Estimating Long-Range External Wake Losses in Energy Yield and Operational Performance Assessments Using the WRF Wind Farm Parameterization

Mark Stoelinga, Ph.D.
Miguel Sanchez-Gomez, MS[1]
Gregory S. Poulos, Ph.D.
Jerry Crescenti, M.S.

ArcVera Renewables
1301 Arapahoe Street, Suite 105
Golden, Colorado 80401 USA

[1] Miguel Sanchez-Gomez is a graduate student at the University of Colorado who worked for ArcVera Renewables.

DOCUMENT HISTORY

Preparer(s): Mark Stoelinga, Lead, Atmospheric Science Innovation and Applications

Reviewer(s): Jerry Crescenti, Director, Wind Energy Analysis Team, Technical Editor, Emily Coulter

Final Review and Approval by: Greg Poulos, CEO, Principal Atmospheric Scientist

Version	Date	Comments
1.0	08/09/2022	Initial issue

Disclaimer

Report:
Document 1.0

Report Standard:
Research Result

Classification:
Confidential

Status:
Final

Key to Report Standard

Research Result: Description of the subject of the report, including methods and conclusions with review from senior-level staff

Review: A brief description without details for general use.

Key to Classification

Strictly Confidential: For recipients only

Confidential: Can be distributed within client's organization

Internal: Not to be distributed outside ArcVera Renewables

Client's Discretion: Distribution at the client's discretion

Published: No restriction

ABSTRACT

ArcVera Renewables carried out a study of long-range (> 50 rotor diameters) external wakes, with emphasis on the tendency of existing engineering wake models to greatly underpredict the strength and longevity of external wind farm wake losses on other projects under some atmospheric conditions. Three wind farm case studies are presented; two onshore in the central United States, and one offshore in the New York Bight lease areas recently auctioned for wind energy development. The first case study demonstrates the inadequacy of standard engineering wake models to capture the magnitude of long-range external wake losses. With that result as motivation, the second case study was used to demonstrate the utility of the WRF mesoscale model with the Wind Farm Parameterization (WFP) to model the wake impacts of distant external turbines more accurately than existing engineering wake models. WRF-WFP produced average external wake losses much closer to, 16% higher than, that derived from SCADA data. In contrast, two engineering wake loss models failed to come close to the actual wake loss deficit; these models under-predicted external wake losses as a small fraction, ⅓ or less, of that derived from SCADA data.

As a further demonstration of the capabilities of WRF-WFP, and to give a view into the potential for large project-to-project wake impacts in the recently auctioned New York Bight offshore lease areas, ArcVera presented a third offshore wind energy case study. ArcVera Renewables designed WRF-WFP simulations of hypothetical wind project turbine arrays that might be built in those areas approximately 5-10 years from today. The simulations were run for a set of 16 days, with winds from the prevailing southwesterly wind direction, selected to maximize the waking of arrays aligned in a southwest to northeast direction. The simulations produced dramatic hub-height project-scale wake swaths that extended over 50 km downwind, with a specific example showing a waked wind speed deficit of 7% extending 100 km downwind from the array of turbines that produced it. When averaged over the selected 16 simulation days, the energy loss at the target lease area due to external wakes from arrays to its southwest was 28.9%. While the 16-day result undoubtedly greatly exceeds the long-term external wake loss for winds from all directions, it is nonetheless illustrative of the potential for much greater external wake losses than have been accounted for in development planning for the New York Bight lease areas; and, as in the two onshore long-distance wake loss case studies, are much larger than engineering wake models predict for the same conditions.

The implications of this study of long-range wakes on the assessment of energy production (or shortfalls thereof) of existing and anticipated future wind farms is material and significant, as unexpectedly large impacts may well be present, and existing non-WRF-WFP-based engineering long-range wake loss methods are shown to be inadequate. The inadequacy of these models for long-distance wakes may be remedied in the future with further validation time-series modeling and concomitantly accurate assessment of time periods when atmospheric stability is high. Still larger implications are clear for long-term project valuation risk, the analysis and assessment of hybrid projects, battery usage risk, and around-the-clock reliable renewable energy power production. Offshore wind farms are equally strongly affected, and the extensive global plans for proximal deployment of offshore wind projects should account for such impacts.

TABLE OF CONTENTS

ArcVera Renewables 1301 Arapahoe Street, Suite 105 | Golden, CO 80401 USA | +1 720.237.2929

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

COD	Commercial Operation Date
D	Rotor Diameter
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	ECMWF Reanalysis, Version 5
EST	Eastern Standard Time
EV-DAWM	Eddy-Viscosity / Deep Array Wake Model
IEA	International Energy Agency
LES	Large-Eddy Simulation
MW	megawatt
SAR	Synthetic aperture radar
SCADA	Supervisory Control and Data Acquisition
TKE	Turbulent Kinetic Energy
WFP	Wind Farm Parameterization
WRF	Weather Research and Forecast Model

ArcVera Renewables 1301 Arapahoe Street, Suite 105 | Golden, CO 80401 USA | +1 720.237.2929

1 INTRODUCTION

When wind energy resource assessments are conducted for planned wind energy projects, one of the most significant and uncertain contributors to that estimate is the energy loss due to wind turbine wakes. Typically, the wake losses are calculated separately for those coming from wakes generated within the project (internal wakes) and those generated by turbines outside the project (external wakes). Until recently the same models have been used for both. These models often predict negligible waked wind speed deficits just a few tens of rotor diameters downwind of the waking turbines. Aggregate effects of wakes from a large array of turbines acting in concert can extend this farm-scale wake effect, but, the general sense in the industry was that wakes from external turbines more than roughly 50D ("D" refers to the rotor diameter of the wake-generating turbine) from the project of interest could be ignored. In Brazil, for example, local renewable energy regulations require compensation for lost energy from new wind farms installed within 20 wind turbine tip-heights (~24D).

Historical work in the 1980's (Nierenberg, 1989, Nierenberg and Kline, 1989) documented significant wake effects 250D downwind in California's passes. More recently, observational evidence gathered over the last decade has begun to change this view. For onshore wakes, the "far wake" region was thought to extend no more than about 15D downwind (McCay et al. 2012). Scanning Doppler radar revealed wakes from single turbines extending at least 30D (Hirth et al. 2012). The offshore environment has always been understood to be more conducive than onshore to wake longevity, because turbines tend to be larger (producing larger wakes), atmospheric conditions tend to be more stable (which slows wake recovery), and the wind flow is less disturbed by underlying surface irregularities. Offshore wakes were thought to extend perhaps as far as 15 km (McCay et al. 2012), corresponding to approximately 125D. However, recent evidence from satellite-based synthetic aperture radar (SAR) measurements over the North Sea (Hasagar et al. 2015; Djath et al. 2018); as well as aircraft measurements in the same region (Platis et al. 2018) have shown wind farm-scale wakes with wind speed deficits of 5-10% extending 50 km or more (> 400D).

