UNDERSTANDING AND QUANTIFYING DIURNAL WAKE LOSSES AND THE IMPACT ON OVERALL WIND FARM PERFORMANCE

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Introduction

When designing the layout of a wind farm, one of the main objectives is to minimize lost production due to turbine wake losses. While effort is made to keep wake losses as small as possible, there will inevitably be impact on the wind farm energy production and the total effect of the wake losses needs to be quantified. Currently, there are wake loss models used in the industry to assess the overall impact of these losses on a wind farm. While it has been shown that these models can capture the total loss due to wakes, these models do not consider differences in the wake losses due to changes in atmospheric stability (i.e. stable vs. neutral to unstable atmospheric conditions).

Objectives of Study

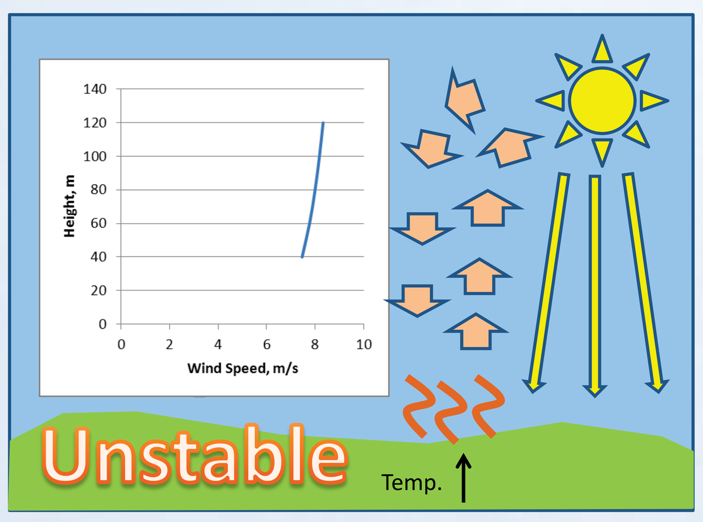
The main objectives of this study were to:

- **Use power production data from an operating wind farm to quantify the difference in wake losses that occur during stable and unstable conditions**
- **Determine the impact on AEP (Annual Energy Production) due to changes in diurnal wake losses**

Definition of Unstable and Stable Atmospheric Conditions

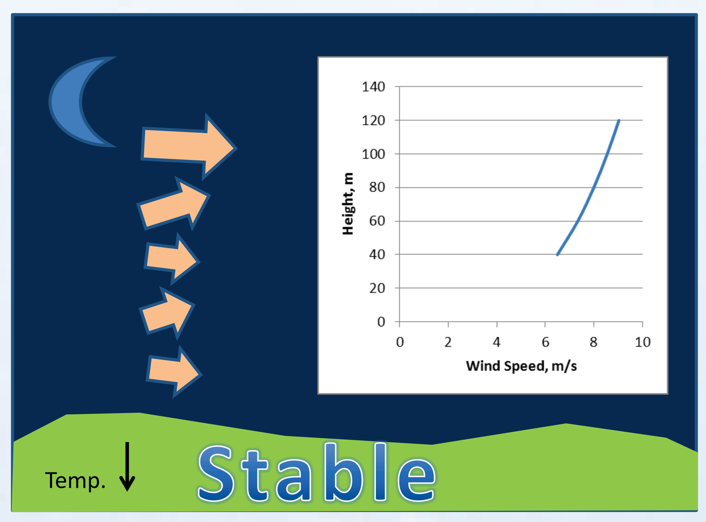
Unstable Atmospheric Condition:

When the sun heats the earth's surface, vertical mixing is induced and lower wind shear is typically observed.

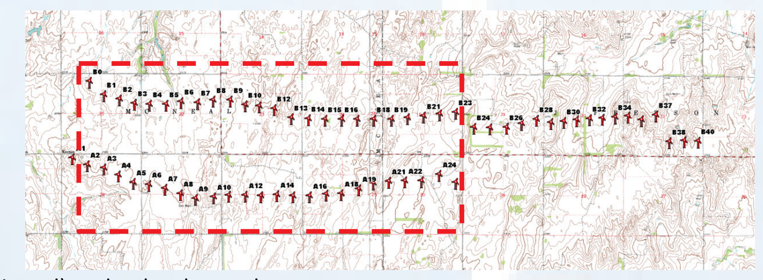


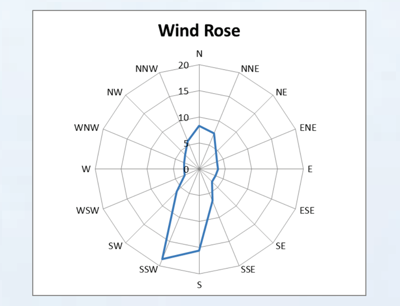
Stable Atmospheric Condition:

After the sun sets, the earth's surface is allowed to cool and the atmosphere reaches a buoyantly stable condition where there is little vertical movement and higher wind shear is observed.



