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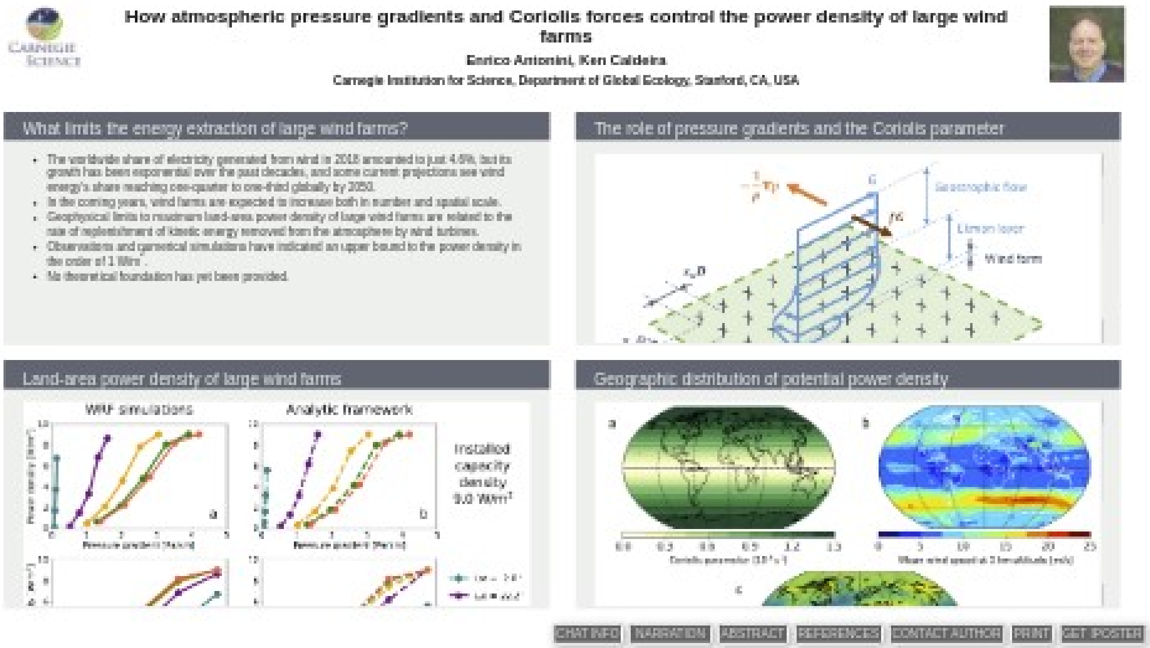

How atmospheric pressure gradients and Coriolis forces control the power density of large wind farms

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What limits the energy extraction of large wind farms?

The role of pressure gradients and the Coriolis parameter

Land-area power density of large wind farms

Geographic distribution of potential power density

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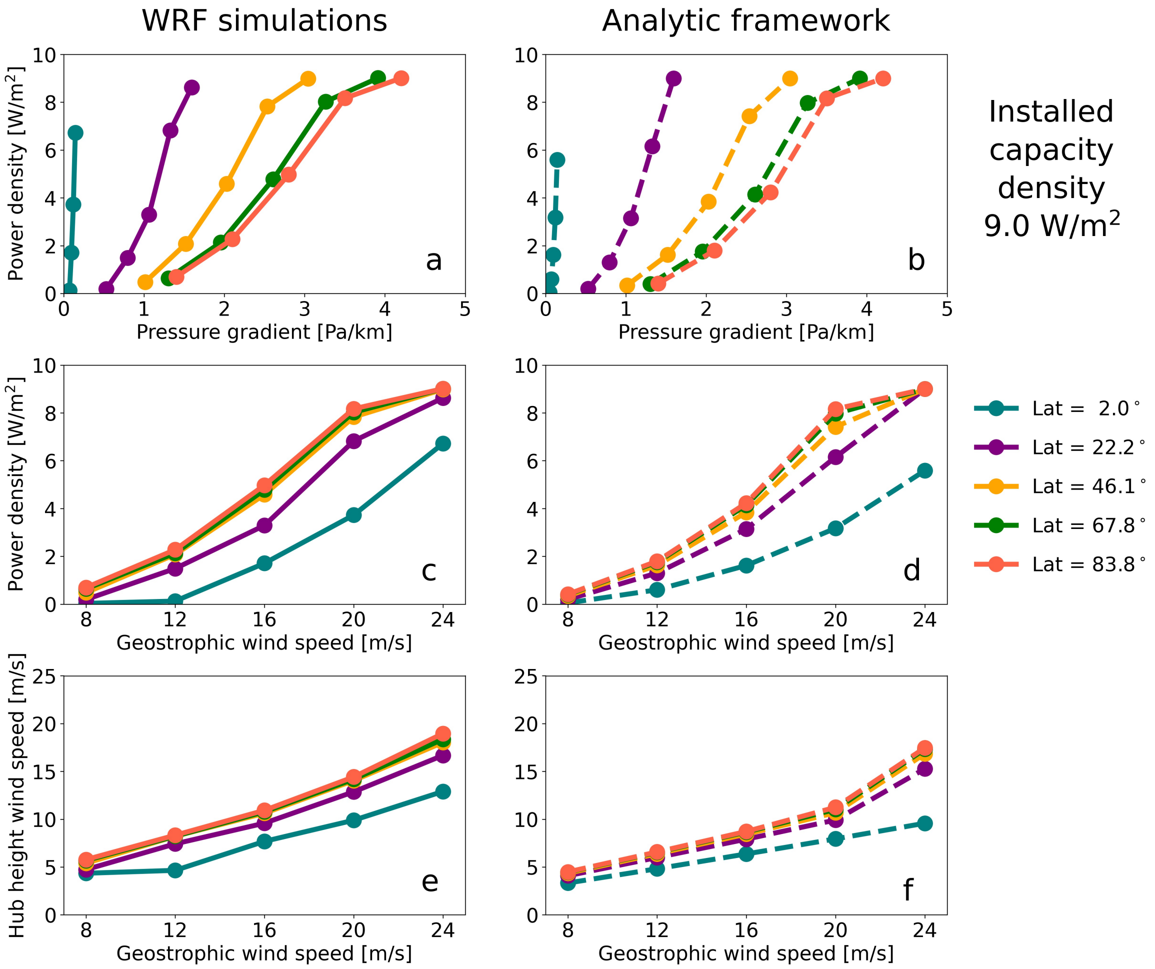
WHAT LIMITS THE ENERGY EXTRACTION OF LARGE WIND FARMS?