This white paper brings to light the significant impacts on energy production due to long-range wakes. We present evidence from two pairs of wind farms in the central United States, in which SCADA data from a downwind "target" wind farm is analyzed before and after a new upwind project was built. We also show the insufficiency of existing wake models to capture the energy losses caused by the distant upwind farm. We describe the accuracy potential of the Wind farm Parameterization (WFP), designed and implemented in the Weather Research and Forecast (WRF) model by Fitch et al. (2012), as a commercially viable tool for estimating the impacts of long-range external wakes and external wake production risk. For the second pair of onshore projects, we demonstrate that WRF-WFP predicts external wake losses much closer to the SCADA-derived values than the conventional engineering models.

Finally, as in recent studies focused on the lease areas offshore of Massachusetts (Rosencrans et al. 2022; Pryor et al. 2022), we apply the WRF-WFP to hypothetical future wind development in the New York Bight Lease Areas recently auctioned in February 2022, to demonstrate the potential for strong, long-range wakes from these lease areas to negatively affect energy production at neighboring wind farms, even those many tens of kilometers away. These hypothetical simulations use the largest reference turbine defined in the IEA Wind reference turbine family, assuming that turbines of this capacity (or larger) will eventually be installed when construction begins in 5-10 years. The results are material to heretofore seldom considered wind energy resource assessment production long-range wake loss risk; in terms of distance downwind (50-100 km) wakes with speed deficits greater than 1 m/s persist and directly impact other lease areas. These predictions are preliminary, considering there is no operational history for these very large turbines with which to validate the long-range wakes they produce within the WRF-WFP. However, confidence in the WRF-WFP has been accumulating based on validation studies already conducted by the research community (see below) and the onshore results presented in the first part of this report. ArcVera already commercially utilizes this tool to assess and reduce risk, and anticipates that tools like the WFP, or other wind farm-aware mesoscale model applications, will become a key part of the wind energy resource assessment (WERA) wind farm-atmosphere interaction (WFAI)/wake loss modeling toolbox.

2 CASE STUDY 1: THE PROBLEM

The challenge of correctly estimating long-range wake impacts can be illustrated with Case Study 1, depicted schematically in Figure 1. Case Study 1 involves a smaller, new project being built 13 km north of an existing larger project in the central United States. Details of the turbine layouts, project capacities, and turbine models are withheld to maintain the projects' anonymity. The existing project is the “target project” at which the impact of external wakes from the new project is evaluated. Four years of SCADA data were available at the target project, with the first two years occurring before the COD of the new project, and the second two years after. While southerlies are the prevailing wind direction, northerlies occupy a secondary frequency peak (see wind rose in Figure 1) and would lead to a project-scale wake impinging upon the target project a substantial portion of the time.

An operational assessment was performed for the target project, using SCADA data from the two separate periods, to determine the long-term energy yield based on the performance of the target project during each period. Reasonable corrections for curtailment, availability, and windiness were made during the period assessed, relative to the long-term, to assure comparability of different periods of record. No other project development occurred within the vicinity during the 4-year study period.

In addition to the operational assessment, wake model experiments were run in which the same project wind climate was applied, but in one experiment, the new project was included, and in the other, it was excluded, and the difference in energy yield at the target project evaluated. This experiment was repeated with two wake models: The Eddy Viscosity / Deep-Array Wake Model (EV-DAWM) available in OpenWind, and the ArcVera Wind Farm-Atmosphere Interaction (WFAI) Model (Poulos et al. 2022). The WFAI model is an empirical loss model built upon and validated against numerous data sets of energy production and measured wind speeds before and after wind farm installations. It was originally developed under the auspices of U.S. Department of Energy scientific research (DOE 1987, 1990), continually upgraded, and commercially used on numerous WERAs at ArcVera for many years.

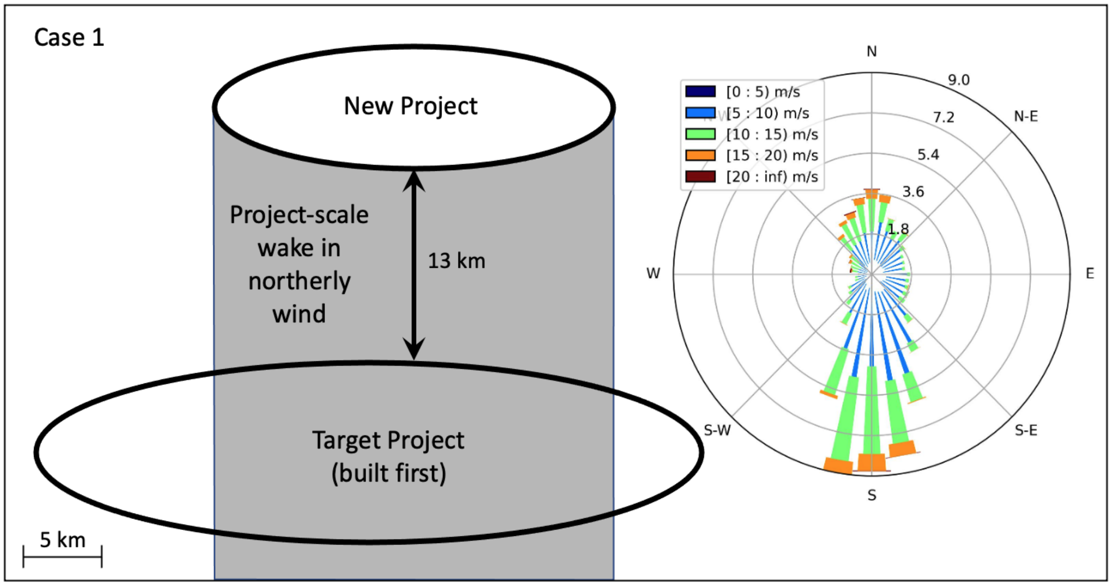

Figure 1. Schematic of the two projects studied in Case Study 1. Ellipses indicate outlines and relative locations of projects. The wind rose is derived from a hub-height met tower within the target project.

