# Tall Tower Measurements of Wake Loss Characteristics Within a Low-Density Wind Farm

**Daniel A. Rajewski*, Eugene S. Takle*, and Samantha L. Purdy***
*Dept. of Agronomy, Iowa State University, Ames, Iowa, USA, drajewsk@iastate.edu

**Abstract**

Tall tower measurements provide detailed characteristics of mean and turbulent properties of wakes. The Iowa Atmospheric Observatory features two identical 120-m tall meteorological towers, one outside and one inside a low-density wind farm to examine wakes from single and multiple turbines. Normalized power differences (inside vs. outside the wind farm) calculated from tower measurements reveal influences of stratification, wind speed, wind shear, and downwind distance in the wind farm. Conditions of strong stability/instability reduce wake losses irrespective of distance. For near-neutral conditions, small power reductions deep in the wind farm indicate the development of a wind-farm boundary layer.

**Keywords:** *In situ measurements, Turbine-turbine interactions, Stratification, Wind-farm boundary layer*

## Introduction:

Few tall-tower networks are available for providing concurrent *in situ* measurements, within and outside of wind farms, for developing new understanding of wind farm underperformance [1]. Validation of simulations with robust observational datasets are especially needed as wind farm expansion continues throughout much of the Central U.S [2]. Wake losses are not well understood and become increasingly important for assessing multiple turbine-turbine interactions and mesoscale effects of wind farms [3,4] during periods of strongly stable stratification [5,6]. In the 2013 Crop/Wind Energy Experiment (CWEX-13) surface flux stations and profiling lidars were deployed during the June-September growing season to evaluate wake interaction near and above the surface from wind turbines in a low-density (spacing > 15D) wind farm. Wake losses were substantially higher (40-60%) during stable stratification when there were combinations of wakes from multiple (3 or more) lines of turbines as compared to daytime hours when wakes dissipated within 10D downwind of the source turbine. We describe a network of two identically configured 120-m tall towers that reveals contrasts in wakes during multiple stratification categories for different distances downwind from the leading line of turbines in the wind farm during June-Sep. 2016.

## Methods

Concurrent measurements of wind speed, wind direction, temperature, and relative humidity at six tower levels (5 m, 10 m, 20 m, 40 m, 80 m, and 120 m) and air pressure at two tower levels (10 m and 80 m) were recorded with 1-Hz sampling resolution at both towers. Wind power was compared from one tower located within a low-density wind farm to the other tower located several km outside of the wind farm to assess wake losses within a segment of a 300 MW wind farm. The wind turbines had 80-m hub height and 82-m rotor diameters. Power coefficients were interpolated from the turbine manufacturer power curve. Differences in normalized power were calculated between the 80-m available power at the reference tower outside the wind farm (A2) to the tower influenced by turbines (A1) as in eq. (1):

$$\Delta P = (P_{A1} - P_{A2}/P_{A2}) * 100\%. \quad (1)$$

Normalized power differences were calculated from 5-min averages of the 1-Hz variables. Periods of rain and little or no power production and met tower flow distortion [7] were eliminated. The normalized power differences were categorized according to downwind distance from wakes originating from single, double, triple, or multiple (>4) turbines and from 3-4 turbines along a line. These wake sectors were determined using the 5-degree wake expansion factor previously applied to measurements from this low-density wind farm and from offshore wind farms [8]. Periods of no turbine influence (No-wake) were also determined for comparison with conditions of turbine-turbine interactions. Wake categories were further examined according to stratification using the 5-m to 40-m tower data as described in [9]. Composite categories were additionally removed for a low sample of observations (n<20). Sensitivities of wakes to

80-m wind speed, and 40-m to 120-m rotor-layer wind shear and wind veer were also determined in stable stratification conditions.

**Preliminary results**

Power reductions of 20-40% due to wakes from single turbines and 20-50% from two consecutive turbines were observed for weakly to moderately stable stratification (Fig. 1). However, the drop in power levelled off or returned to near zero when wake interactions occurred among many turbines for x>60D. In stronger thermal stability/instability, available power at A1 was weakly dependent on downwind distance and was above or similar to power at A2 both during the influence of wakes and in No-wake conditions. Our analyses confirmed the evidence of a wind-farm boundary layer with a homogenizing of turbulence scales and overall reduced wind speed as flow from above the wind farm replenishes momentum loss from wind turbine wakes [10]. Future studies will explore differences in turbulence characteristics and their influence on the wind farm microclimate.

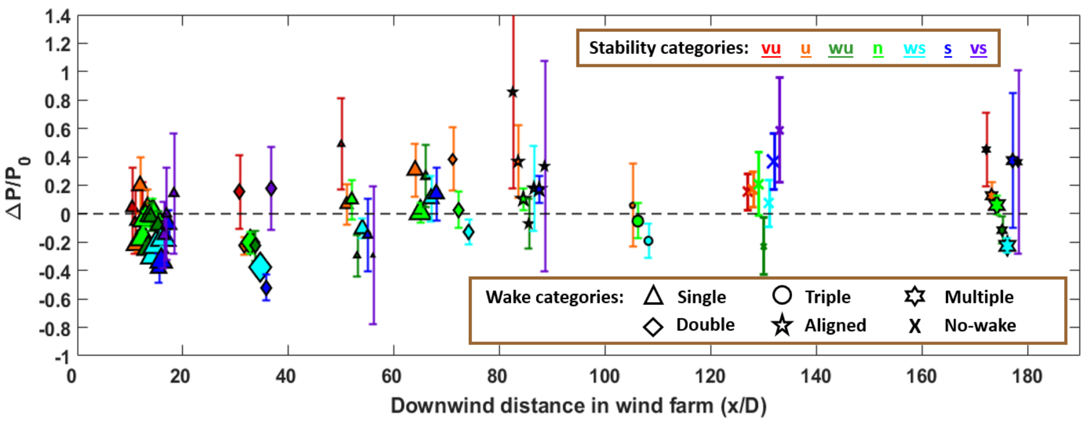


Fig. 1. Normalized power difference between the A1 tower (within the wind farm) and the A2 tower (outside of the wind farm) for conditions of No-wake and several types of turbine-turbine interactions over 7 categories of stratification. The size of the symbols represents the sample size for each composite.

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