

## SUPPLEMENTARY MATERIAL

### A comparison of methods for assessing power output in non-uniform onshore wind farms

Andrea Staid, Claire VerHulst, Seth D. Guikema

#### 1. DATA QUALITY

The data for both farms was cleaned and filtered based on several metrics. For Farm 2, the met tower data was filtered to remove extreme datapoints (i.e., where temperature or pressure values were outside of a normal range for the area) and datapoints with very large disagreement between the two temperature readings within the farm. In this case, the values were filtered according to historical measured data at a nearby airport. Deviations larger than 10°C were removed. Additional filtering was done based on the availability and curtailment data for both farms in order to have as complete of a dataset as possible for accurate comparison to wake models. Ideally, only data in which availability equalled 1 and curtailment equalled 0 would be used so that every turbine would be fully operational, as is the case in the model runs. In reality, this limited the size of the dataset quite considerably and we instead chose more lenient thresholds for filtering. The remaining data used for analysis contains all of the data points in which all turbines have an availability value above 0.8 and a curtailment value below 0.2, meaning that every turbine was available at least 80% of the 10-minute interval and was curtailed no more than 20% of the interval. This limits the viable data considerably, resulting in approximately 11,400 observations for Farm 1 and 15,600 observations for Farm 2.

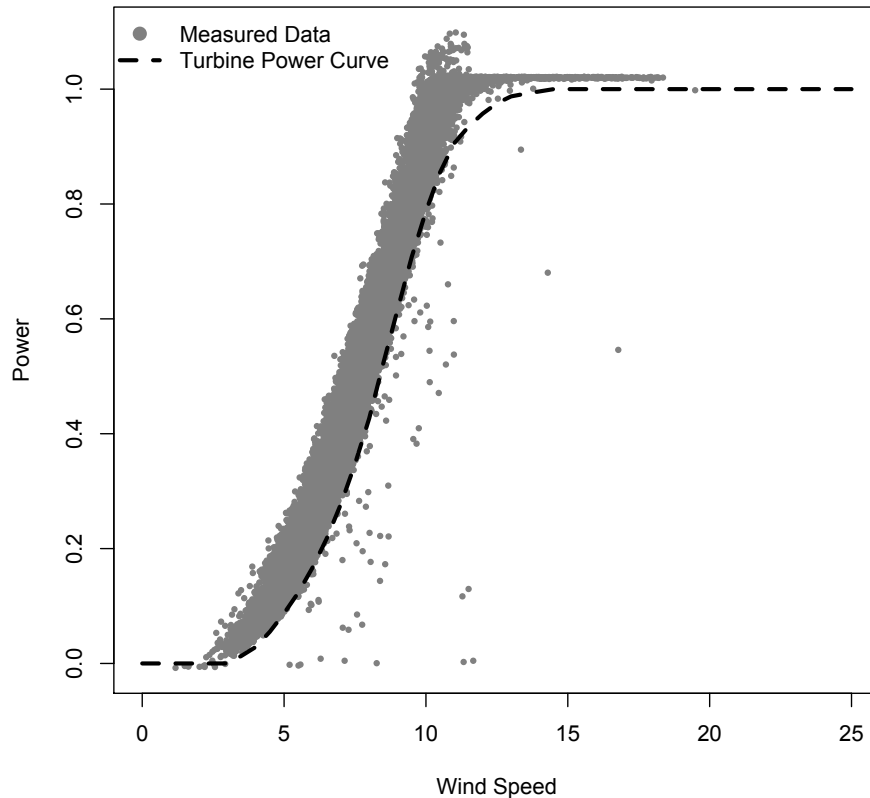
When working with real data, there is always the question of its accuracy. The results of any analysis using the data are only meaningful if the data itself is trusted. There are several possible sources of error in the available wind farm data. The met towers could be out of calibration, either in wind speed or direction. The turbines themselves could have sensors that are out of calibration, either for power or wind speed. The data provider assured us that the power measurements were accurate. This is, to the farm owner, the most important parameter and they have a strong interest in ensuring its validity. However, the power data can also be checked against the nacelle wind data, and vice versa. The wind data is measured behind the blades, so it is not identical to the incoming wind seen by the turbine. However, it is safe to assume that the drop in velocity through the blades remains consistent over time for different wind speeds and that is also similar across turbines. Thus, a plot of the individual turbine wind speed versus power should follow the manufacturer's power curve quite closely, but with a slight offset due to the wind measurement taken behind the blades, as opposed to in front. Figure 1 shows this plotted for a single turbine from Farm 2. The plots for all turbines in both farms are remarkably similar. It is safe to conclude that the turbine data (power and wind) are accurate.

