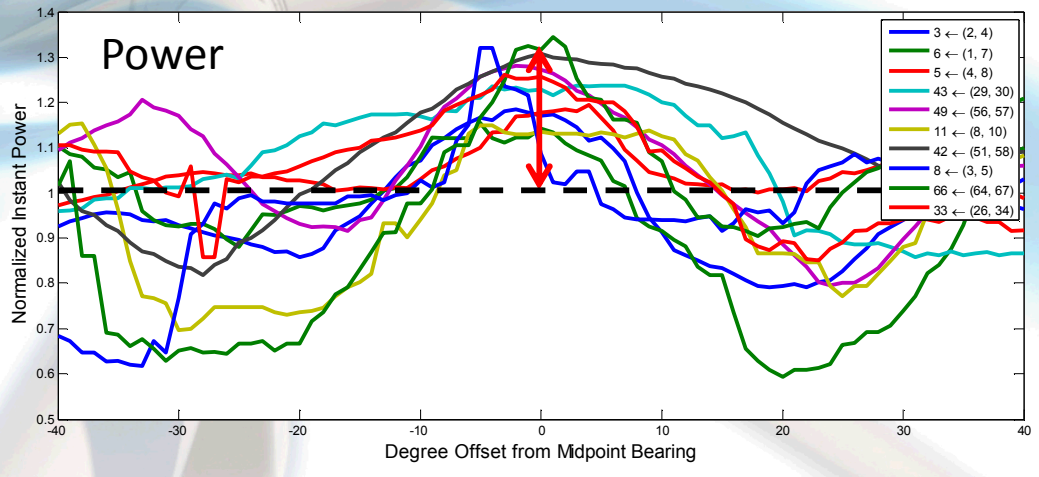


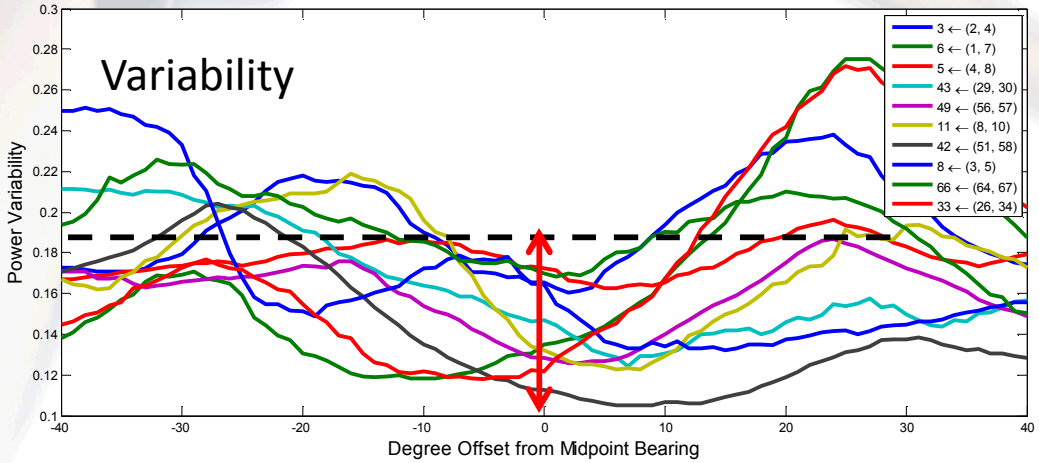


Speedup channels

- Profiles are plotted relative to a bearing of the mid-point between two upwind turbines
- An performance from 1.1 to 1.3 over norm (=1) is found
- Centerline power variability is found to be lower than ambient level
- Both effects are generally not included in wake models







