A Comparison of Methods for Assessing Power Output in Non-Uniform Onshore Wind Farms

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About Sandia

- Sandia National Laboratories – Albuquerque, NM
- ~10,000 employees at the New Mexico site
- My group:
  - Discrete Math and Optimization, within an organization for Enhanced Decision Making
  - Combines computer science, operations research, data analysis, cognitive psychology, and human factors
  - Research-focused, with a wide range of applications
    - Infrastructure risk and resilience
    - Renewable energy planning and integration
    - High performance computing
    - Cyber security
    - Data visualization
    - Lots more...
Wind Power Prediction

- Used in several ways:
  - Short-term operations decisions
  - Long-term planning

- Cost of bad estimates:
  - Short-term: Pay penalties if production is lower than bid, May need to curtail if production is higher (lost revenue)
  - Long-term: Farm won’t meet financing contracts; potential for huge losses

- Critical for wind’s success – fighting an uphill battle against dispatchable fossil-fuel generation
Long-Term Power Estimation

- How much will a new wind farm produce?
  - Resource assessment, farm planning: Wake-decay models
    - Model the fluid interactions among turbines to estimate what a farm would produce
    - Couple with measurements of wind conditions
    - Result is estimate of a farm’s expected generation
  - Understanding turbine interaction is critical to accurate farm-level power production estimates
- Farm power is a function of:
  - Number of turbines: **KNOWN**
  - Wind conditions: **MEASURED AND/OR PREDICTED**
  - Terrain effects: **KNOWN AND/OR MODELED**
  - Wake effects: **HARD TO MEASURE, OFTEN MODELED**
Turbine Wake Effects

Incoming Wind: $v_0$

Turbine 1

Turbine 2

$v_0$

$v_1$

Wake Area

constructed through a zoomed portion of the DD domain oriented roughly parallel to the mean wind direction and passing through two turbines (Figure 5). Turbine-to-turbine interaction is captured by this cross section as the wake of turbine 59 impacts the inflow of turbine 48 (Figure 5(b)). The wake of turbine 48 shows slower wind speeds within its wake than that of turbine 59. Turbines 47 and 49, located adjacent to turbine 48 in the same row, produce considerably less hub height wind speed reduction within their wakes than turbine 48. Their upstream flow is

Figure 4. Terrain-following DD horizontal wind speed (m s$^{-1}$) synthesis at hub height (80 m) from (a) 1559 UTC, (b) 1616 UTC, (c) 1636 UTC, (d) 1654 UTC, (E) 1705 UTC, and (F) 1715 UTC on 6 June 2012. Black dots represent turbine locations. Wind vectors are overlaid. The colorbar range is adjusted in each panel to emphasize wake structure. North is aligned with increasing Y-distance.

Figure 5. (a) Zoomed DD horizontal wind speed (m s$^{-1}$) at hub height (80 m) from a single volume at 1559 UTC (volume 24) on 6 June 2012. (b) Vertical cross section of horizontal wind speed (m s$^{-1}$) along the plane represented by the dashed black line in (a). The black vertical rectangles represent the turbine locations along the cross section to the top of the rotor sweep. (c) Vertical profiles of horizontal wind speed for various locations within the wind field as denoted by the squares in (a). Gray horizontal lines represent the depth of the rotor sweep.

Coupling Doppler radar-derived wind maps with turbine data


Literature on Wake Models

- They’re great; even the most basic models do well
  - Jensen Model is a standard baseline
- Strong agreement between model and observations in validation tests

- BUT – validation tests primarily done using offshore (or very near-shore) farms with uniform layouts
- Do the results still hold in other cases?
CHAPTER 4. ASSESSING POWER OUTPUT IN NON-UNIFORM ONSHORE WIND FARMS

The Jensen model can be used to calculate the velocity deficits in the turbine wakes, and this calculation is based on steady-state wind. For one constant wind direction, the deficits are calculated as a snapshot in time. Thus, the Jensen model is best suited for large scale resource assessment and is not the best option for evaluating real-time or rapidly changing wind power production. For the cases presented here, the data exists as 10-minute averages and, for some of the analysis, has been filtered to represent only conditions that are as close to steady-state as possible by using only the datapoints where both met towers in the farm agree in the measured wind direction. The Jensen model should work well under these limitations and can be used for farm power production estimates.

The Jensen model determines the effect that a turbine wake will have on a downstream turbine. The wake velocity deficit at a downstream turbine relative to the velocity seen by an upstream turbine is determined by

\[
\delta V = \frac{1 - \sqrt{1 - C_T}}{(1 + 2kx)^2} \left( \frac{A_o}{A} \right)
\]

where \(C_T\) is the turbine thrust coefficient, \(k\) is the wake decay coefficient, and \(x\) is the downstream distance at which the deficit is measured. For a turbine that sees only a partial wake from an upstream turbine, a correction is applied based on the fractional area of overlap, \(A_o\) and the swept rotor area \(A\). For a large wind farm with multiple turbines, the deficit seen by any one turbine is a combination of all of the upstream wakes that interact with that turbine. This results in the following formulation that gives the overall velocity deficit as a result of the superposition of multiple upstream wakes as given by Katic et al.

\[
\frac{u}{u_0} = 1 - \sqrt{\sum_{j \in J} (\delta V_j)^2}
\]

\(J\) is the set of upstream turbines with wakes impacting a given downstream turbine. The choice of the parameter \(k\) determines the rate at which the wake decays behind a turbine, and it is dependent on the ambient turbulence, turbine-induced turbulence, and atmospheric stability. The choice of \(k\) should depend on the atmospheric stability, and this has been shown to have a strong influence on wake behavior. Namely, stable conditions result in a slower wake recovery and therefore larger velocity deficits at downstream turbines. There is some consensus on a value of 0.075 for onshore applications and lower values (i.e., 0.04 or 0.05) for offshore applications to reflect the lower turbulence generally found offshore or near-shore.