The wind direction as measured at the met towers can be checked against expected farm performance metrics. For example, it is known that there will be reductions in power production for a turbine sitting directly behind another turbine when the wind is aligned with the turbines. This can be used to check the calibration of the measured wind direction. Figures 2 and 3 show the average power ratio of two adjacent turbines as a function of wind direction in Farm 1 and Farm 2, respectively. When the wind is aligned with an imaginary line connecting the two turbines, one would expect to see a drop in the power (or wind) ratio. This often has a shape similar to a bell curve as there is partial wake interaction as the wind direction moves away from direct alignment. This dip in relative power does not occur at the expected measured wind direction for either of the farms or either of the met tower measurements. For Farm 1, both met towers seem to have a direction offset error in the measurements. Further comparisons of turbines in Farm 1 confirm an offset at met tower 1 of +30° and at met tower 2 of +22°. For Farm 2, further comparisons confirm an offset at met tower 1 of -79° and at met tower 2 of -58°. The measured wind direction has been corrected by these values for subsequent comparisons across models.

#### 2. RELEVANCE OF WAKE MODELS

Wake models such as the Jensen model are appropriate in cases where turbines in a farm are spaced closely enough so that the wakes from leading turbines do interact with downstream turbines. The exact distance at which a wake ceases to impact downstream turbines depends on the turbine size, the amount of turbulence in the surrounding flow, and any characteristics interfering with the flow, such as terrain features. At a minimum, it has been found that a wake can propagate for a distance of 8-10 rotor diameters, and this distance can be even longer if the turbulence is low [1]. Optimal turbine spacing, taking into account both wake effects and the economic cost of increased spacing, may be closer to 15-25 rotor diameters in some settings [2]. In the case of Farm 1, empirical evidence has shown wake effects propagating more than 15 diameters downstream under certain flow conditions [3]. Thus, it is reasonable to expect wake effects to be present in these two farms for spacings of 15 diameters, and the effects are expected to be substantial for spacings less than 10 diameters.

Figures 4 and 5 show the distribution of minimum spacing for the turbines in Farm 1 and 2, respectively. These plots incorporate the farm layout throughout the entire dataset, i.e., we have calculated the minimum upstream turbine



**Figure 1.** Normalized turbine power is plotted as a function of the wind speed measured on the turbine nacelle behind the blades for a single turbine in Farm 2. The turbine power curve is overlaid.