Methodology of Study and Wind Farm Description





Wind Farm Description

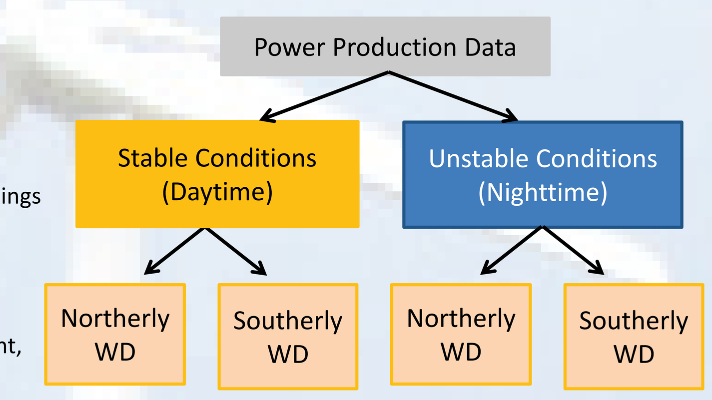
- 66 turbines in two rows (A – south and B – north)
- A string – 25 turbines
- B string – 41 turbines
- Approximately 16 months of production data

Data Filtering

- Removed times of icing and curtailment
- Included only the 48 turbines that experience wakes (circled in red) and only when at least 44/48 are operating
- Included only southerly (130 ° – 230°) and northerly (310° - 50°) wind direction sectors
- Limited shear alpha to 0 – 0.2 during the day (unstable conditions) and 0.2 – 1.0 at night (stable conditions)

Data Analysis Methodology

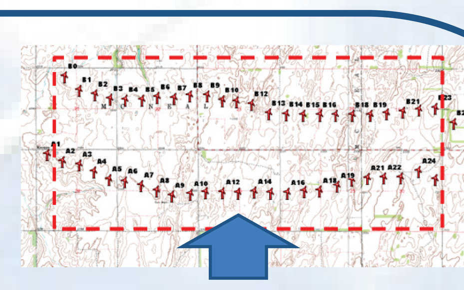
- Free-stream wind speed across the wind farm was estimated based on the turbine sonic anemometer readings and a sectorwise RAMWind terrain model
- Average power production from A and B strings were calculated on an hourly basis
- Data was separated into day (7 AM – 6 PM) and night (7 PM – 6 AM) and into southerly and northerly wind directions.
- Average power of the A and B strings were plotted against wind speed for each data group (i.e day and night, north and south)
- Average power was binned in 1 m/s intervals and the mean average power was calculated and compared.



