The warmth of wind power

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As wind turbines harvest energy, they redistribute heat in the lower atmosphere. Farmers have been exploiting the effect for decades.

This past year, the US generated 300 billion kilowatt-hours from wind turbines. That's 7.3% of the country's electricity demand, more power than is produced by any other renewable technology, including hydroelectricity. Although the turbines don't pollute the air with greenhouse gases, many recent studies conclude that they nonetheless warm the lower atmosphere near the ground—albeit temporarily and at night.

Wind turbines now reach heights of 300 m, with each blade 50 m in length—half a football field. The US has about 60 000 turbines and that number will increase as they are deployed in clusters up to thousands per county to reach future power targets. As they harvest kinetic energy, those turbines reduce wind speeds and introduce wake turbulence, which in turn alters the exchange of heat, moisture, and momentum between Earth's surface and the lower atmosphere. Curiously, the effects don't appear limited to the turbines' immediate vicinity; they are detectable tens of kilometers downwind. Understanding wind turbines' effects on the environment is important as they become increasingly common fixtures in our landscape.

Power from the wind

Differences in solar heating between Earth's equator and its poles give rise to pressure gradients that produce the planet's wind currents. Friction with the surface slows them. Those balancing effects help maintain our climate. The influence of friction is particularly strong in the lowest 1–3 km, where about half of all turbulent atmospheric dissipation occurs. Wind turbines are therefore contained in a column of air that naturally dissipates atmospheric power at an average rate of about 1 W/m^2.

Let's put that average input power in context. In 2018 the US electricity consumption rate was about 0.07 W/m^2. Wind power could meet a substantial fraction of that rate, but doing so would require covering a significant portion of the nation's land surface with turbines. Operational US wind farms currently occupy less than 1% of the country's land area and generate electricity at rates between 0.5 and 1.5 W/m^2. (The rate has a wide spread because of several factors, including the farms' sizes, turbine density, and how windy different areas are.) Still, the comparability of the dissipation and generation rates is striking and evidence of the farms' efficiency at extracting energy from the wind.

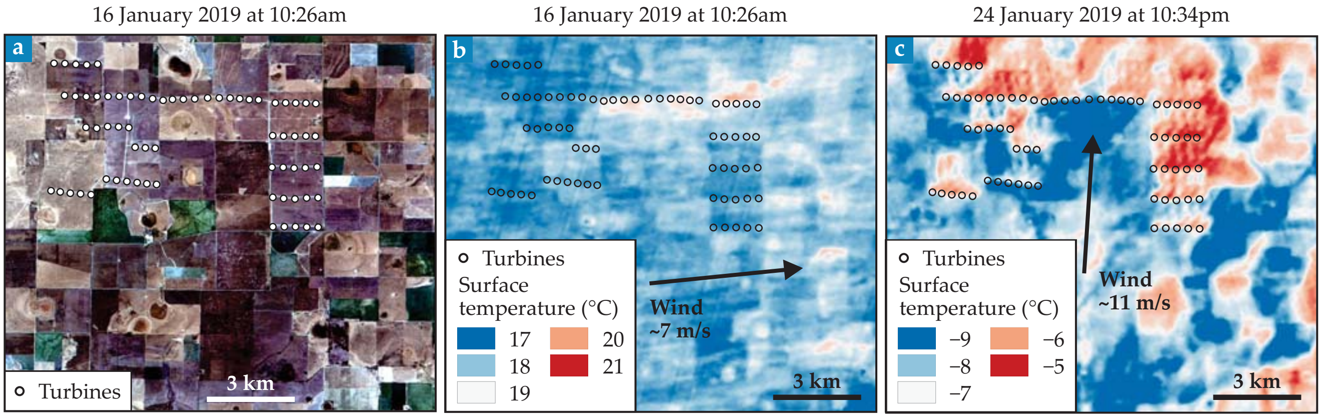
Redistributing heat

Wind turbines alter the climate through atmospheric mixing—by redistributing heat in the lower atmosphere, which is completely unrelated to the mechanisms of climate change. The natural differences in atmospheric mixing between day and night strongly influence the turbines' effect on the downwind climate. During the day, solar radiation heats the ground surface, which drives convection from the ground. The process homogenizes wind speeds, air temperature, and humidity to heights of 1–3 km, well above the physical extent of the turbines. The upshot is that wind turbines operating during the day are enveloped in an already well-mixed column of air and have little effect on the surface temperature.