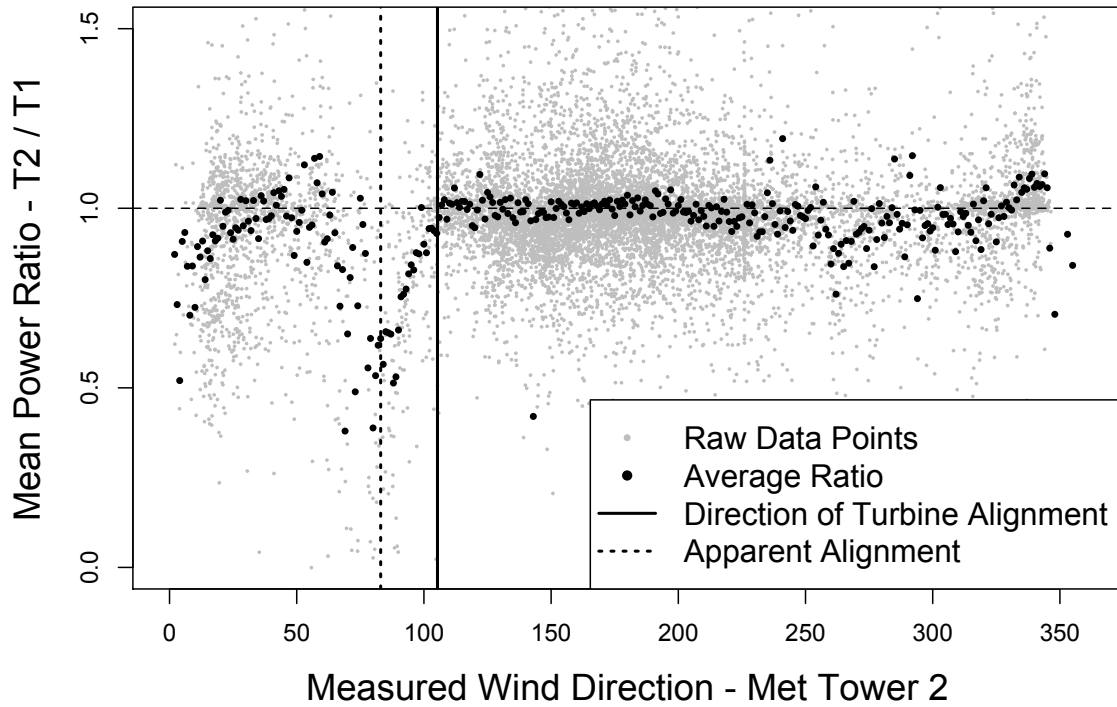
distance for any turbines sitting within a  $15^\circ$  cone of potential influence. This upstream distance obviously varies with wind direction, but these figures capture the frequency for which any turbines see a certain level of upstream spacing in the dataset based on the actual observed wind directions. For each farm, a significant portion of upstream turbine spacing falls below 15 rotor diameters. For Farm 1, 26% of turbine datapoints have a minimum spacing of less than 15 diameters. For Farm 2, that number jumps to 60%, with almost 32% of datapoints at 10 diameters or less. These two wind farms should be good candidates for wake-effect models. The direction-dependent spacing in the farms is low enough that significant wake effects are expected.

### 3. CHOICE OF WAKE DECAY AND THRUST COEFFICIENTS

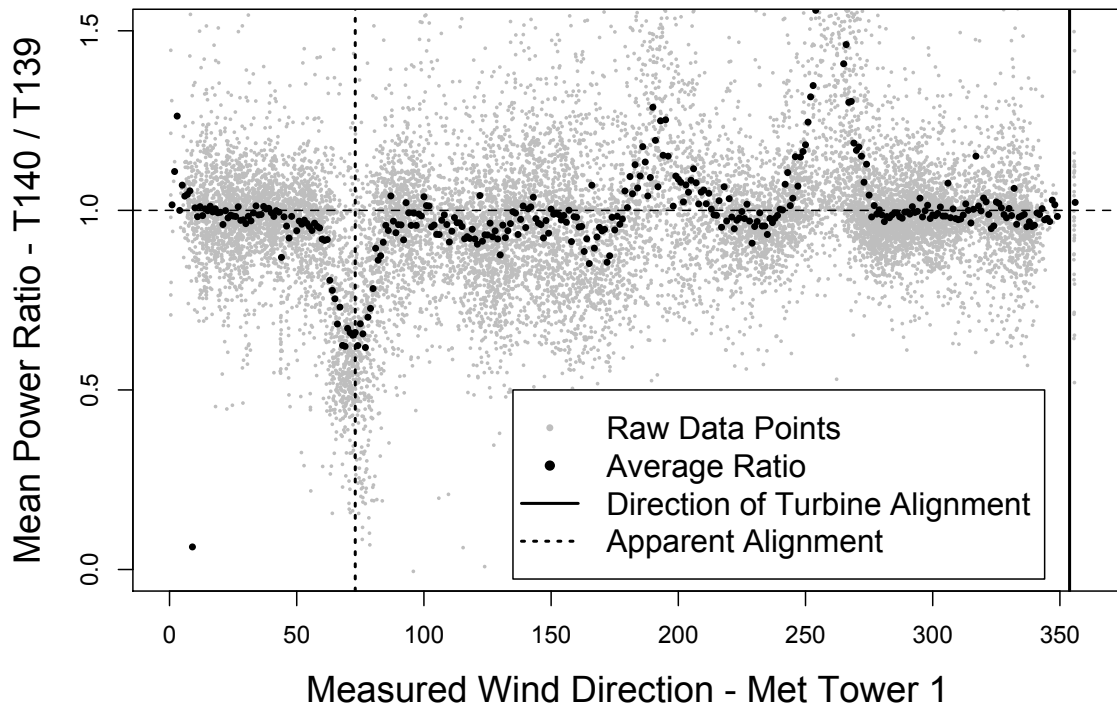
There is no data on the levels of turbulence or atmospheric stability in either Farm 1 or Farm 2, and the best guess for the value of  $k$ , the wake decay coefficient for use in the Jensen model implementation, is therefore the industry-standard value for onshore farms of 0.075. The exact thrust coefficient curve is also unknown for these turbines, but again, an initial guess was used for the previous comparison. Initial tests of the Jensen model with these 'best-guess' parameter values led to poor representation of the actual farm behavior. Therefore, we decided to perform a sensitivity analysis on the choice of the  $k$  and  $C_T$  parameters.