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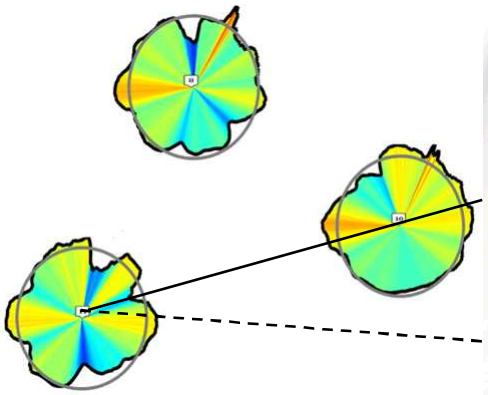
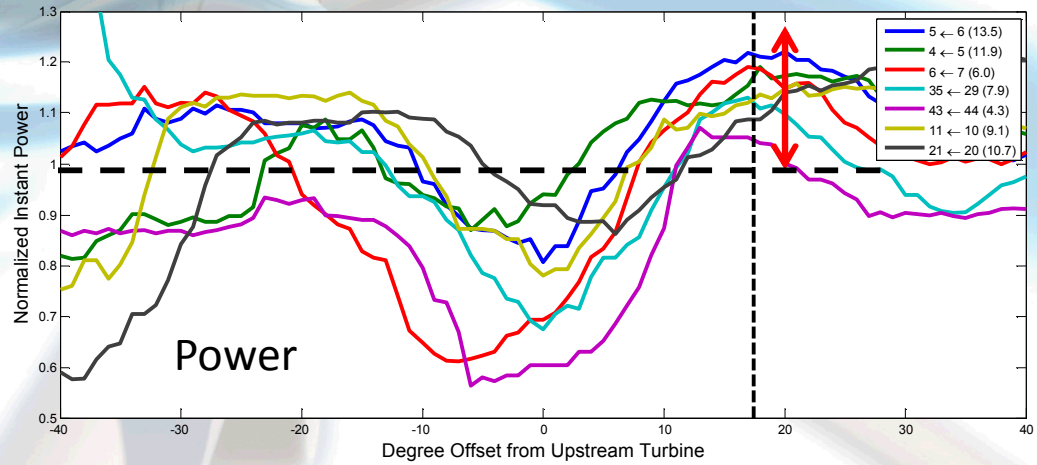
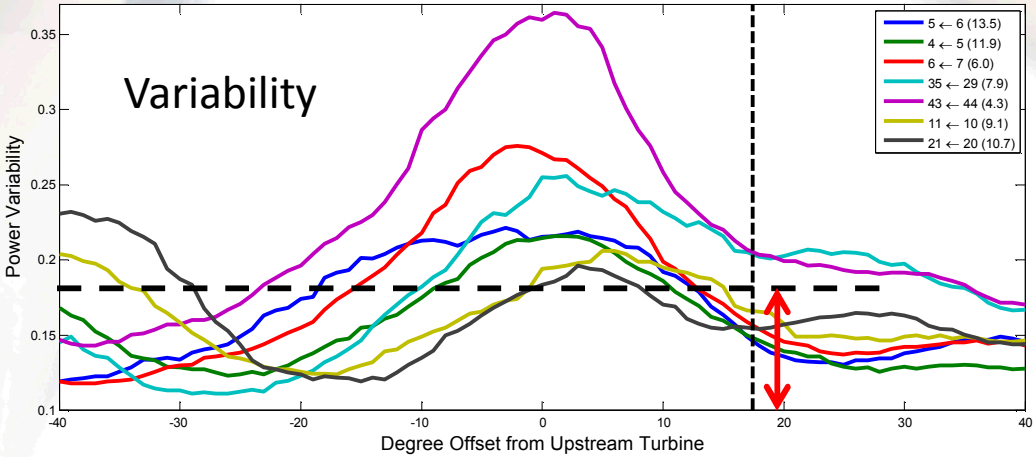
Shear-point speedup

- Profiles are plotted aimed directly at the upwind turbine, where the clockwise upstream airflow is free of obstruction
- Between 15 an 20 degrees speedup with a power boost of 1.1 and 1.22 over average is found
- Power variability in this range is found to be lower than ambient level
- Both effects are generally not included in wake models







