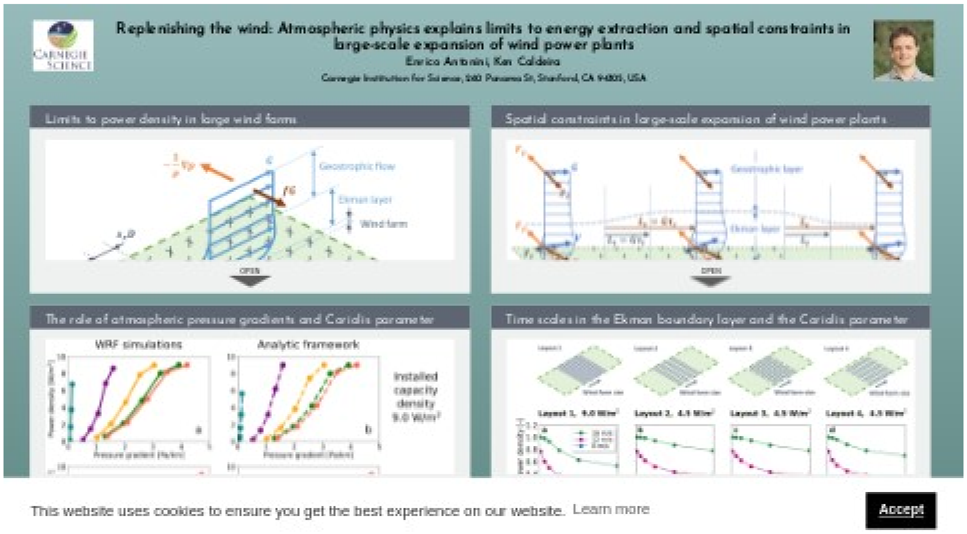
Replenishing the wind: Atmospheric physics explains limits to energy extraction and spatial constraints in large-scale expansion of wind power plants