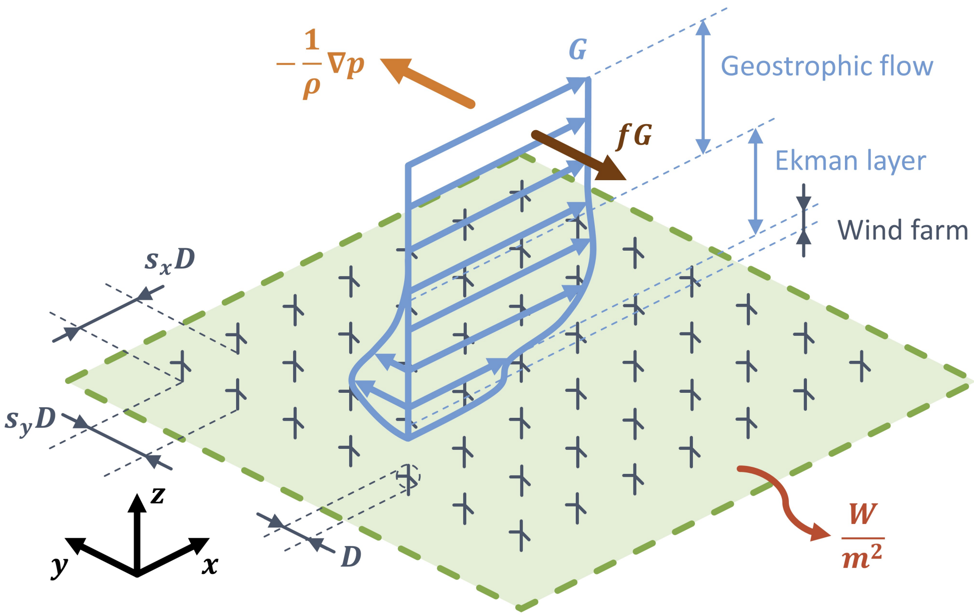
- The worldwide share of electricity generated from wind in 2018 amounted to just 4.6%, but its growth has been exponential over the past decades, and some current projections see wind energy's share reaching one-quarter to one-third globally by 2050.
- In the coming years, wind farms are expected to increase both in number and spatial scale.
- Geophysical limits to maximum land-area power density of large wind farms are related to the rate of replenishment of kinetic energy removed from the atmosphere by wind turbines.
- Observations and numerical simulations have indicated an upper bound to the power density in the order of 1 W/m^2.
- No theoretical foundation has yet been provided.

LAND-AREA POWER DENSITY OF LARGE WIND FARMS



Power density and hub height wind speed for a large wind farm with an installed capacity density of 9 W/m^2 as a function of the Coriolis parameter, *f*, (latitude-dependent) and pressure gradient or geostrophic wind. Left panels (a, c, e) show results from the atmospheric simulations conducted with the Weather Research and Forecasting (WRF) simulation tool, whereas right panels (b, d, f) show results from the analytic expressions. Panels a and b show power density values as a function of pressure gradient, panels c and d show the power density values as a function of geostrophic wind speed, and panels e and f show hub height wind speed as a function of geostrophic wind speed. The results are provided for the set of Coriolis parameters 0.05, 0.55, 1.05, 1.35, and 1.45 $\cdot$ 10^{-4} rad/s^{-1}, which corresponds to the set of latitudes 2.0, 22.2, 46.1, 67.8, and 83.8° N. The hypothetical wind farm considered has an installed capacity density of 9 W/m^2. The analytic treatment uses standard literature values for coefficients and includes no tunable parameters.

