CARNEGIE SCIENCE

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

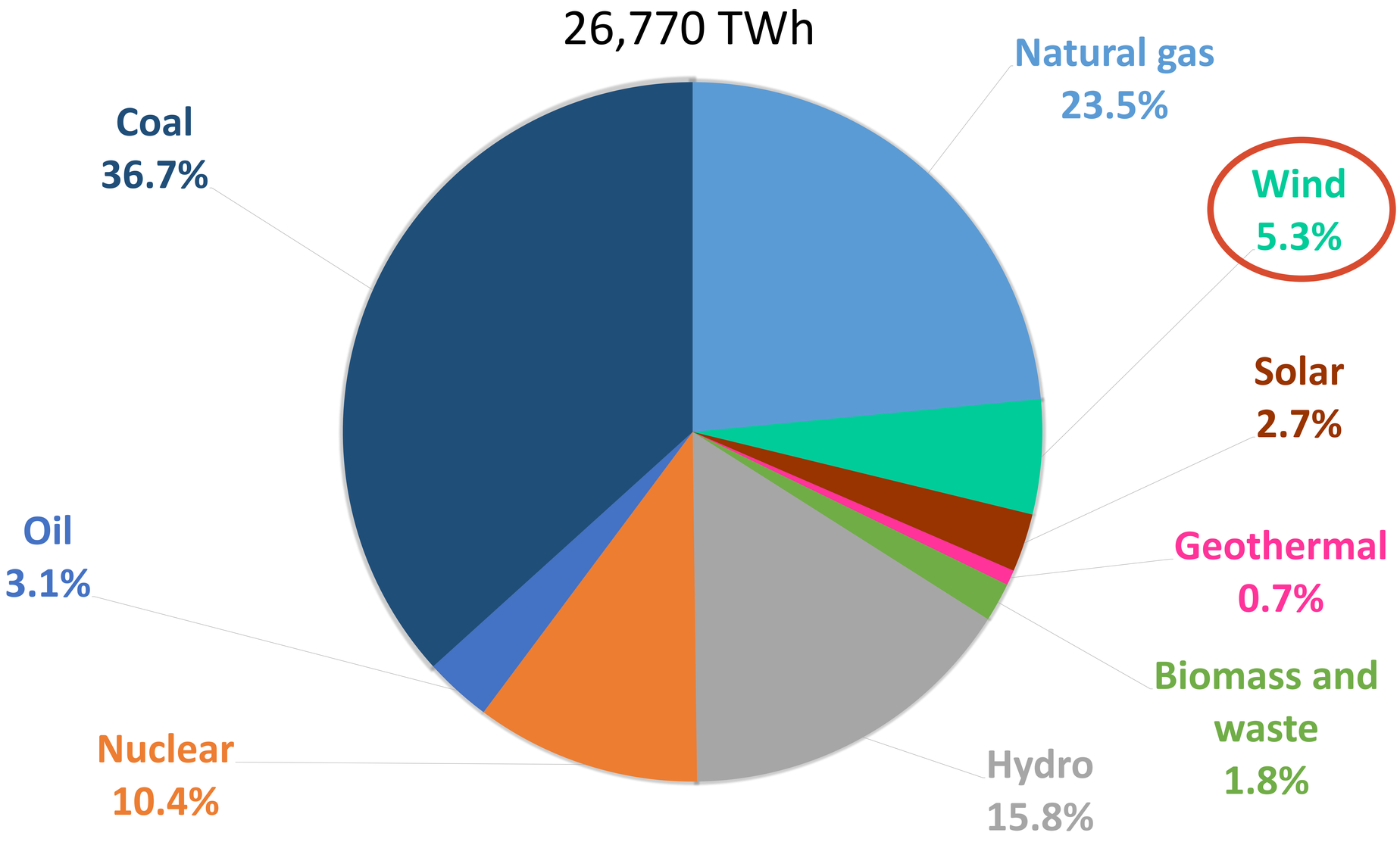
Theme 1: Wind Resource, Wind Farms and Wakes