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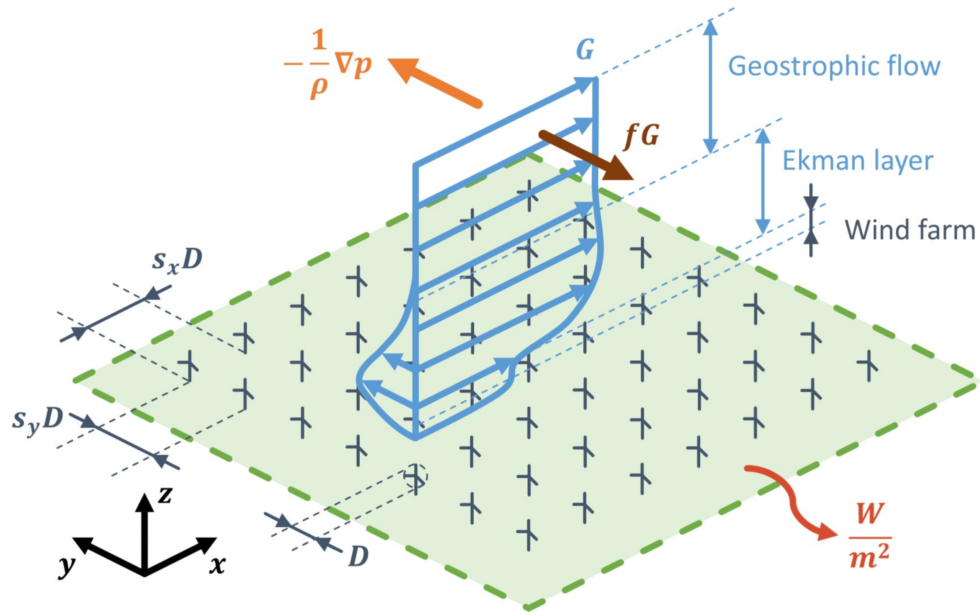
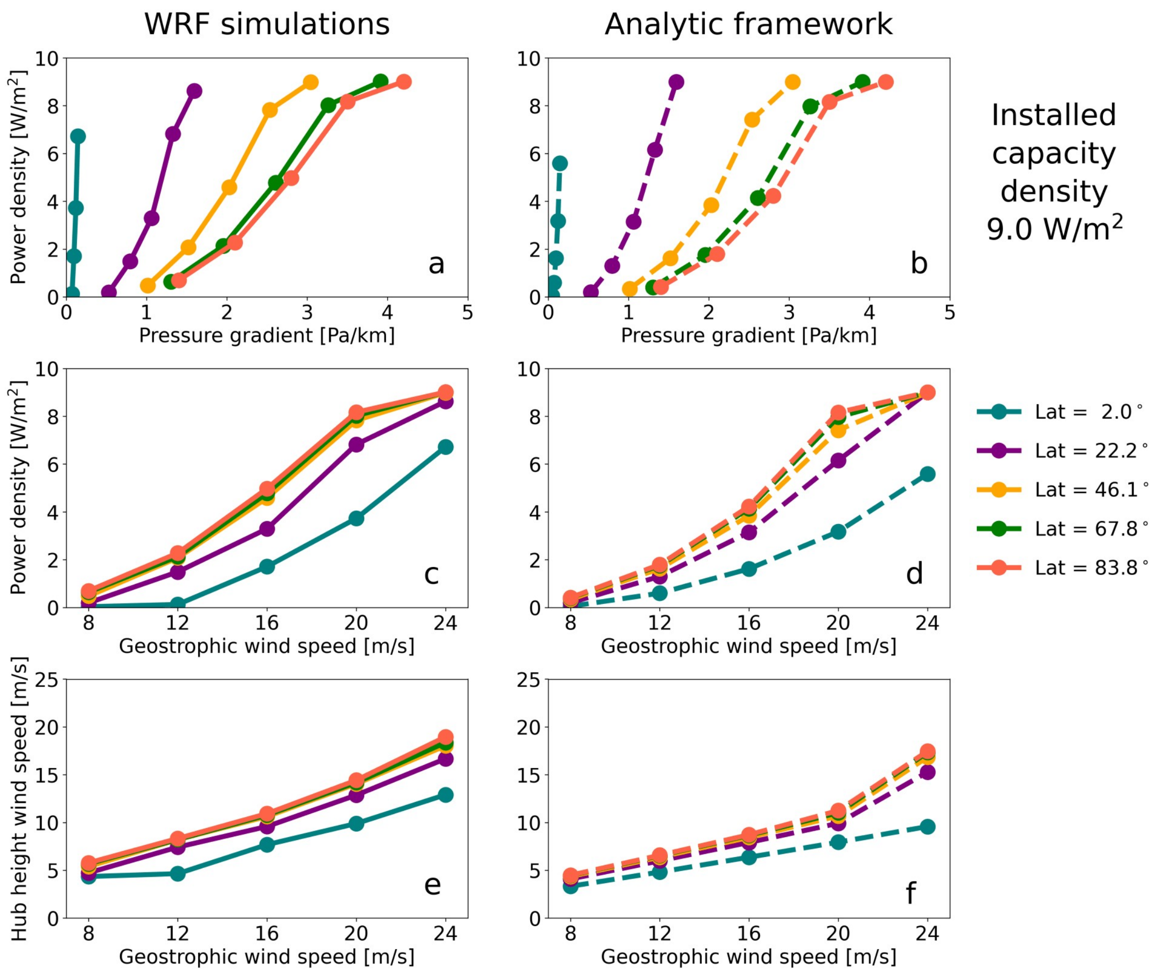
PRESENTED AT:

LIMITS TO POWER DENSITY IN LARGE WIND FARMS



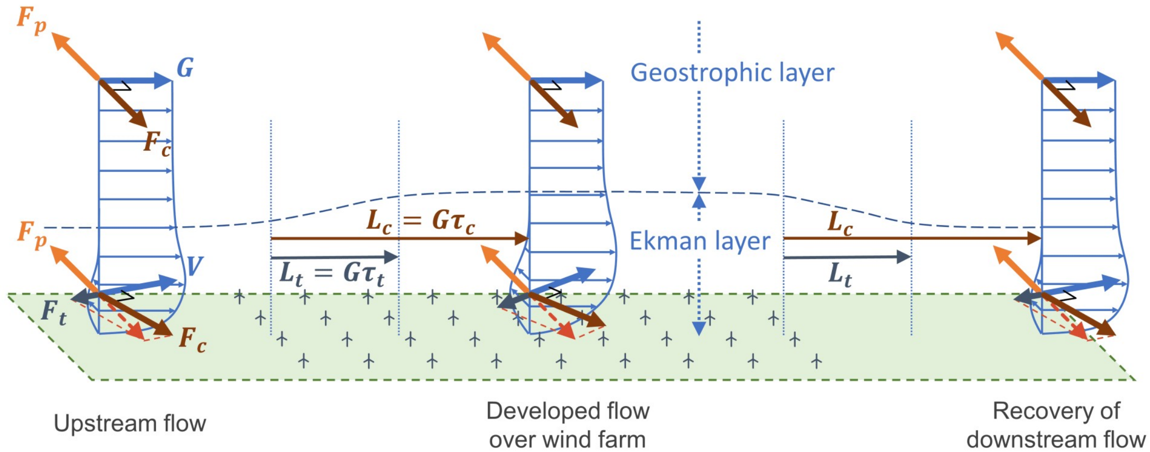
- The geophysical limit to maximum land-area power density of large wind farms is related to the rate of replenishment of kinetic energy removed from the atmosphere by wind turbines.
- Observations and numerical simulations have indicated an upper bound to the power density in the order of 1 W/m^2.
- Here, we study the role of atmospheric pressure gradients and the latitude-dependent Coriolis parameter in the power density of large-scale wind farms by means of both numerical atmospheric simulations and analytic expressions.