Table 1 provides the results of the before and after SCADA-based operational assessment, and the wake model predictions. While the SCADA analysis indicated that the presence of the new wind farm reduced production at the target wind farm by 3.6%, both the wake models indicated a nearly negligible impact of the new wind farm. The wake models were unable to predict even a small fraction of the observed wake loss from an external wind farm 13 km away.

Table 1. SCADA-derived and modeled long-range annual-average external wake losses at Target Project for Case Study 1. Losses are expressed as the percent of gross energy.

Source of Estimate	Long-Range External Wake Loss
SCADA	3.6%
EV-DAWM	0.1%
WFAI Model	< 0.1%

While these engineering wake loss models have been well validated against internal wake and WFAI losses of wind farms based on production data, they have been less well, or unvalidated, at long-range. This long-range wake loss weakness is exposed in this case study.

3 A POTENTIAL SOLUTION: MESOSCALE MODELING WITH A WIND FARM PARAMETERIZATION

The Weather Research and Forecasting model (WRF, Skamarock et al. 2019) is a numerical weather prediction model that has been in use globally by academic and national research institutions, national weather prediction agencies, and private companies with weather and climate concerns since it was first developed and released in 2000. It is classified as a "mesoscale model," which means it is designed to simulate weather phenomena covering spatial scales from 2 km to 2000 km (numerically resolved with grid spacing of 200 m to 200 km Chapter 10, Pielke, 1984), but has been used successfully at both larger scales and smaller scales, in the latter case as a "large eddy simulation" or LES model, with a grid spacing of 10 m or less). It is used routinely in the wind energy industry for short-term energy forecasting and retrospective energy assessment. ArcVera Renewables has over 45 years combined experience using WRF and similar mesoscale models for various applications, including using WRF and WRF-LES in wind energy forecasting and assessment for over a decade.

In 2012, in response to the increasing interest in wind energy development and the potential physical interactions between wind farms and the weather and climate of the surrounding region, Fitch et al. (2012) developed and implemented in WRF a capability referred to as the Wind Farm Parameterization (WFP), which models the deceleration of winds by turbines within a WRF model grid box, based on the turbine thrust characteristics. The kinetic energy removed by the turbines is distributed between electric power generation and turbulence production. The wind deceleration interacts with the full atmospheric dynamics simulated by WRF, allowing for downwind transport of the waked wind speed deficits, and feedbacks to the flow such as upwind blockage from the simulated combined induction zone effects of wind turbines, flow deflection around wind farms, gravity wave development and impacts on wind flow patterns,, and the complex movement and distortion of wake swaths within time-dependent curved or sheared wind flows. Importantly, the roles of time-varying atmospheric stability, particularly stable atmospheric conditions, and turbulence on wake recovery are realistically represented in meteorological physics within WRF with WFP.

The waked wind speed deficits simulated by WRF-WFP have been validated in several research studies, mostly at North Sea offshore wind projects, including Fitch et al. (2012), Hasagar et al. (2015), Platis et al. (2018), and Siedersleben et al. (2018). In addition, many studies have conducted sensitivity and other tests with WFP, leading to improvements and recommendations for best use (Lee and Lundquist 2017; Archer et al. 2020; Siedersleben et al. 2020; Tomaszewski and Lundquist 2020; and Larsén and Fischereit 2020). Based on these studies, the WFP has been modified and improved and continues to be actively developed in the research community. Therefore, the WFP should be considered a well-validated tool that continues to improve as part of ongoing active research and development. ArcVera's work and the research cited above provides ample validating evidence that WRF-WFP captures the fundamental physics of wind turbine interactions with the atmosphere.

4 CASE STUDY 2: A DEMONSTRATION OF WRF-WFP

Case Study 2 is similar to Case Study 1, in that it involves an existing project, and a new project built to its north (Figure 2). Two key differences from Case Study 1 are that the new project is much larger than the target project; and that the new project is closer to the target project (only 5 km away, as opposed to 13 km in Case Study 1). The wind rose in Figure 2 indicates that a project-scale wake from the new project would impinge on the target project a substantial portion of the time. In Case Study 2, rather than performing a long-term-adjusted operational assessment for the before and after periods, we evaluated 10-minute SCADA energy production data from the Target Project and ran model simulations only during a selection of days in which maximum waking of the target project by the new project was expected. Maximum waking was expected in northerly flow conditions, with wind speeds in the steep, non-linear section of the target project's power curve. Care was taken to select a set of times in which the wind speed distributions in the before and after period matched, so as not to skew the result due to different wind climates. A total of 1300 hours (~54 days) of SCADA production and simulated winds were used.