Speaker: Enrico Antonini

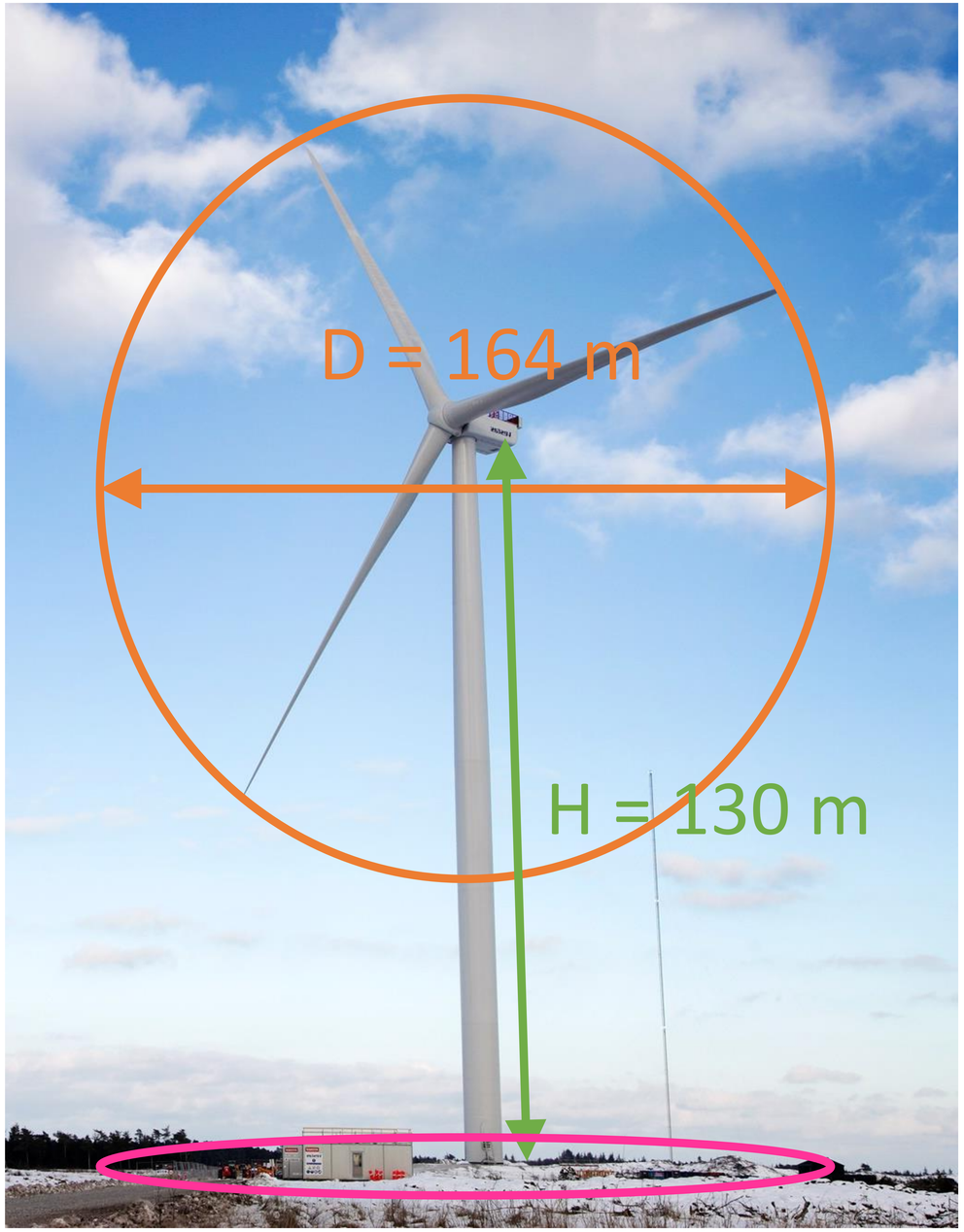
Authors: Enrico Antonini and Ken Caldeira

Why are we interested in large wind farms?

World electricity generation by source (2019)



How do we measure the performance of wind turbines/farms?