THE ROLE OF ATMOSPHERIC PRESSURE GRADIENTS AND CORIOLIS PARAMETER



- Here, we show the power density and hub height wind speed values resulting from the WRF simulations and the analytic expressions for a set of pressure gradients and Coriolis parameters.
- The numerical model and analytic expressions provide results with a high level of agreement, demonstrating that the mechanisms at play in the analytic solution largely govern the behavior of the fluid dynamical model.
- 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 higher energy availability and, consequently, higher potential power density, suggesting that the power density of regional-scale wind farms is largely resource- and location-dependent.

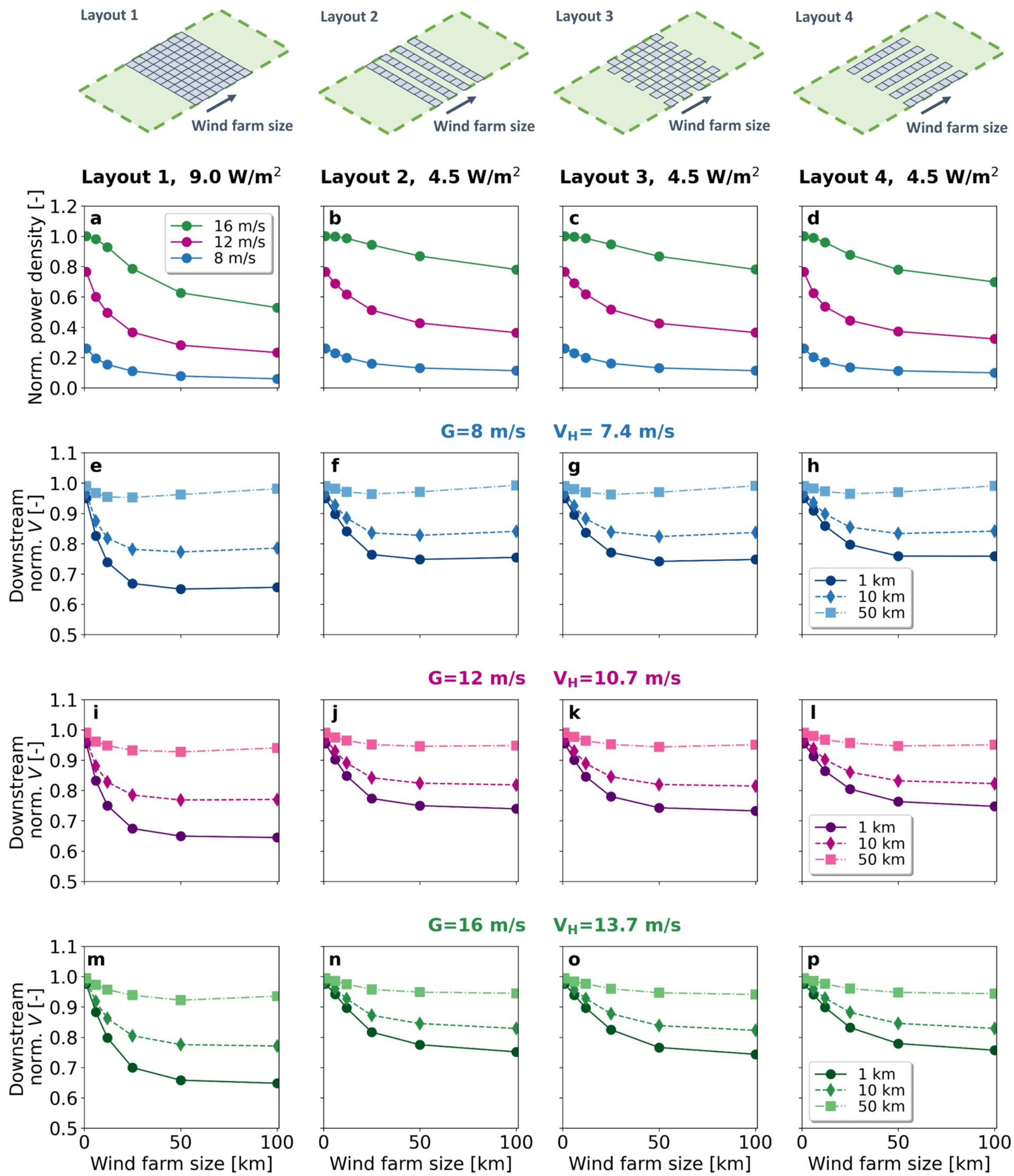
SPATIAL CONSTRAINTS IN LARGE-SCALE EXPANSION OF WIND POWER PLANTS



- The spatial scale of a wind farm affects both its mean generation per unit of land and the extension of wake shadowing on neighboring plants. As spatial scales increase, mean generation decreases and wake extension increases.
- Land-area power densities of small wind farms can exceed 10 W/m^2 and wakes are several rotor diameters in length. In contrast, large-scale wind farms have an upper-limit power density in the order of 1 W/m^2 and wakes that can extend several tens of kilometers.

- Here, we address two important questions: (1) How large can a wind farm be before its generation reaches energy replenishment limits, and (2) How far apart must large wind farms be spaced to avoid inter-wind-farm interference?
- We characterize controls on these spatial and temporal scale by running a set of idealized atmospheric simulations using the Weather and Research Forecasting (WRF) model.

TIME SCALES IN THE EKMAN BOUNDARY LAYER AND THE CORIOLIS PARAMETER



- Here, we show normalized average power density and normalized wind speed in the wind farm wakes as a function of wind farm size, turbine layout, and geostrophic wind speed. The wind speed is shown at three distances downstream of each simulated wind farm (1, 10 and 50 km) and it is normalized by its undisturbed value at the hub height.
- Time scales related to the forces at play can give a physical explanation to and characterize transitional scales in wind farm performance and wake characteristics.
- Within a turbulent time scale, most of the flow adjusts to the new surface roughness, whereas the flow becomes almost completely adjusted after a length given by the Coriolis time scale.

- Power generation and wind speed within and over the wind farm show that a time scale inversely proportional to the Coriolis parameter governs such transition, and the corresponding length scale is obtained by multiplying the time scale by the geostrophic wind speed.
- Wind farms smaller than this result in greater power densities and shorter wakes. Larger wind farms result instead in power densities that asymptotically reach their minimum and wakes that reach their maximum extent.

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ABSTRACT

When wind turbines are arranged in clusters, their performance is mutually affected, and the energy generation is reduced relative to what it would be if they were widely separated. Land-area power densities of small wind farms can exceed 10 W/m^2 and wakes are several rotor diameters in length. In contrast, large-scale wind farms have an upper-limit power density in the order of 1 W/m^2 and wakes that can extend several tens of kilometers. Here, we address three important questions: (1) What controls and limits the replenishment of kinetic energy removed from the atmosphere by large-scale wind farms, (2) How large can a wind farm be before its generation reaches energy replenishment limits, and (3) How far apart must large wind farms be spaced to avoid inter-wind-farm interference? We characterize limits to energy extraction and spatial constraints in large-scale expansion of wind power plants by running a set of idealized atmospheric simulations using the Weather and Research Forecasting (WRF) model. We illustrate that energy transport to large-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. We show that a length scale obtained by multiplying a characteristic time scale by the geostrophic wind speed defines at what size a wind farm hits energy replenishment limits. Wind farms smaller than this result in greater power densities and shorter wakes. Larger wind farms result instead in power densities that asymptotically reach their minimum and wakes that reach their maximum extent.

REFERENCES

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

[2] E.G.A. Antonini, K. Caldeira, "Spatial constraints in large-scale expansion of wind power plants", Proceedings of the National Academy of Sciences, Vol. 118, No. 27, p. e2103875118, 2021.