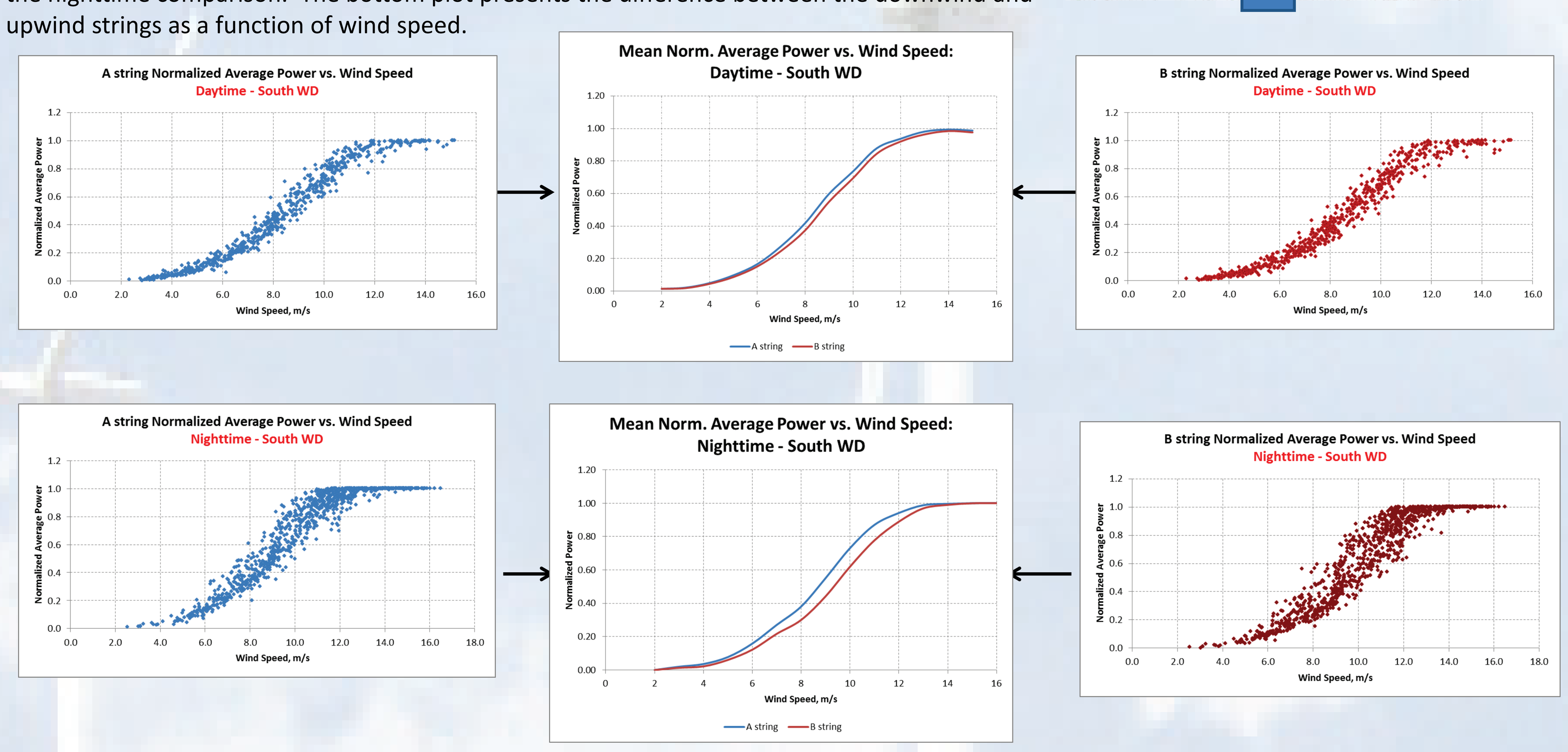
Results of Day and Night Average Power vs. Wind Speed comparison

During Southerly Winds

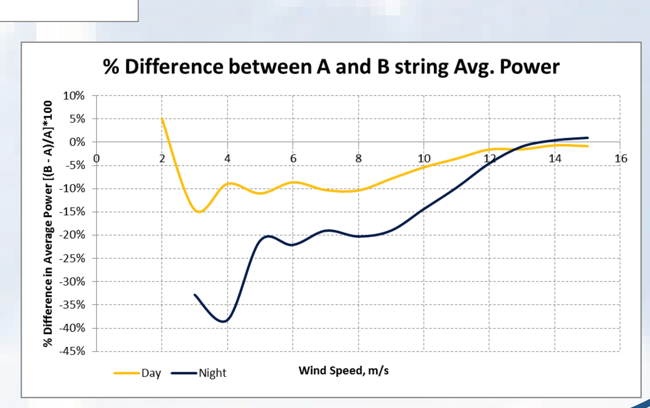
(B string is waked)



In this section, the average normalized power production as a function of wind speed for the A and B strings are compared during stable and unstable conditions during southerly winds. The top set of plots shows the comparison during daytime hours and the second set of plots shows the nighttime comparison. The bottom plot presents the difference between the downwind and upwind strings as a function of wind speed.



