Wind Farm Blockage: Searching for Suitable Validation Data

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Wind turbine interaction and energy production

- Fluid dynamic interaction between wind farm turbines changes the power production at each turbine relative to what it would produce in isolation.

- The effect can be large and must be accounted for in energy production assessments (EPAs).

- The energy production change due to turbine interaction is usually called a “wake loss” because...
The wakes-only approach to turbine interaction

EPAs almost always assumes that turbine interactions are limited to wakes and their impact on turbines downstream—any influence of the turbines on conditions upstream or laterally is ignored.
The wakes-only approach to turbine interaction (continued)

The wakes-only approach assumes that the highlighted turbine produces the same amount of energy in each of the three situations below.

We are not aware of any direct evidence substantiating this assumption.
Method
Data analysis approach

Objective: Find out whether and to what degree the wind farm affects the wind speed measured at Mast P.

Method (high-level):
- Choose a direction sector where the masts are not waked.
- For this sector, determine the wind speed relationship between Mast P and Mast R—before and after the commercial operation date (COD).

Key Metric: The percent change in the wind speed ratio between Mast P and Mast R, $\Delta U_{P,R}$. 
DNV GL CFD approach – Solver, domain, and boundary conditions

- STAR-CCM+, steady RANS, $k$-$\varepsilon$, buoyancy included
- All boundaries, except the ground, are at least 15 km from the wind farm
- At least five inlet directions simulated at each site, clustered around sector of interest
- Neutral BL and stable BL, **with and without turbines**

**Neutral BL**

**Stable BL**

Atmospheric stability within and above BL simulated
DNV GL CFD approach – Representing the wind turbines

- Wind turbines represented with a simple actuator disk
- Body forces applied based on curves of $C_t$, power, and rotor speed
- Simulated wind speeds are close to peak $C_t$, where any blockage effect would be maximized
Results
Onshore Wind Farm A – Description

- 87 Turbines in east-west rows
- 3.2 D between turbines
- 20 D between rows
- Simple terrain*

Data filtered to between 345 and 15 degrees, 5-9 m/s, at target mast

More than a year of data at each mast before and after COD

*Max – min elevation is 20 m
Onshore Wind Farm A – Results

DNV GL CFD predicts local blockage to be responsible for a 1.2% slowdown at Mast P2.

Δ\( U_{P2,R1-4} \) = -4

Δ\( U_{P1,R1-4} \) = -2

Change in wind speed after COD at perimeter mast relative to reference masts

Colors = % change in hub-height wind speed relative to freestream

Measured results were sensitive to choice of reference mast.

DNV GL CFD predicts local blockage to be responsible for a 1.2% slowdown at Mast P2.
Onshore Wind Farm C
**Onshore Wind Farm C – Description**

- 100 Turbines in east-west rows
- 3 D between turbines
- 13 D between rows
- Simple terrain*

* Max – min elevation is 21 m

Data filtered to between 345 and 15 degrees, 5-9 m/s, at target mast

Less than a year of data at each mast before and after COD—5 months post-COD

**Distance to nearest turbine**

- R8: 15 rotor diameters
- P5: 5 rotor diameters
- P6: 2 rotor diameters
Onshore Wind Farm C – Results

Wind farm blockage slows flow approaching from the north.

**Colors** = % change in hub-height wind speed relative to freestream

Change in wind speed after COD at target mast relative to reference mast

- $\Delta U_{P5,R8}$
- $\Delta U_{P6,R8}$

DNV GL CFD predicts the wind speed at Mast R8 to be 1.3% less than freestream.

CFD predicts *local* blockage to be responsible for a 1.2-1.5% slowdown at Masts P5 and P6.
Summary of results from the four wind farms (two not shown)

• Wind-farm-scale blockage is consistently evident in the CFD simulations

• Measurements point to a slowdown occurring upstream of each wind farm, implying the presence of wind-farm-scale blockage

• Uncertainty in the $\Delta U_{P,R}$ values derived from measured data is probably not a lot smaller than the magnitude of those values; however, the sign of the wind speed change is very consistent—i.e. negative for 18 of 19 mast pairs

• The measured slowdowns are relative to reference masts, but it is not difficult to logically progress to the conclusion that the wind speeds also decrease relative to freestream
The implications of wind-farm-scale blockage
The wakes-only approach is likely invalid in many cases, resulting in a bias in energy production predictions for the front row of turbines.

The highlighted turbine is not operating in freestream, undisturbed conditions, as is typically assumed.

The blockage effect is not limited to just a redistribution of energy production along the first row.