Here,  $k$  is varied between 0.01 and 0.1, in increments of 0.01, and  $C_T$  is varied between 0.2 and 0.9 in increments of 0.1 to represent a wide range of plausible values for both parameters. The calculated velocity deficits were then used to predict the power output of each turbine, and the sum of turbine predictions was compared to the actual results for the farm power production. The predictions were also compared for different wind speed values to account for the variation of  $C_T$  with wind speed. Data was separated into three bins of either low ( $< 5$  m/s), medium ( $5 - 10$  m/s), or high ( $> 10$  m/s) wind speed and prediction errors (in terms of mean absolute error and root-mean squared error) were calculated separately for each. The prediction error results from this sensitivity analysis can be seen in Figures 6 and 7 for Farm 1 and 2, respectively.

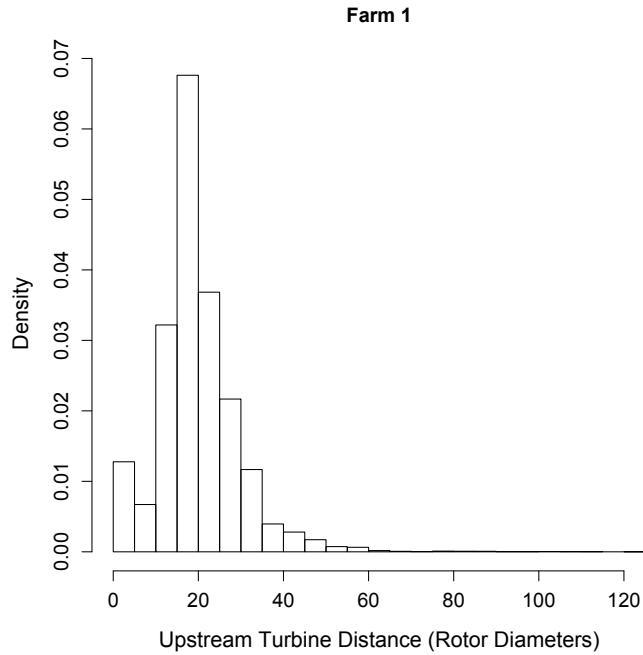
The mismatch between the Jensen model and the actual data was high for the initial 'best-guess' values for  $k$  and  $C_T$ , and it intuitively follows that a reduction in prediction error would drive the values away from these initial guesses. The