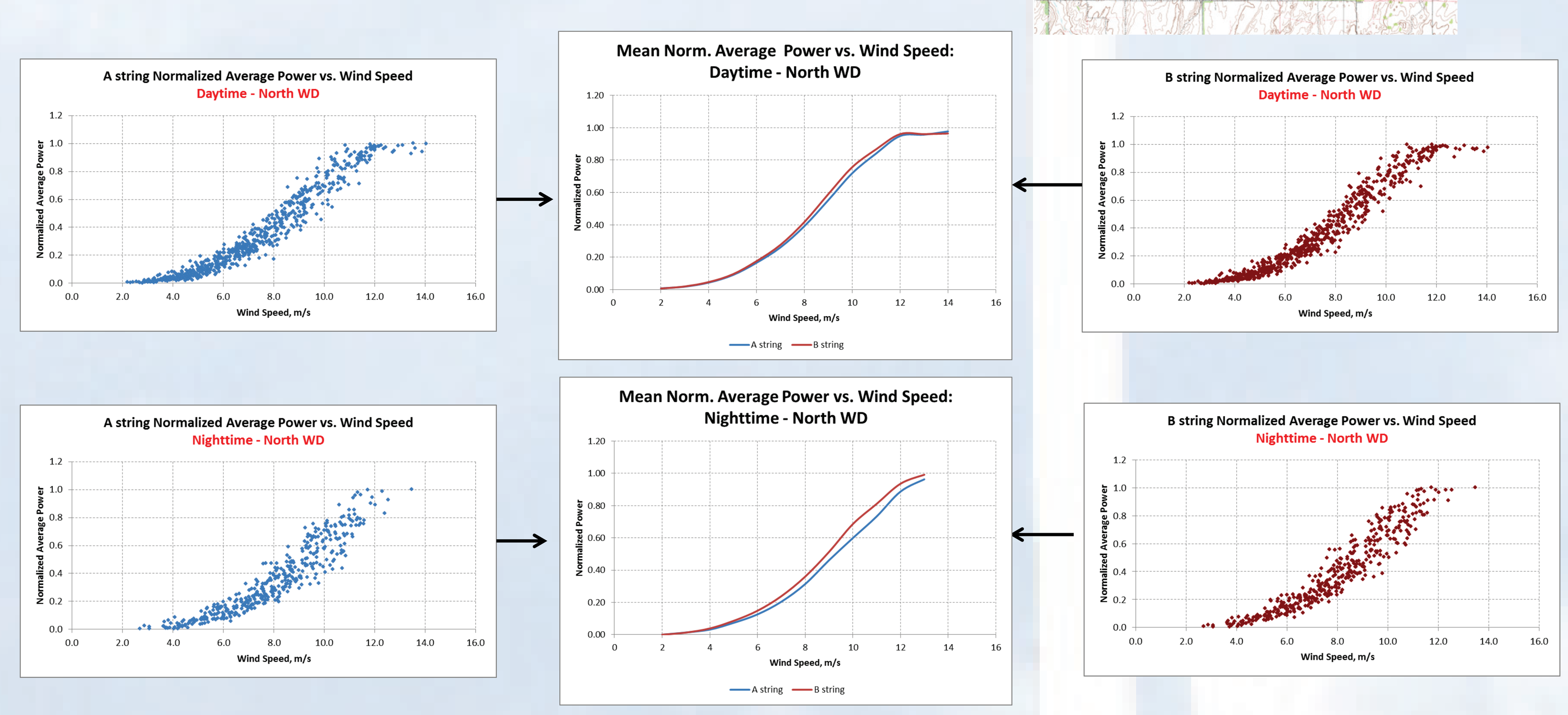
- During southerly winds, the B string is in the wake of the A string therefore the average power of the A string is expected to be higher than the B string.
- The difference between the average power of the A and B string is significantly larger at night (i.e. during stable conditions).
- **During southerly winds, the average ratio between night and day wake losses = 2.05.** In other words, the wake losses at night are approximately double the wake losses during the day.



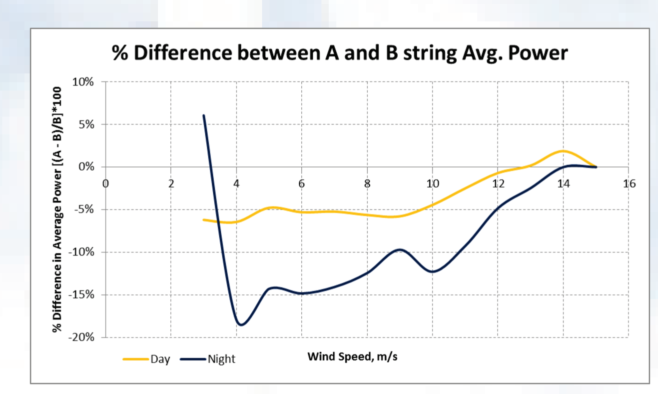
During Northerly Winds

(A string is waked)

The plots below show the comparison of the average power produced by A and B string turbines during northerly winds where the A string is in the wake of the B string.



