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The scaling of wind farm shadows and their consequences for energy generation

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Wind energy can play a fundamental role in the transition towards near-zero emissions energy systems. Wind farms are composed by groups of turbines that transform kinetic energy from the wind into grid electricity. Each wind turbine produces a decrease in wind speed, caused by the extraction of energy, and commonly known as wake. Isolated turbine wakes have been extensively studied, specially to maximize the production of power when they are placed in a farm. However, much less attention has been given to the shadows (or wakes) that full wind farms can create, and the consequences derived from them.

Our study is focused on addressing two main questions regarding wind farm shadows. First we assess how wind farm shadows and electricity generation scale with the farm size. Second we determine how far apart should neighboring farms be to ensure negligible effects to each other. For that, we performed simulations with the Weather Research and Forecasting model using the wind farm parameterization. We ran five different wind farm sizes located over the United States wind belt and, three runs without the farm that composed an ensemble control for comparison. Simulations had two nested domains with resolutions of 9km and 3km, and were run for the winter season 2013-2014.

Wind farm shadows appear further down from the perimeter of the wind farm, with larger lengths than the wakes retrieved for isolated turbines. We found that farm shadows length increases with the wind farm size, but asymptotes to lengths between 65-85km when the farm width approaches $\sim$100km. Instead, the density of electricity generation has an inverse correlation with the farm size increase, until it asymptotes towards 1W/m2 when the farm width is around 100km, as well. Yet even small wind farms generated shadows which are longer than the recovery length scales of the flow behind an individual turbine.

We further quantified the shadow extension for different farm sizes, and analyzed the power loss that a large wind farm can potentially cause to a small wind farm when it is located at different distances from the larger farm edge. For that we placed a small wind farm (9km x 9km) at 12km, 24km, 36km, and 48km from the edge of a larger farm (81km x 81km). The power extracted by the small wind farm decreased for each distance respectively to 13.3%, 7.9%, 5.3% and 3.3% of the power of an isolated farm.

Results from this study indicate that the efficiency in electricity generation from the wind does not only depend on the wind farm location and the layout of individual turbines, but also on the interactions that may exist between neighboring farms. This highlights the need to quantify wind farm shadows and consider their implications during the planning and design phase of siting new farms.