THE ROLE OF PRESSURE GRADIENTS AND THE CORIOLIS PARAMETER

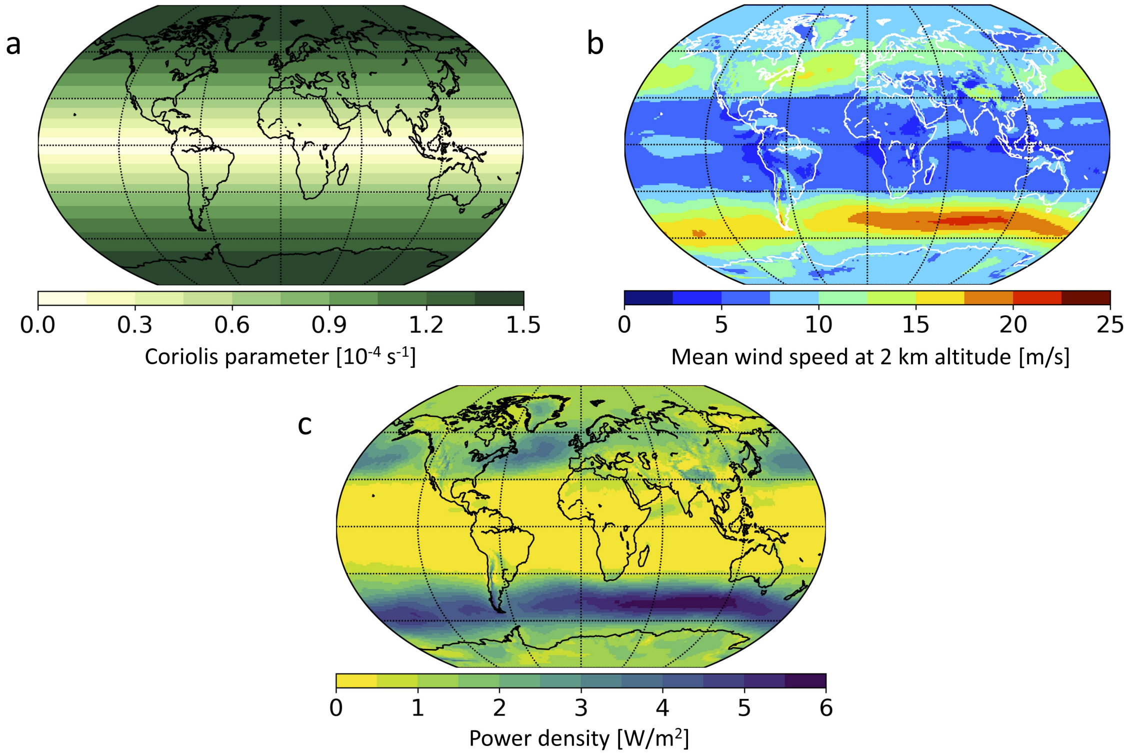


The geostrophic wind, G, is the result of the balance between the pressure-gradient force, $-1/\rho\,\nabla p$, and the Coriolis force, fG, where f is the Coriolis parameter. Wind turbines of diameter D are arranged on a regular grid with horizontal spacings of dimensions s_xD and s_yD. The power density of the wind farm is expressed in W/m^2.

The winds aloft, far enough from the wind turbine array, would not feel the surface drag and create a geostrophic balance: the pressure gradient would be orthogonal to the direction of wind flow and in balance with the apparent Coriolis force.

When winds close to the surface are slowed because of the drag, the apparent Coriolis force would be reduced and no longer balance the pressure-gradient force. The wind flow would no longer be orthogonal to the pressure-gradient force, and this force would then be able to impart energy to the system.

GEOGRAPHIC DISTRIBUTION OF POTENTIAL POWER DENSITY



Geographic distribution of the Coriolis parameter (a), geostrophic wind speed (b), and resulting power density for a large wind farm (c). The Coriolis parameter depends on the latitude and is straightforward to calculate. The geostrophic wind is estimated for 2019 from ERA5 reanalysis data at 2 km altitude above ground level. Given the spatial distribution of Coriolis parameter and geostrophic wind speed, the power density can be estimated with the analytic expressions.

ABSTRACT

The extraction of energy from the atmosphere by large wind farms is limited by its potential availability and replenishment rate. Although observations and numerical simulations have indicated an upper bound to the power density in the order of 1 W/m^2, no theoretical foundation has yet been provided. Here, we study the role of atmospheric pressure gradients and the latitude-dependent Coriolis parameter on the power density of large-scale wind farms by means of both numerical atmospheric simulations and an analytical framework. We illustrate that energy transport to regional-scale wind farms is primarily governed by horizontal pressure gradients and their interaction with the Coriolis force and turbine-induced surface drag within the latitude-dependent Ekman layer. Higher pressure gradients and lower Coriolis parameters promote a higher energy availability and, consequently, a higher potential power density, suggesting that the power density of regional-scale wind farms is largely resource- and geographic-dependent.

REFERENCES

Antonini, E.G.A., Caldeira, K., "Atmospheric pressure gradients and Coriolis forces provide geophysical limits to power density of large wind farms", Applied Energy, 281, 116048, 2021.

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