Vestas V164-9.0MW

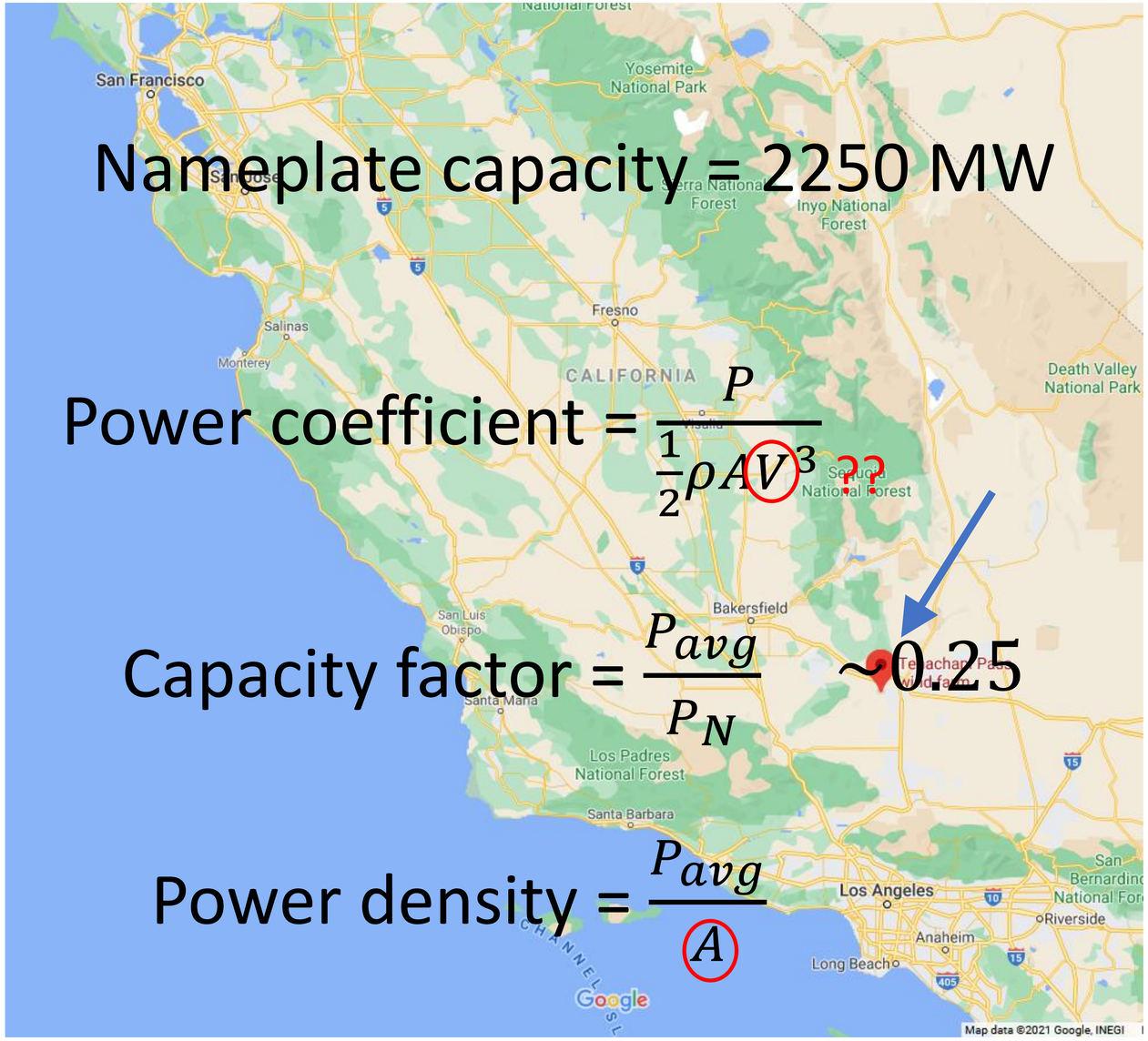
Nameplate capacity = 9 MW

Power coefficient = $\frac{P}{\frac{1}{2}\rho A V^3}$ ~0.35-0.45