*The sum of the production of the upstream row turbines is very likely to be materially lower than the sum of each of these turbines operating in isolation (i.e. in truly freestream conditions)*.
Prediction bias related to blockage is not limited to the first row

Current practice in the wind industry:

- Wind farm flow models are used to predict wakes
- The models are tuned to predict the row-by-row variation in energy production
- Validations are conducted with energy production normalized by production in the upstream row

If blockage causes an upstream row to underproduce isolated operation by 2%, approaches that ignore blockage will on average overpredict energy production for the entire wind farm by the same 2%.
Turbine interaction losses corresponding to the simulated conditions at the three wind farms (turbines operating at peak $C_t$)

$\sum P_{WO}$ is the sum of the turbine powers converted to represent wakes-only predictions

$\sum P_i$ is ideal power generation for the wind farm (i.e. the sum of each turbine producing as if operating in isolation)

$\eta_A = 1 - L_{TI}$

Figure 8: Turbine interaction loss and wakes-only prediction bias at three onshore wind farms (A, B, and C) as derived from RANS simulations of the $30^\circ$ sector centered on $0^\circ$. $L_{TI,WO}$ is the turbine interaction loss as would be predicted using the wakes-only approach. $L_{TI,N}$ is the neglected portion of the total turbine interaction loss, and $Bias$ is the resulting energy prediction bias.
Blockage and energy impact, a summary

• Observations and CFD results at four projects suggest that wind-farm-scale blockage slows approaching flow to a degree that cannot reasonably be neglected

• Blockage effects likely represent a material bias in energy assessment procedures used throughout the industry

• There remain gaps in the available empirical record and the uncertainty in this data analysis should not be ignored
  
  • Two independent analyses of the data have increased confidence in the findings
  
  • We continue to look for additional field measurements

• In the meantime, the balance between evidence supporting and contravening the wakes-only approach is now so one-sided that its continued use is difficult to justify

**Opportunity:** Accounting for two-way coupling between the atmosphere and the wind farm has the potential to benefit wind farm design, power performance testing, and even wind farm control—further driving down cost of energy
Validating blockage predictions
Measuring blockage effects

- Wind farm flow modelling and measurement campaigns focus on wakes
- All wake prediction tools used in the industry are ultimately validated against full-scale field observations
- More completed prediction tools (i.e. those that also account for blockage) will also require validation

- Measurements related to blockage are needed
Measuring blockage effects

How does the production of the highlighted turbine differ when operating in a wind farm as compared to operating in isolation?

Not possible to run the experiment

Workaround: Measure other blockage effects such as upstream wind speed reduction and production pattern of unwaked turbines

If a wind farm flow model predicts these “observable” effects accurately, it increases confidence in the predictions of the unobservable effects (i.e. wind farm vs. isolated production).
Measuring blockage effects

• Challenge
  • Not aware of any field measurement campaigns focused on blockage effects
  • The wind speed changes due to blockage are generally smaller and vary more gradually as compared with wakes, making the blockage impact harder to observe

• Potential sources of useful data
  • Wind tunnel
  • Turbine SCADA data
  • Meteorological masts
  • Scanning lidar (preferably, dual)

• Ideally used in combination
Wind tunnel measurements


Wind tunnel measurements are useful, but not sufficient

- Lateral and top walls can influence the blockage
- Stratification in the atmosphere is likely an important contributor to blockage
- Will findings scale?
- Regardless, could be good for validation
The observed production patterns for unwaked turbines at Horns Rev are consistent with the possible presence of wind-farm-scale blockage.

Insight into the cause is limited and the effect on overall wind farm energy production is unknown. The authors believed the cause to relate to Coriolis and that the wall effects would be “AEP neutral”.

Meteorological masts

- At a given site, we need at least one mast near the perimeter and another mast far from the wind farm, with concurrent measurements before and after COD.
- This situation is rare.
- Conclusions are limited to the wind speed at a single location (Mast P) relative to another location (Mast R).
- The experiment cannot fully isolate the impact of the wind farm.
- Can be a useful complement to turbine SCADA data and scanning lidar.
Scanning lidar or radar (dual scanners would be nice)

- Data taken before and after COD needed to better isolate the spatial variation of mean wind speed caused by the wind farm
- Very useful when combined with multiple upstream masts and turbine SCADA data

Takeaway

• Blockage needs to be accounted for in wind energy assessments

• To do so reliably will require measured data for model validation

• Availability of such data is currently lacking

• We need measurement campaigns that specifically target blockage effects
Thank you for listening

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SAFER, SMARTER, GREENER
Onshore Wind Farm B
Onshore Wind Farm B – Description

>80 Turbines in east-west rows
3.0 D between turbines
10 D between rows
Moderately complex terrain*

Data filtered to between 345 and 15 degrees and 5-9 m/s, at target mast

More than a year of data at each mast before and after COD

*Max – min elevation is 90 m
Onshore Wind Farm B – Results

Wind farm blockage slows flow approaching from the north

Colors = % change in hub-height wind speed relative to freestream

Change in wind speed after COD at perimeter relative to reference masts

Significant blockage apparent well upstream of the wind farm

Measured results were sensitive to choice of reference mast

\[ \Delta U_{P3,R5-7}, \Delta U_{P4,R5-7} \]
Bias in power curves

• For a given freestream wind resource, accurate prediction of a turbine’s energy production requires (1) a power curve that faithfully represents the turbine’s production when operating in isolation and (2) an accurate estimate of how that production changes when the other wind farm turbines are present. This paper focuses on the second requirement; however, blockage may also represent a bias in the first.

• The industry assumes that the power curves used in EPAs are a function of freestream wind speed, but to the extent that these curves are influenced by and are consistent with PPT (measured) curves, this assumption is very likely false.

• The measured curves should be corrected to account for the impact of local blockage from the tested turbine on the PPT mast, as well as for any influence of the wind farm on the wind speed relationship between the PPT mast and the rotor face. The objective is a curve that can accurately predict the production of an isolated turbine operating in a known set of freestream conditions.