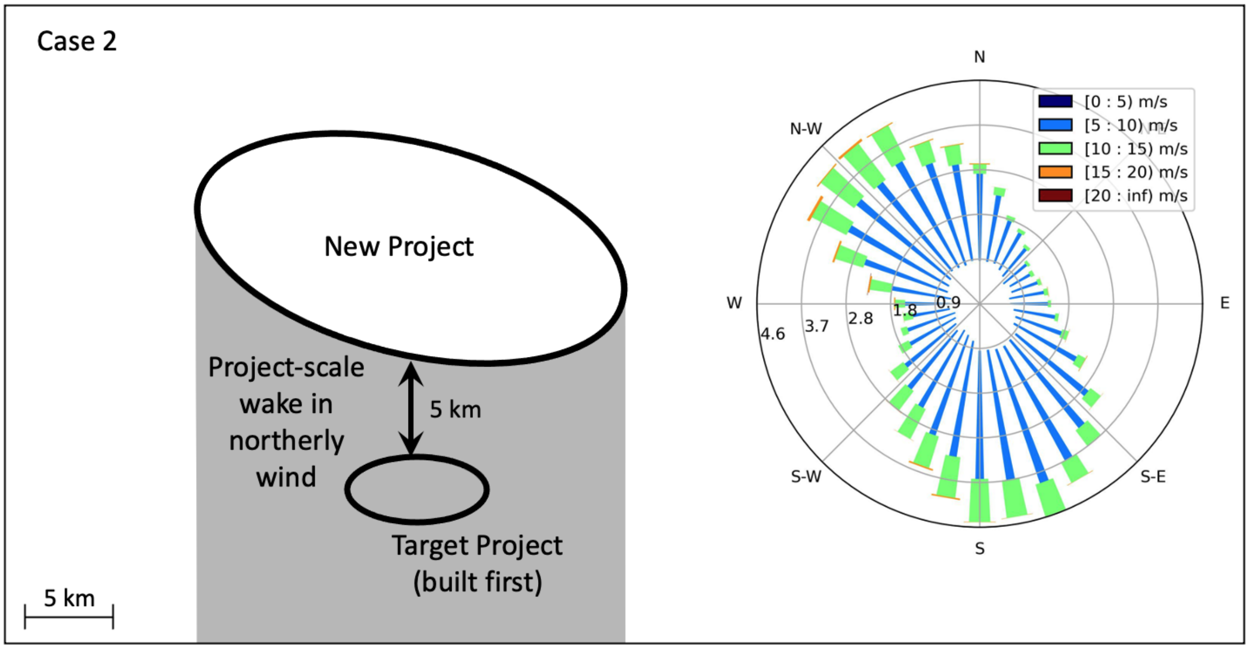

Figure 2. Schematic of the two projects studied in Case Study 2. Ellipses indicate approximate outlines and relative locations of projects. The wind rose is derived from an ERA5 Reanalysis node within the target project.

For Case Study 2, wake model simulations were also performed for the "before" and "after" periods (i.e., with and without wakes from the New Project), using both EV-DAWM and ArcVera WFAI. In addition, WRF-WFP was run for the same selected set of times, with three simulations performed for each of the selected dates, one with no turbines, one with only the target project turbines, and one with new project and target project turbines. We used WRF version 4.2.1, which includes a key code correction for the WFP identified by Archer et al. (2020).

The study used WRF model grid with 1.0-km spacing and obtained initial and boundary conditions from the ERA5 Reanalysis data set (Hersbach et al. 2020). Waked wind speed deficits due to the new project were evaluated from the difference between the "new and target turbines" run and the "only target turbines" run. For illustration, an example of waked wind speed deficit simulated by WRF-WFP at one time is shown in Figure 3. It depicts all wakes from both projects by showing the difference between the "new and target turbines" run and the "no turbines" run during a time of north-northeasterly wind flow. Note that the project-scale wake swath from the new project not only envelopes the smaller target project but continues with substantial magnitude (at least 1 m/s) to the domain boundary over 30 km south-southwest of the new project.

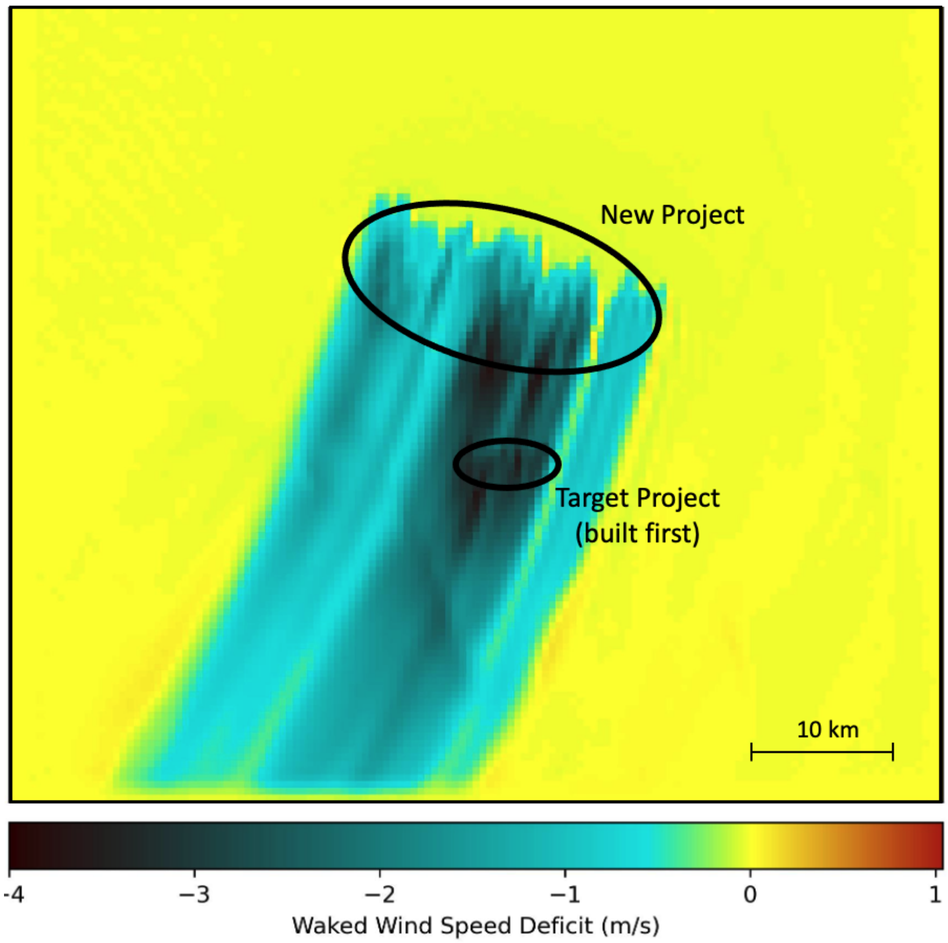

Figure 3. Waked wind speed deficit at hub height from the WRF-WFP, in m/s (color scale at bottom), at 10 pm local time on a mid-summer day at the projects in Case Study 2. Ellipses indicate approximate outlines and relative locations of projects. Hub height wind speed at this time was 9.5 m/s.

The average wake loss during the selected periods is shown in Table 2. Because the times were selected to maximize the wake impacts of the new project on the target project, the loss numbers are much higher than the long-term mean values shown for Case Study 1. Additionally, the time points were segregated into unstable and stable categories based on negative or positive values of the bulk Richardson number. The SCADA analysis indicates a large external wake impact of 23.8% by the new project on the target project, averaged over the selected time points. As expected, the SCADA analysis also shows wake impacts to be stronger during stable periods than during unstable periods. The WRF-WFP model overpredicts the external wake loss during the selected time points, but only by a factor of 1.16 (16% overprediction). It also correctly identifies the stronger wake impact during stable conditions. Meanwhile, as in Case Study 1, the engineering wake loss models underpredict the effect by a large amount; they predict only a small fraction of the SCADA-derived wake loss in energy.

ArcVera Renewables 1301 Arapahoe Street, Suite 105 | Golden, CO 80401 USA | +1 720.237.2929

Table 2. SCADA-derived and modeled long-range external wake losses at Target Project for Case 2 for the selected 1300 hours of northerly wind direction, with separate results by stability class. Losses are expressed as the percent of gross energy. Percent frequency of occurrence of stable and unstable conditions are shown in column headings.