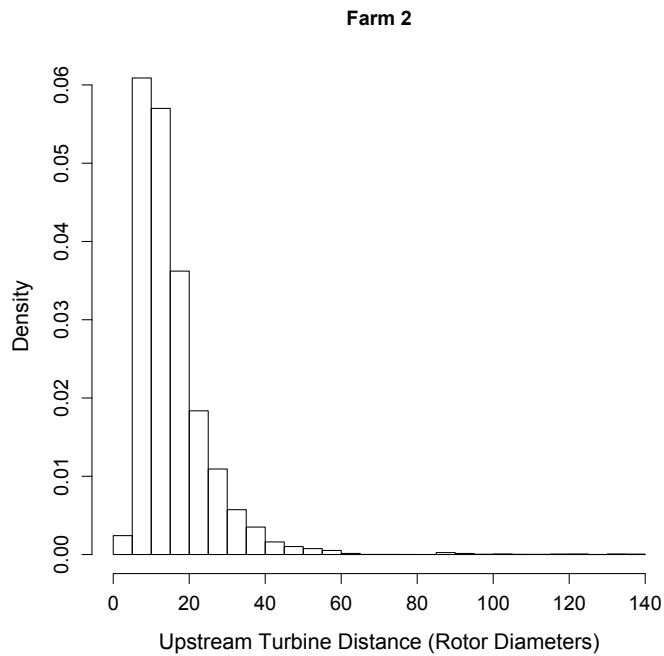
**Figure 2.** Relative power of turbine 2 compared to turbine 1 as a function of measured wind direction at met tower 2 in Farm 1. The turbines are aligned at an angle of 105°, and the expected drop in power should occur at this wind direction. In fact, we can see that the actual drop occurs at approximately 83°, so the direction measurement is too high by 22° for met tower 2.



**Figure 3.** Relative power of turbine 140 compared to turbine 139 as a function of measured wind direction at met tower 1 in Farm 2. The turbines are aligned at an angle of 353°, and the expected drop in power should occur at this wind direction. In fact, we can see that the actual drop occurs at approximately 73°, so the direction measurement is too high by 281°(or too low by 79°) for met tower 1.