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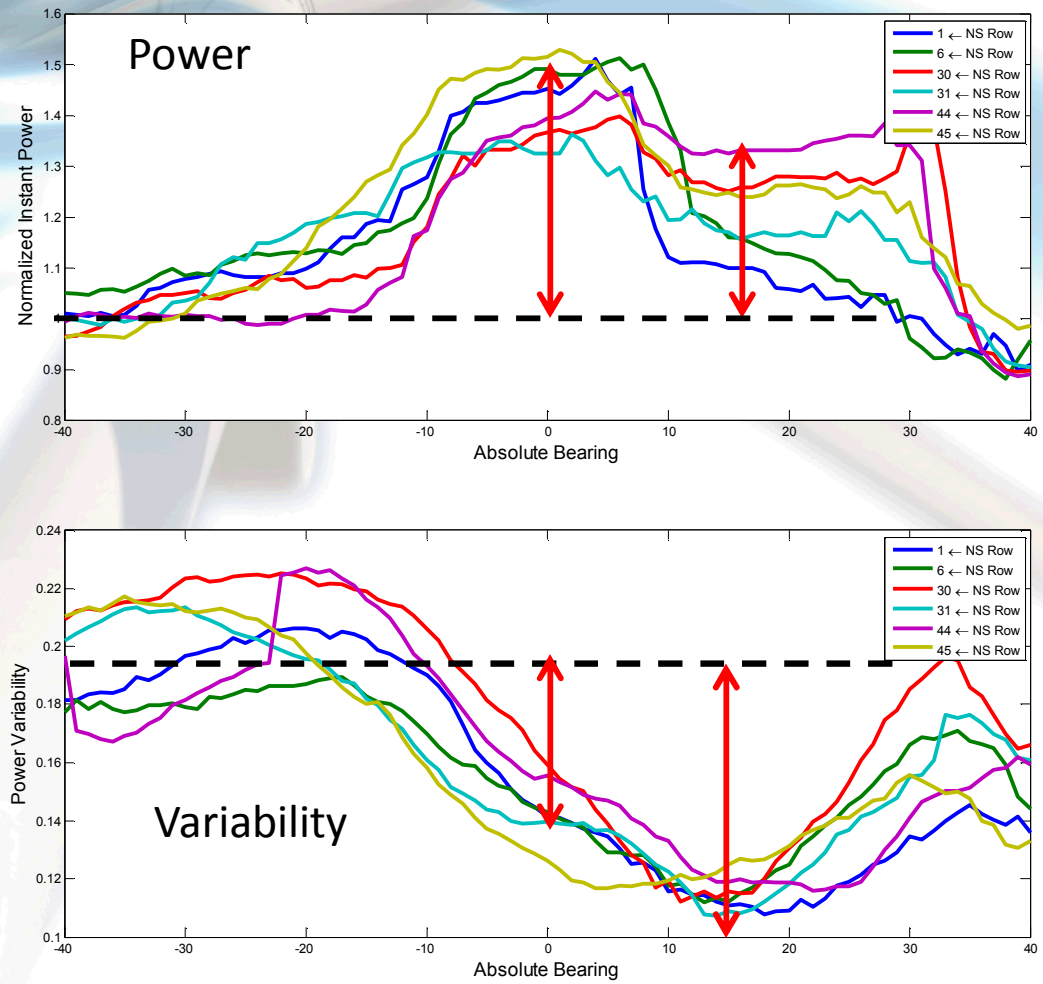
Speedup from multiple turbines

- Six turbines face rows of turbines at due north
- Profiles are plotted at absolute bearing (0= North)
- Speedup power boost of 1.3 and 1.5 over average is found
- Clockwise a 15 to 20 degrees, speedup is still found, and the power variability in this region is found to be significant lower than ambient level
- Complexity is larger at this angle because the effects are a combination of speedup and waking and landscape roughness
- The effects are generally not included in wake models



Conclusion

- The novel directional analysis applied has proven effective in mapping wake deficit in a complex wind farm layout
- Three new wake effects have been discovered
  - Speedup channels from two upstream turbines
  - Shear point speedup from one upstream turbine
  - Shear point speedup from multiple upstream turbines or an upstream farm
- The new speedup effects identified are generally not included in wake modeling
- High power associated with the speedup effects is counter-intuitively associated with low power variability
- The discovered effects cold affect turbine reliability in a positive way