	Long-Range External Wake Loss		
Source of Estimate	All Times	Stable Conditions (67.5%)	Unstable Conditions (32.5%)
SCADA	23.8%	29.1%	12.8%
EV-DAWM	5.7%	not tested	not tested
ArcVera WFAI Model	0.2%	not tested	not tested
WRF-WFP	27.7%	32.6%	17.5%

5 CASE STUDY 3: EXTERNAL WAKES FROM HYPOTHETICAL WIND FARMS IN THE NEW YORK BIGHT LEASE AREAS

5.1 CONFIGURATION

As a further demonstration of the capabilities of WRF-WFP, and to give a view into the potential for large project-to-project wake impacts in the recently auctioned New York Bight offshore lease areas, ArcVera Renewables ran WRF-WFP simulations of hypothetical wind projects that might be built in those areas perhaps 5-10 years from today. The hypothetical arrays, depicted in Figure 4, were designed as follows. The turbine is the IEA Wind 15-MW Reference Turbine, with a hub height of 150 m and a rotor diameter of 240 m. Turbines of this size and capacity are now starting to be commercially marketed. In 5-10 years, offshore wind energy projects may utilize turbines of this size or larger. We designed the arrays with a turbine spacing of 1.0 nautical miles (1.85 km) in the east-west direction, and 0.75 nautical miles (1.39 km) in the north-south direction, based on our current understanding of what the relevant jurisdictional agencies will require and the measured wind rose. 10 km (42D) gaps were enforced between turbine arrays; there are 3 km gaps between lease areas. Prevailing winds are southwesterly.

Three arrays were designed:

- Northern Array
    - Lease Area 0538
    - 85 turbines
    - Treated as the target project
- Central Array
    - Lease Area 0539
    - 118 turbines
    - Treated as an external project
- Southern Array
    - Lease Areas 0541 and 0542
    - 157 turbines
    - Treated as an external project

The WRF model was configured similarly to Case Study 2, except with slightly finer horizontal grid resolution (800 m). 16 case study dates were selectively chosen to provide maximum time with winds from the 190°-240° sector and speed in the range of 6-11 m/s. Under these conditions, the waking of the target array (0538) by areas 0539, 0541, and 0542 is maximum, not only because they are directionally aligned with the wind, but because in southwesterly flow (the prevailing direction, especially in the warm season), typically there is warm air moving over colder water, resulting in stabilization of the flow and longer-lived wakes. The wind speed range, positioned in the steepest part of the turbine power curve, was chosen to maximize the energy sensitivity to the waked wind speed deficits. The annual wind rose at floating lidar E06 (Figure 4, right side) indicates that the conditions described above frequently occur, though the chosen set of times have much higher wake losses than a long-term mean that accounts for the entire wind rose. For each simulation day, the model was run for 24 h starting at 7:00 AM EST, with a 6-h spin-up period from 1:00 AM to 7:00 AM EST. Model output was produced every 10 minutes.

For each chosen day, three simulations were run, which included the effects of:

1. No turbines (Simulation 1)
2. Turbines at the Southern (0541/0542) Array only (Simulation 2)
3. Turbines at both the Central (0539) and Southern Arrays (Simulation 3)

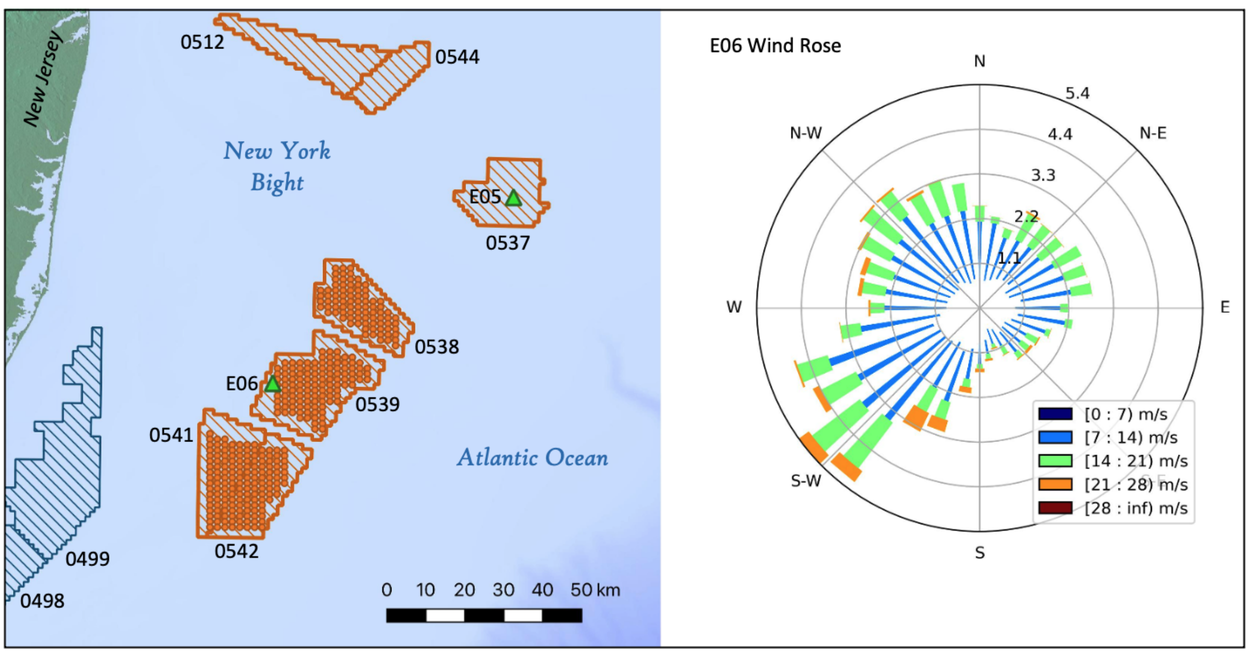

Figure 4. Map of New York Bight offshore lease areas (orange outlines). New Jersey lease areas are also shown (blue outlines). Orange dots indicate hypothetical turbine arrays in lease areas 0538, 0539, 0541, and 0542. Green triangles indicate floating lidar sites E05 and E06. The wind rose in the right panel is from lidar measurements at site E06.

Wind speed deficits on the Northern Array (Lease Area 0538) due to external wakes from the Southern Array only were evaluated from Simulation 2 minus Simulation 1. Wind speed deficits due to external wakes from the Central and Southern Arrays only were evaluated from Simulation 3 minus Simulation 1.

5.2 RESULTS

An example of waked wind speed deficit from the WRF-WFP simulations is shown in Figure 5. The left panel shows the effect of turbines in only the Southern Array, whereas the right panel shows the effect of turbines in both the Southern and Central Arrays. The dominant feature of these plots is the long-range project-scale wake swath extending from the arrays to the north-northeast. Even at the northern edge of the domain, over 100 km downwind of the Southern Array, the long-range wake from the Southern Array only (left panel) maintains a 0.7 m/s (or 7%) hub-height wind speed deficit; and 80 km downwind of the Central Array, the long-range wake from the Southern and Central Arrays combined (right panel) maintains a 1.0 m/s (or 10%) wind speed deficit. The waked speed deficits within the target (0538, Northern) array are 1.6 m/s (16%) from the Southern Array only, and 2.5 m/s (25%) from the combination of the Southern and Central Arrays. Note that no turbines from the Northern Array were included in the simulations, so the entire speed deficit within the Northern array is due to external wakes from the Southern and Central Arrays.

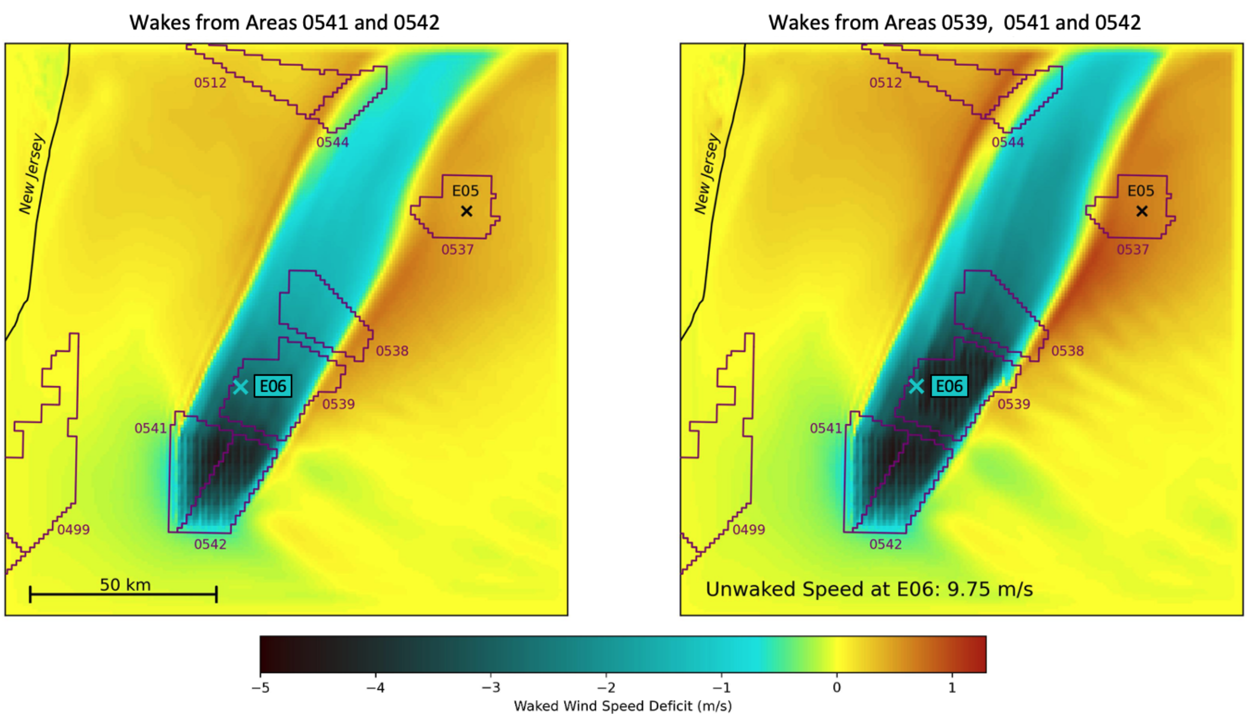

Figure 5. Waked wind speed deficit at hub height (m/s, color scale at bottom), from the WRF-WFP simulations of the New York Bight lease areas, at 1530 EST, 24 Feb 2020. "x" symbols indicate the locations of floating lidars.

In addition to the project-scale wake, other prominent WFAI features emerge in these plots. A region of speed deficit upwind of the projects indicates project-scale blockage, up to 0.5 m/s in some locations, with wave-like structures embedded in it. Downwind, the wake swath is flanked by areas of significant speed enhancement (> 0.5 m/s), which are a subject of future scientific study. Over the long term, when these flanking wind acceleration zones pass over downwind projects, the accelerations partially offset the wake losses incurred at other times, reducing the long-term mean external wake loss.

Energy-based losses at the Northern Array due to external wakes at the Central and Southern Arrays for the 16 days of the simulation were calculated, along with corresponding predictions from the EV-DAWM and ArcVera WFAI models. Results are shown in Table 3. No validation of the results is possible due to the hypothetical nature of the turbine arrays. However, the results illustrate the potential for large external wake losses. Even if the long-term mean external wake loss at the Northern Array is, for example, one-quarter of the loss from this set of 16-days with enhanced waking conditions, that still represents a very large loss due only to external wakes. But equally important is the result, consistent with those of the first two case studies, that the engineering wake models estimate only a small fraction of the external wake loss predicted by the WRF-WFP.

Table 3. Modeled long-range external wake losses at New York Bight Lease Area 0538 for the 16 selected days of primarily southwest wind direction, with separate results for wakes from Lease Area 0539 only, and from the combination of Lease Areas 0539, 0541, and 0542. Losses are expressed as the percent of gross energy.

	Long-Range External Wake Loss at Area 0538	
Source of Estimate	From 0539 only	From 0539, 0541, & 0542
EV-DAWM	0.5%	5.3%
ArcVera WFAI Model	< 0.1%	0.2%
WRF-WFP	13.0%	28.9%

5.3 SENSITIVITY TESTS

Considering the large magnitude and length of wakes predicted by WRF-WFP in the New York Bight lease areas, and lack of validating data for the large hypothetical wind turbines used in the simulations, ArcVera consulted with Professor Julie Lundquist's research group at the University of Colorado to consider the uncertainty in these model predictions of large, long-range wakes. A suggestion that emerged was to test the sensitivity of the wakes to two configurable parameters that recent studies have demonstrated are important for the magnitude of wakes predicted by WRF-WFP: the number of vertical levels beneath the rotor layer, and the amount of turbine-produced turbulence that is injected into the model simulation.

Tomaszewski and Lundquist (2020) found that using more vertical levels reduces mixing and increases wake longevity (though they found the sensitivity modest). We used only 2 vertical levels beneath the rotor, so we tested increasing that to 4 levels.

The turbulent kinetic energy (TKE) factor (a tunable parameter) scales the amount of turbine-induced turbulence injected into the model flow. A value of 0.0 injects no turbine-induced turbulence, whereas a value of 1.0 injects the full amount consistent with the turbine power and thrust curves. The appropriate amount is not a settled matter, with the original Fitch (2012) paper injecting the full amount (but testing sensitivity to half or double the full amount). Archer et al. (2020) recommended only one-quarter of the full amount be injected to best match large-eddy simulations that they conducted, and Larsén and Fischereit (2021) found that a value of 1.0 validated better than 0.25. Others have argued that none of the turbine-induced turbulence should be injected into the model flow at the scales resolved by the model (Jacobson and Archer 2012; Volker et al. 2015). In our simulations for both Case Studies 2 and 3, we used a TKE factor of 0.0, so we tested higher values, up to 1.0.

Table 4 shows the parameter values tested in the sensitivity experiments, and the resulting relative change in wake strength compared to the control experiment (green highlight, 0.0%), which used the configuration indicated in the upper left cell of the table (zero turbulence injected, and two model vertical levels below the rotor layer). The wake strength was defined as the area-integrated wind speed difference within the wind speed deficit swath north and east of lease area 0539 . This definition yields a higher value if either the wake's magnitude or areal size increases.

Table 4. Sensitivity test results. The control configuration (green highlight) is the upper left cell in the table, with 2 model levels beneath the rotor layer, and a TKE factor of 0.0%. The value in each cell represents the change in wake strength relative to that of the control configuration. All values are positive, meaning that all sensitivity tests produced stronger wakes than in the control configuration.

		Turbine TKE Injection Factor			
		0.00	0.25	0.50	1.00
Number of model levels beneath rotor	2	0.0%	not tested	not tested	8.0%
	4	0.7%	6.6%	7.7%	8.4%

The increase in vertical levels beneath the rotor slightly increased the wake strength, consistent with Tomaszewski and Lundquist (2020). The increase in turbulence also increased the wake strength. The latter result is counterintuitive considering that greater turbulence would be expected to enhance wake recovery, and this does occur within the waking turbine array, but downwind of it the opposite occurs: the wake is enhanced. Fitch et al. (2012) and Rybchuk et al. (2021) found the same counterintuitive result. In summary, the original configuration actually produced the *weakest* wakes of all the configurations tested. A TKE injection factor of 0.0 was found to produce rather accurate results in Case Study 2, and an increase in TKE injection factor could reduce accuracy based on these sensitivity tests.

6 CONCLUSIONS

ArcVera Renewables carried out a study of long-range (> 50 rotor diameters) external wakes, with emphasis on the tendency of existing engineering wake models to greatly underpredict the strength and longevity of external wind farm wake losses on other projects under some atmospheric conditions. Three wind farm case studies are presented; two onshore in the central United States, and one offshore in the New York Bight lease areas recently auctioned for wind energy development. The first case study demonstrates the inadequacy of standard engineering wake models to capture the magnitude of long-range external wake losses. With that result as motivation, the second case study was used to demonstrate the utility of the WRF mesoscale model with the Wind Farm Parameterization (WFP) to model the wake impacts of distant external turbines more accurately than existing engineering wake models. WRF-WFP produced average external wake losses much closer to, 16% higher than, that derived from SCADA data. In contrast, two engineering wake loss models failed to come close to the actual wake loss deficit; these models under-predicted external wake losses as a small fraction, ⅓ or less, of that derived from SCADA data.

As a further demonstration of the capabilities of WRF-WFP, and to give a view into the potential for large project-to-project wake impacts in the recently auctioned New York Bight offshore lease areas, ArcVera presented a third offshore wind energy case study. ArcVera Renewables designed WRF-WFP simulations of hypothetical wind project turbine arrays that might be built in those areas approximately 5-10 years from today. The simulations were run for a set of 16 days, with winds from the prevailing southwesterly wind direction, selected to maximize the waking of arrays aligned in a southwest to northeast direction. The simulations produced dramatic hub-height project-scale wake swaths that extended over 50 km downwind, with a specific example showing a waked wind speed deficit of 7% extending 100 km downwind from the array of turbines that produced it. When averaged over the selected 16 simulation days, the energy loss at the target lease area due to external wakes from arrays to its southwest was 28.9%. While the 16-day result undoubtedly greatly exceeds the long-term external wake loss for winds from all directions, it is nonetheless illustrative of the potential for much greater external wake losses than have been accounted for in development planning for the New York Bight lease areas; and, as in the two onshore long-distance wake loss case studies, are much larger than engineering wake models predict for the same conditions.

The implications of this study of long-range wakes on the assessment of energy production (or shortfalls thereof) of existing and anticipated future wind farms is material and significant, as unexpectedly large impacts may well be present, and existing non-WRF-WFP-based engineering long-range wake loss methods are shown to be inadequate. The inadequacy of these models for long-distance wakes may be remedied in the future with further validation time-series modeling and concomitantly accurate assessment of time periods when atmospheric stability is high. Still larger implications are clear for long-term project valuation risk, the analysis and assessment of hybrid projects, battery usage risk, and around-the-clock reliable renewable energy power production. Offshore wind farms are equally strongly affected, and the extensive global plans for proximal deployment of offshore wind projects should account for such impacts.

REFERENCES

Archer, C. L., Wu, S., Ma, Y., & Jiménez, P. A., 2020: Two Corrections for Turbulent Kinetic Energy Generated by Wind Farms in the WRF Model. Mon. Wea. Rev., 148, 4823–4835, https://doi.org/10.1175/MWR-D-20-0097.1.

Brower, M. C., and N. M. Robinson, 2012: The Openwind Deep-Array Model—Development and Validation. AWS Truepower Report.

DOE SBIR Program U.S. Department of Energy. "United Industries Report No. 8701: Numerical Model for Predicting Turbine Array Performance in Complex Terrain, Phase 1." Washington D.C., 1987.

DOE SBIR Program U.S. Department of Energy. "United Industries Report No. 8917: Numerical Model for Predicting Turbine Array Performance in Complex Terrain, Phase 2: Final Technical Report." Washington D.C., 1990.

Djath, B., Schulz-Stellenfleth, J., and Cañadillas, B., 2018: Impact of atmospheric stability on X-band and C-band synthetic aperture radar imagery of offshore windpark wakes, J. Renew. Sustain. Ener., 10, 043301, https://doi.org/10.1063/1.5020437.

Fitch, A. C., Olson, J. B., Lundquist, J. K., Dudhia, J., Gupta, A. K., Michalakes, J., and Barstad, I., 2012: Local and Mesoscale Impacts of Wind Farms as Parameterized in a Mesoscale NWP Model, Mon. Weather Rev., 140, 3017–3038, https://doi.org/10.1175/MWRD-11-00352.1.

Hasager, C., P. Vincent, H. Vincent, R. Husson, A. Mouche, M. Badger, A. Peña, P. Volker, J. Badger, A Di Bella, A. Palomares, E. Cantero, P. Correia, 2015: Comparing satellite SAR and wind farm wake models. Journal of Physics: Conference Series. 625. 10.1088/1742-6596/625/1/012035.

Hersbach, H., and Coauthors, 2020: The ERA5 global reanalysis. Quart. J. Roy. Meteor. Soc., 146, 1999–2049, https://doi.org/10.1002/qj.3803.

Hirth, B. D., J. L. Schroeder,W. S. Gunter, and J. G. Guynes, 2012: Measuring a utility-scale turbine wake using the TTU Ka mobile research radars. J. Atmos. Oceanic Technol., 29, 766–771.

Jacobson, M. Z., and C. L. Archer, 2012: Saturation wind power potential and its implications for wind energy. Proc. Natl. Acad. Sci., 109(39), 15681.

Larsén, X.G., and J. Fischereit, 2021: A case study of wind farm effects using two wake parameterizations in the Weather Research and Forecasting (WRF) model (V3. 7.1) in the presence of low-level jets. Geoscientific Model Development, 14(6): 3141-3158.

Lee, J. C. Y., and Lundquist, J. K., 2017: Evaluation of the Wind Farm Parameterization in the Weather Research and Forecasting Model (Version 3.8.1) with meteorological and turbine power data, Geoscientific Model Development, 10, 4229–4244, https://doi.org/10.5194/gmd-10-4229-2017.

Mckay, P., R. Carriveau, D. S-K Ting, and T. Newson, 2012: Turbine Wake Dynamics. Advances in Wind Power: 65-84. INTECH. Web.

Nierenberg, R. and J. Kline, 1989: Macro-scale wake effects. WindStats Newsletter. Spring 1989. Vol. 2, No. 2, ISSN 0903-5648, 2 pp.

Nierenberg, R., 1989: Macro-scale wake effects. Windpower, 1989, San Francisco, CA, September, 9 pp.

Pielke, R. A., 1984: Mesoscale Meteorological Modeling. New York, N. Y.: Academic Press, 612 pp.
Platis, A., Siedersleben, S. K., Bange, J., Lampert, A., Baerfuss, K., Hankers, R., Canadillas, B., Foreman, R., Schulz-Stellenfleth, J., Djath, B., Neuman, T., and Emeis, S., 2018: First in situ evidence of wakes in the far field behind offshore wind farms, Sci. Rep., 8, 2163, https://doi.org/10.1038/s41598-018-20389-y.
Poulos, G. S., E. Jones, and J. Crescenti, 2022: Validation: Replacing wake loss modeling with wind farm-atmosphere interaction loss modeling. Journal of Energy in Southern Africa, August, 28 pp.
Pryor, S. C., R. J. Barthelmie, T. J. Shepherd, A. N. Hahmann, and O. M. Garcia Santiago, 2022: Wakes in and between very large offshore arrays. J. Phys.: Conf. Ser. 2265 022037
Rosencrans, D. J., J. K. Lundquist, M. Optis, and N. Bodini, 2022: Quantifying the uncertainty of wake impacts across the Atlantic outer continental shelf. 13th Conference on Weather, Climate, and the New Energy Economy. Houston, Texas, American Meteor. Soc. https://ams.confex.com/ams/102ANNUAL/meetingapp.cgi/Session/60432
Rybchuk, A., T. Juliano, J. Lundquist, D. Rosencrans, N. Bodini, M. Optis, 2021: The sensitivity of the Fitch wind farm parameterization to a three-dimensional planetary boundary layer scheme. 10.5194/wes-2021-127.
Siedersleben, S. K., Platis, A., Lundquist, J. K., Djath, B., Lampert, A., Bärfuss, K., Cañadillas, B., Schulz-Stellenfleth, J., Bange, J., Neumann, T., and Emeis, S., 2020: Turbulent kinetic energy over large offshore wind farms observed and simulated by the mesoscale model WRF (3.8.1), Geoscientific Model Development, 13, 249–268, https://doi.org/10.5194/gmd-13-249-2020.
Siedersleben, S. K., Platis, A., Lundquist, J. K., Lampert, A., Bärfuss, K., Cañadillas, B., Djath, B., Schulz-Stellenfleth, J., Bange, J., Neumann, T., and Emeis, S., 2018: Evaluation of a wind farm parametrization for mesoscale atmospheric flow models with aircraft measurements, Meteorol. Z., 27, 401–415, https://doi.org/10.1127/metz/2018/0900.
Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, Z. Liu, J. Berner, W. Wang, J. G. Powers, M. G. Duda, D. M. Barker, and X.-Y. Huang, 2019: A Description of the Advanced Research WRF Version 4. NCAR Tech. Note NCAR/TN-556+STR, 145 pp. doi:10.5065/1dfh-6p97.
Tomaszewski, J. M., and Lundquist, J. K., 2020: Simulated wind farm wake sensitivity to configuration choices in the Weather Research and Forecasting Model Version 3.8.1, Geoscientific Model Development, 13, 2645–2662, https://doi.org/10.5194/gmd-13-2645-2020.
Volker, P. J. H., J. Badger, A. N. Hahmann, and S. Ott, 2015: The Explicit Wake Parametrisation V1.0: a wind farm parametrisation in the mesoscale model WRF, Geosci. Model Dev., 8, 3715–3731, https://doi.org/10.5194/gmd-8-3715-2015, 2015.

ArcVera Renewables 1301 Arapahoe Street, Suite 105 | Golden, CO 80401 USA | +1 720.237.2929