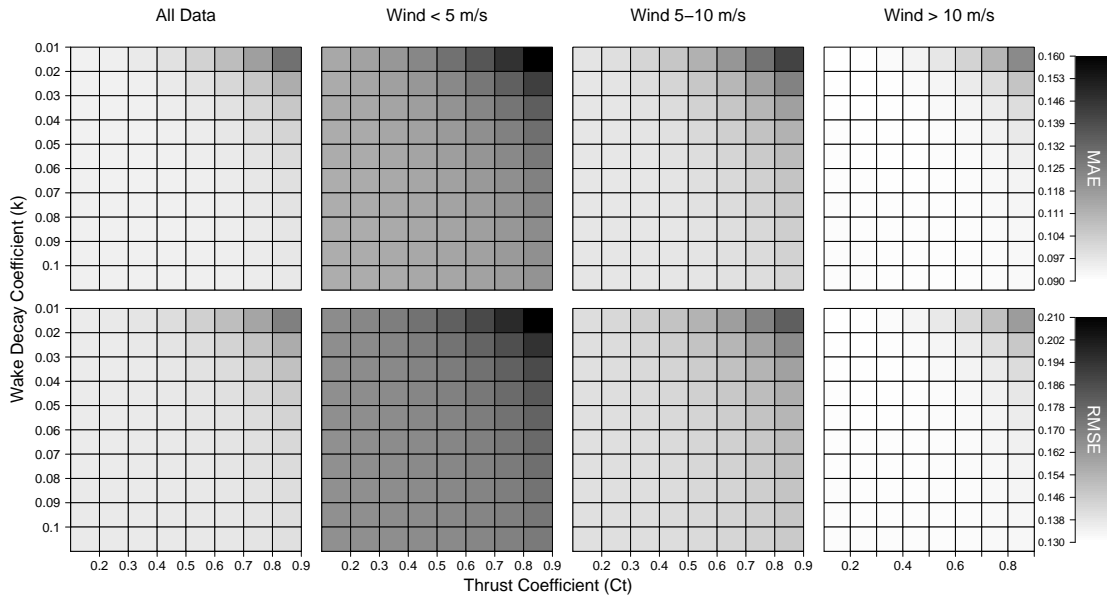


**Figure 4.** Minimum upstream turbine spacing for Farm 1

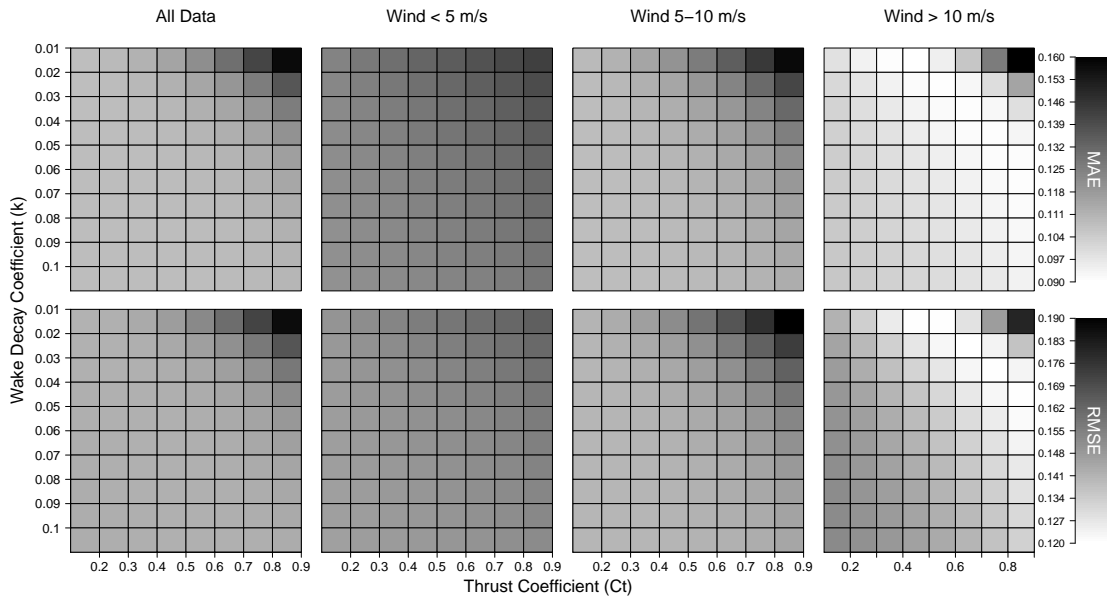


**Figure 5.** Minimum upstream turbine spacing for Farm 2

lowest errors occur on the extreme ends of the tested ranges, and these end values are at the very edge of what could reasonably be expected in a real wind farm. The Jensen model simply fails to capture the true wind dynamics present, even when accounting for the possibility of extreme turbulence or unrealistically low thrust coefficients. The one exception is the case of Farm 2 at high wind speeds. The lowest errors for this particular case occur across a band of low wake



**Figure 6.** Mean absolute error (MAE) and root-mean squared error (RMSE) for Farm 1 power production as a function of  $k$  (y-axis) and  $C_T$  (x-axis) calculated using velocity data from met tower 1



**Figure 7.** Mean absolute error (MAE) and root-mean squared error (RMSE) for Farm 2 power production as a function of  $k$  (y-axis) and  $C_T$  (x-axis) calculated using velocity data from met tower 1

decay coefficients and mid-high thrust coefficients. High wind speeds are generally associated with increased atmospheric stability and therefore decreased turbulence, and the model may be capturing this relationship. However, thrust coefficient values are typically lower at high wind speeds, so the trend towards higher  $C_T$  values is counterintuitive.

Overall, the errors are lower for higher wind speeds. This is an artifact of the shape of a turbine power curve, since the steepest part of the curve lies in the medium-range wind speeds of 5 – 10 m/s. Here, small errors in wind speed result in relatively large errors in power production. At higher wind speeds, where the power curve flattens out, the same small error in wind speed results in only a marginal error in power due to this flattened curve.

## REFERENCES

1. Manwell JF, McGowan JG, Rogers AL. *Wind energy explained: theory, design and application*. John Wiley & Sons, 2010.
2. Meyers J, Meneveau C. Optimal turbine spacing in fully developed wind farm boundary layers. *Wind Energy* 2012; **15**(2):305–317.
3. Hirth BD, Schroeder JL, Gunter WS, Guynes JG. Coupling Doppler radar-derived wind maps with operational turbine data to document wind farm complex flows. *Wind Energy* 2015; **18**(3):529–540.