At night, in the absence of solar-driven convection, the atmosphere is typically not well mixed above 50–150 m. That thin layer of calm air buffers the atmosphere from surface friction and allows vertical gradients in wind speed, temperature, and humidity to develop. Those nighttime conditions are well known in meteorology. As wind power is roughly proportional to the cube of the wind speed, there are clear advantages to utilizing longer blades, taller towers, and elevated topography to reach the faster winds aloft. Engineered to extract kinetic energy rather than redirect the winds around them—like the canopy of a tree—the slowing of the wind steepens the vertical wind-speed gradient, dramatically increasing the vertical mixing rates of higher-altitude air with air near the surface. Other factors, such as the turbines' orientation in rows and the wind farm's area, can influence the extent and magnitude of the changes. When that typically warmer, drier air from aloft is carried downward and mixed in with the surface air, surface temperatures increase.

More substantial climatic effects are therefore expected at night than during the day, even from the same turbines at the same location with the same incoming wind speeds. Day–night differences have been discussed in nearly a dozen studies using surface- or space-based observations over Texas, Iowa, Illinois, and California. Directly attributed to turbine–atmosphere interactions, the effects include differences in temperature, turbulence, and evaporation rates. Also measured abroad, the effects included slower wind speeds and increased turbulence extending 50–75 km downwind of Germany's offshore wind plants.

The recent release of several free public data sets now makes assessing wind power's surface warming relatively straightfor-



NASA'S *LANDSAT 8* SATELLITE measured the surface warming effect from wind power over a northern Texas location (34.77° N, −102.05° E) in the winter of 2019. **(a)** The daytime image (16 January, 10:26am) shows how the 100 km^2 region would appear from above to the human eye. **(b)** A coincident surface-temperature map is shown of the area at the same time. **(c)** One week later (24 January, 10:34pm), the satellite measured night surface temperatures in the region. (Data from Lee Miller.)

ward. The US Geological Survey maintains the US Wind Turbine Database, which includes geospatial data and technical specifications on about 60 000 operational US wind turbines. Data from NASA's *Landsat 8* satellite is also free and publicly available. Although primarily used for monitoring vegetation, *Landsat 8* also measures ground surface temperatures—or, more specifically, emissivity in the IR—at a spatial resolution of 8100 square meters.

Imaging local heat

Over the past seven years, *Landsat 8* has acquired 306 daytime images and 32 nighttime images over northern Texas. After filtering the data of cloudy conditions when the surface is invisible to the satellite, I examined images taken during the winter of 2019. The two 16 January 2019 daytime images, shown in the figure's panels a and b, are typical: No warming effect is visible in that day's temperature map (panel b). A nighttime warming effect, however, is apparent in panel c. That image was captured at 10:34pm on 24 January—the earliest nighttime snapshot of the region since 16 January.

With below-freezing temperatures and northward winds moving at 11 m/s at the height of the turbines, the 2–4 °C warming extended several kilometers downwind of the turbines and became more spatially extensive with successive downwind rows. That downward entraining of warmer air does not likely occur every night downwind of every turbine, though. (Indeed, no warming effect was evident in the nighttime image on 9 January 2019, a week earlier.)

The precise conditions required to create the warming effect are unclear, so I am uncertain how routine or widespread they are in Texas or elsewhere, especially given the limited availability of nighttime *Landsat 8* observations. The effect is also likely dependent on near-surface turbulence and wind speed. Nonetheless, other observational studies using coarser (1×1 km^2) resolution satellite data over a different Texas wind farm estimated an annual nighttime warming effect of 0.3 °C. A modeling study estimated that effect closer to 0.6 °C, on average.

Although the link between wind power and warmer surface temperatures may come as a surprise, avocado, citrus, and apple farmers have operated airplane-like propellers on towers since the 1940s to minimize frost damage to their crops. A validation study in 1970 concluded that a "wind machine" warmed surface temperatures during spring nights by about 2 °C over an area of 20 acres. Other climatic effects, such as changes in evaporation and heat fluxes, may also occur downwind, but they are difficult to measure with satellite sensors.

All renewable technologies affect the climate insofar as they redistribute heat, momentum, and moisture to generate electricity. The warming effects of wind power should not be cause for immediate alarm. They will continue to occur—predominantly inside the wind-farm area—only for as long as the demand for turbine-based electricity exists. And scientific research on the topic is still in its infancy.

Wind power's relevance to climate goes beyond surface warming. The turbines also likely affect precipitation, as warm, dry air from above displaces cooler, more moist air at the surface and increases the rate of evaporation. But that issue is beyond the scope of this Quick Study. Few would question that 20 years from now, wind turbines will be much more pervasive than they now are in the central US—their number is currently growing by about 3000 each year. The opportunity for researchers is to understand the turbines' admittedly intermittent effects today to inform our land-use policies and environmental expectations in a wind-powered future.

Additional resources

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