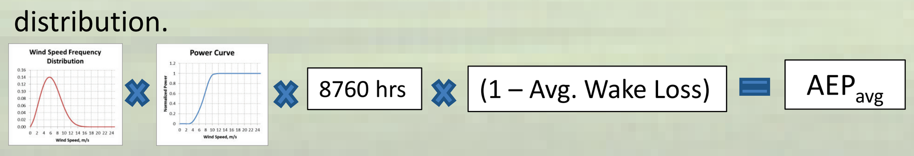
- Conversely, during northerly winds, the A string is in the wake of the B string therefore the average power of the B string is expected to be higher than the A string.
- Similarly, the difference between the average power of the two strings is significantly larger during stable conditions.
- **During northerly winds, the average ratio between night and day wake losses = 2.49.**



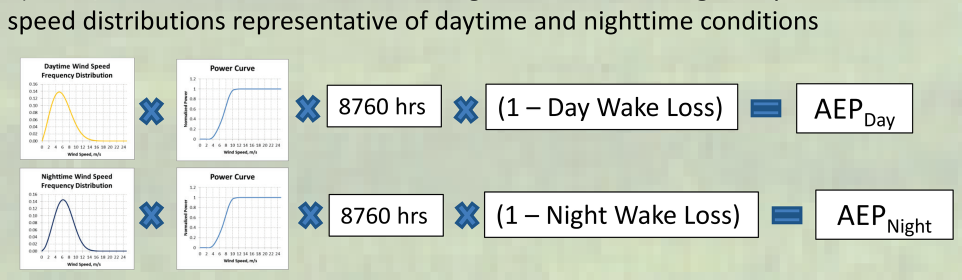
Error in AEP Estimation due to Diurnal Wake Losses

Results from this study show that the average ratio between the wake losses experienced during stable and unstable conditions range from 2 – 2.5. To determine the impact of diurnal wake losses on the annual energy production, wind speed distributions from 6 different sites across the U.S. were analyzed and AEP was estimated two different ways and then compared.

1) AEP was calculated assuming an average wake loss and using one, overall wind speed distribution.

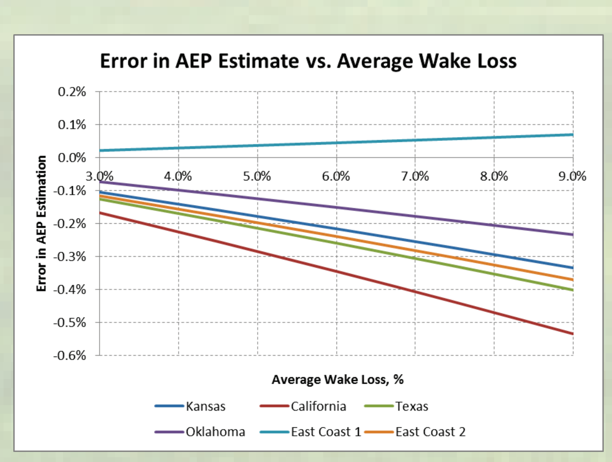


2) Then, the AEP was estimated assuming that the ratio of night/day wake loss = 2.0 and using wind speed distributions representative of daytime and nighttime conditions



3) The percent error in AEP was then calculated for a range of average wake losses (3.0% to 9.0%). The results of the analysis are shown in the table and plot below.

$$\% \, Error \, in \, AEP = \left[\frac{AEP_{Avg} - (AEP_{Day} + AEP_{Night})}{(AEP_{Day} + AEP_{Night})}\right] \times 100$$



- The error in the AEP estimation increased with average wake loss.
- With an average wake loss of 3%, the error in AEP ranged from -0.17% to 0.02%.
- With an average wake loss of 9%, the error range increased to -0.53% to 0.07%.
- The error in AEP was largest at sites with significantly different diurnal wind speed distributions such as the site in California

Avg Wake Loss	KS	CA	TX	OK	MD1	MD2
3.0%	-0.10%	-0.17%	-0.13%	-0.07%	0.02%	-0.12%
4.5%	-0.16%	-0.25%	-0.19%	-0.11%	0.03%	-0.18%
6.0%	-0.22%	-0.34%	-0.26%	-0.15%	0.05%	-0.24%
7.5%	-0.27%	-0.44%	-0.33%	-0.19%	0.06%	-0.30%
9.0%	-0.33%	-0.53%	-0.40%	-0.23%	0.07%	-0.37%

Summary and Next Steps

- Power production data from an operating wind farm was analyzed to examine the difference in wake losses that occur during stable versus unstable atmospheric conditions.
- The average power produced by the northern string was compared to the average power produced by the southern string during northerly and southerly wind directions and during daytime and nighttime conditions.
- The average ratio between night and day wake losses ranged from 2.05 to 2.49.
- The impact on AEP estimation was analyzed at 6 different sites across the U.S.
- The error in the AEP estimation increased with higher average wake losses.
- At sites with an average wake loss of 9%, the error in the AEP estimation ranged from -0.53% to +0.07%
- The next step is to determine the most appropriate way to incorporate diurnal wake losses due to changes in atmospheric stability into our wake loss models.

RAM Associates

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