The thrust coefficient, \(C_T\), comes in the form of a turbine-specific curve that is a function of incoming wind velocity. A typical curve has the highest \(C_T\) value at low wind speeds (i.e., \(C_T = 0.9\) for winds 5 m/s) and then drops as wind speed increases (i.e., to a value of 0.2 above 20 m/s.). With set values of \(k\) and \(C_T\), the velocity deficits can be evaluated at each turbine in a farm for a given wind direction and compared to the actual data averaged over that same wind direction. The difference between the actual data and the Jensen deficit calculations for a wind direction of 180° are shown in Figures 4.6 and 4.7 for
Is Jensen Model Applicable?

- Wakes can propagate for distances of 8-10 rotor diameters, further if turbulence is low
- Empirical evidence from Farm 1 has shown wakes propagating more than 15 rotor diameters
- Expected wake impacts for both farms at 15 rotor diameters, with substantial effects for anything less than 10 diameters
Non-uniform, Onshore Farms

Farm 1
Flat Terrain
100 1.5MW Turbines

Farm 2
Very Flat Terrain
140 1.5MW Turbines
Available Data

- Over 2 years of data
- Met Mast Data
  - 10-minute averages
  - Speed, direction, temperature
- Individual Turbine Data
  - 10-minute averages
  - Power, wind (behind blades), availability, curtailment
Working with Real Data

- Challenges of real data:
  - Cannot trust blindly
  - Need to verify quality and accuracy of data

- Simple and Obvious
  - Remove extreme data points (e.g., temperature values outside of historical range for region)
  - Remove points when readings from two met towers deviate significantly (e.g., air pressure 6km away not expected to vary much)

- More Subjective
  - Verify accuracy of wind speed, wind direction, and wind power
  - How to tell if measurements are accurate?
  - Filter by availability and curtailment, want maximum availability and minimum curtailment to best match model results
Wind Speed and Power

- Wind turbines follow a power curve, specific to each make and model.
- At the turbine level, power production should follow this curve nearly exactly (subject to minor degradation due to age or build-up of dirt, bugs, ice, etc.).
- Use nacelle wind speed and turbine power as a quality check for each other.
Wind Direction – Farm 1

- Check wind direction against expected farm performance metrics
- Farm 1: Offset of +30° for Tower 1 and +22° for Tower 2
Wind Direction – Farm 2

- Farm 2: Offset of -79° for Tower 1 and -58° for Tower 2
Did We Get It Right?

- Known behavior from adjacent turbines due to wake effects
  - This now appears in the corrected data

![Diagram showing power relative to leading turbine for different turbine numbers. The diagram includes box plots for measured data and wake model, with turbine numbers 1, 2, 3, and 4 labeled.]
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Agreement with Jensen

Farm 1: Actual data minus Jensen estimates
- Velocity Deficit
  - 0.095
  - 0.0475
  - 0
  - -0.0475
  - -0.095

Wind Direction

Farm 2: Actual data minus Jensen estimates
- Velocity Deficit
  - 0.18
  - 0.09
  - 0
  - -0.09
  - -0.18

Wind Direction
Choice of k and C_t Coefficients

- All Data
- Wind < 5 m/s
- Wind 5–10 m/s
- Wind > 10 m/s

Wake Decay Coefficient (k)

Thrust Coefficient (C_t)
Alternative Methods

- **Statistical Models**
  - Best performing models: Random Forest and Multivariate Adaptive Regression Splines (MARS)
    - Turbine-based
      - Training using either met data only or met data and farm layout data
    - Farm-based

- **Aggregated Turbines**

- **NREL dataset for resource assessment**

\[
C_{\text{wake}} = 1 - \frac{1}{20} \left( \frac{n_{\text{turbines}} - 1}{7} \right)
\]
Tested parametric and non-parametric models – Focused on two non-parametric models for further evaluation and model tuning based on low errors

- Random Forest uses a large number of uncorrelated trees, each built using a randomly-selected subset of predictor variables
- Multivariate Adaptive Regression Splines (MARS) allow for a combination of linear basis functions to best fit the data locally

Models were trained using 70% of the available data, tested on the remaining 30%

Holdout analysis with 20 replications was done to assess model stability
Predictive Accuracy

Farm 1 Errors

Farm 2 Errors

Statistical Models  Jensen Model  Aggregated Turb.  NREL

Statistical Models  Jensen Model  Aggregated Turb.  NREL
Summary

- Jensen model fails to capture turbine interactions in complex farms
  - Too many uncertainties to model accurately
  - Too little is known about stability of wind conditions throughout the farm
  - Measurements at two towers do not provide enough information
- Statistical models do well, even with no farm-specific data
  - Models can be accurately applied to new farms
- Questions the value of having a perfect forecast
  - Are we focusing too much on improved wind speed forecasts?
Questions?

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Research Submitted to *Wind Energy*: