NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

ACTIVE WAKE REDIRECTION CONTROL TO IMPROVE ENERGY YIELD

Matthew J. Churchfield[1], Paul Fleming[1], Elise DeGeorge[1]
Bernard Bulder[2]
Stanley M. White[3]

[1]National Renewable Energy Laboratory
[2]Energy Research Centre of the Netherlands
[3]Fishermen's Energy

Introduction

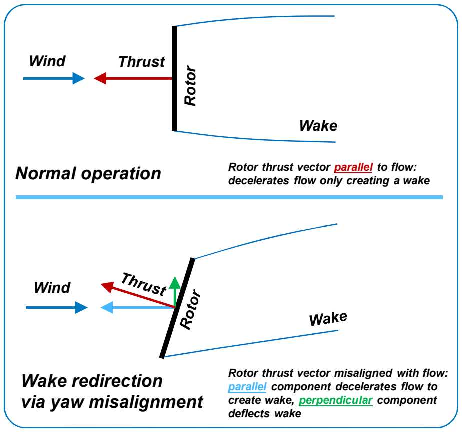

Figure 1: A diagram describing the physics of wake redirection. The turbine rotors are shown as viewed from above and are represented as black lines. The top diagram shows a turbine under normal operation, and the bottom diagram shows one with yaw misalignment causing wake redirection.

Wind turbine wake effects lead to significant reductions in wind plant efficiency while also elevating fatigue loads of internal turbines leading to overall increases in cost of energy.

Wakes can be "redirected" by misaligning the rotor thrust vector with the wind vector by applying rotor yaw misalignment (see Figure 1). Normally, yaw misalignment is undesirable due to reduced energy capture, but the benefit of reducing wake effects is thought to provide a net increase in power production. This is a wind-plant-level control strategy, different from today's control systems in which each turbine tries to capture as much energy for itself with no regard to the other turbines in the plant.

In this work, we tested wake-redirection control by performing numerical experiments with high-fidelity computational fluid dynamics (CFD) simulations of the proposed 25-MW Fishermen's Atlantic City Windfarm (FACW).

Our simulations show that wake-redirection control has the potential to create significant increases in efficiency, but the impact on fatigue loads requires further study.

Method

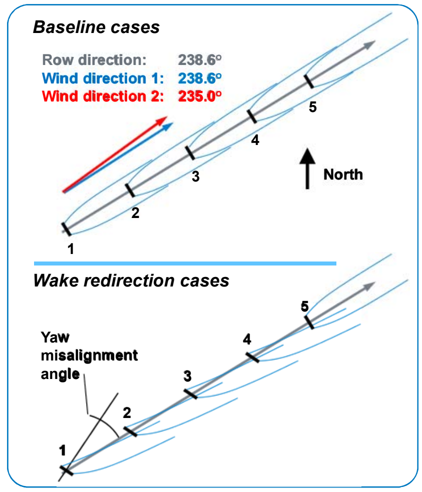

Figure 2: The layout of the simulated Fishermen's Atlantic City Windfarm (as viewed from above). The black lines denote turbine rotors; the blue lines denote the wakes. The top panel depicts the baseline cases in which no wake redirection is applied, and the bottom panel depicts the setup of the redirection cases.

Simulation

- **We used large-eddy simulation (LES), a type of CFD that resolves turbulence in the flow (i.e., atmospheric inflow and wake turbulence).**
- **Each 15-minute simulation was computed on 1,800 computer cores over 60-70 hours (125,000 CPU-hours) on the National Renewable Energy Laboratory's Peregrine high-performance computing system.**

Site

- **Fishermen's Atlantic City Windfarm is a proposed offshore wind plant with five 5-MW turbines off of Atlantic City, New Jersey.**
- **The turbines are arranged in a single row and spaced 9.1 rotor diameters (about 1 km) apart.**
- **A predominant wind direction is from the southwest, well aligned with the turbine row.**

Numerical Experiment

- **The inflow wind used in the simulations is from the southwest and has a speed of 9 m/s and a turbulence intensity of 5%, which are common conditions for flow from this direction.**
- **Two inflow directions are tested: i) row aligned and ii) misaligned with the row by 3.6° (see Figure 2).**
- **For each inflow direction, a baseline simulation was performed with the turbines aligned with the wind, and then a series of wake-redirection cases were simulated in which a common yaw misalignment angle was applied to turbines 1-4. Turbine 5 does not wake other turbines, so yaw misalignment is not necessary.**
- **Power and out-of-plane blade bending moment were analyzed.**

Results

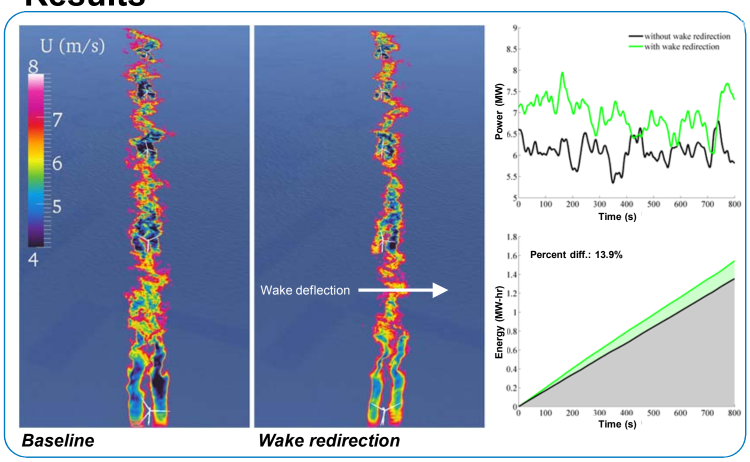

Figure 3: The color images at left compare contours of instantaneous velocity (U) in the turbine wakes with and without wake-redirection control. Wake deflection is clearly visible in the wake-redirection case. The line plots compare the power production and energy capture over an 800-s period of the baseline and wake-redirection cases.

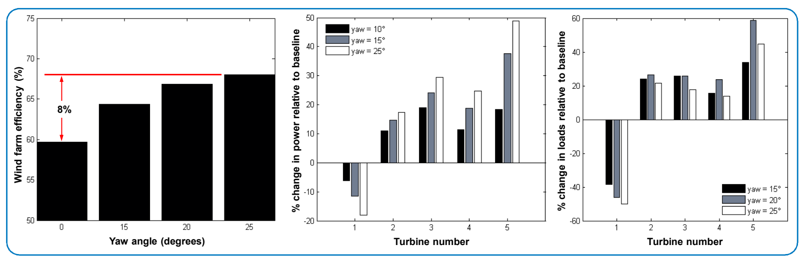

Figure 4: The effects of wake-redirection control for the row-aligned wind case. (Left) Wind plant efficiency as a function of yaw misalignment angle of turbines 1-4 for this wind condition. (Middle) Percent change in power production of each turbine relative to the baseline (no redirection) case. (Right) Percent change in root-mean-square blade flapwise bending loads for each turbine relative to the baseline case.

Key Results

- **Simulations showed that for the tested wind conditions (relatively low turbulence intensity characteristic of offshore and below-rated wind speed), wake redirection control has significant benefits for power production (see Figure 3). For the row-aligned wind case, an 8% increase in plant efficiency was observed (see Figure 4 - left). For the offset wind case (not shown), a 10% increase was observed.**
- **Significant yaw error is necessary to provide any significant wake redirection. Values in the range of 15 to 25 degrees of misalignment are typical.**
- **The first turbine in the row experienced a decrease in power production, but all subsequent turbines experienced a significant increase, especially the last turbine in the row that had no yaw misalignment (see Figure 4 – middle).**
- **Fatigue loads (see Figure 4 – right)**
  - **The first turbine in the row may experience a load increase or decrease depending on yaw misalignment direction. One direction counteracts vertical shear-induced fatigue giving a net decrease in fatigue loads, and the other direction adds to the shear-induced fatigue.**
  - **Turbines 2-5 can experience a fatigue load increase when redirection changes the situation from full waking to partial waking, but this is not a common case. Individual blade pitch control holds promise in mitigating the elevated fatigue loads.**
  - **Fatigue loads may decrease when redirection completely unwakes turbines 2-5.**

Conclusions

- **Wake redirection has a demonstrated potential to increase wind plant efficiency**
  - **For a given watersheet area, more power**
  - **For a desired power, less watersheet area/fewer turbines required**
- **We observed 8%-10% increases in efficiency when the wind is in the general row direction. We estimate that for the 9 m/s, 5% turbulence intensity component of the wind distribution, this translates to a 1.5% increase in annual energy production (AEP), but more simulations over a wider variety of conditions are required to better quantify these AEP increases.**
- **Certain wind directions combined with wake-redirection control may increase fatigue loads, but other directions may decrease them. Studying the average effect of redirection on a variety of different loads over more wind directions is necessary to fully understand changes to fatigue loads.**
- **Wake redirection would have greater benefits in larger wind farms with many rows and multiple waking directions, and possibly smaller turbine spacings.**
- **Wake-redirection control would be fairly straightforward to implement because no inter-turbine communication is necessary; each turbine needs knowledge of only the wind plant layout and wind direction. Such a control scheme could be retrofitted on the existing fleet.**

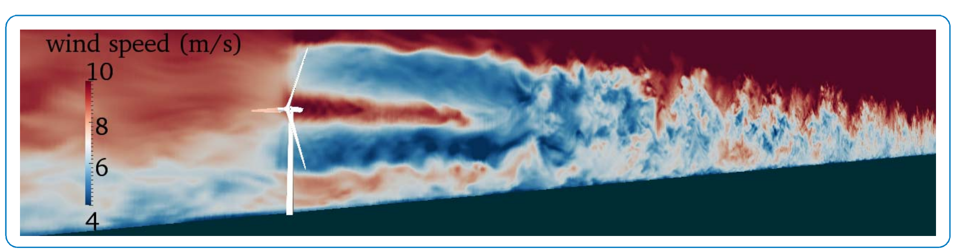

Figure 5: A contour of streamwise instantaneous velocity in the wakes along the simulated Fishermen's Atlantic City Windfarm row of turbines. The turbulent, unsteady nature of the wakes is clearly visible.

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory. Funding for the work was provided by the DOE Office of Energy Efficiency and Renewable Energy, Wind and Water Power Technologies Office.

This work was funded through the U.S. Department of Energy Offshore Advanced Technology Demonstration Project Program. Computations were performed on the National Renewable Energy Laboratory's Peregrine high-performance computing system.

AWEA Offshore WINDPOWER Conference & Exhibition
Atlantic City, New Jersey
October 7-8, 2014
NREL/PO-5000-62763