Capacity factor = $\frac{P_{avg}}{P_N}$ ~0.2-0.6

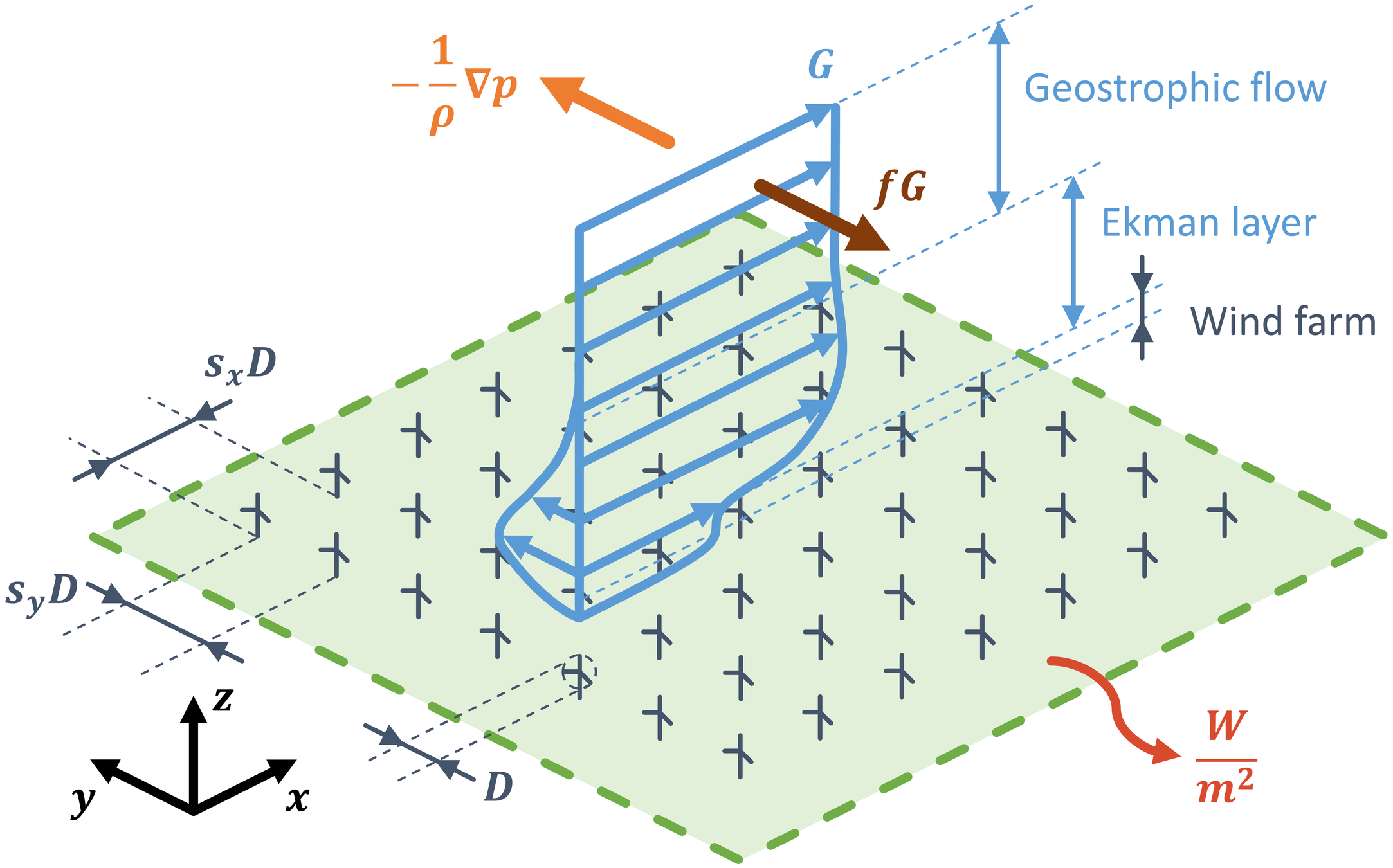
Power density = $\frac{P_{avg}}{A}$ ~100-200 $\frac{\mathrm{W}}{\mathrm{m}^2}$

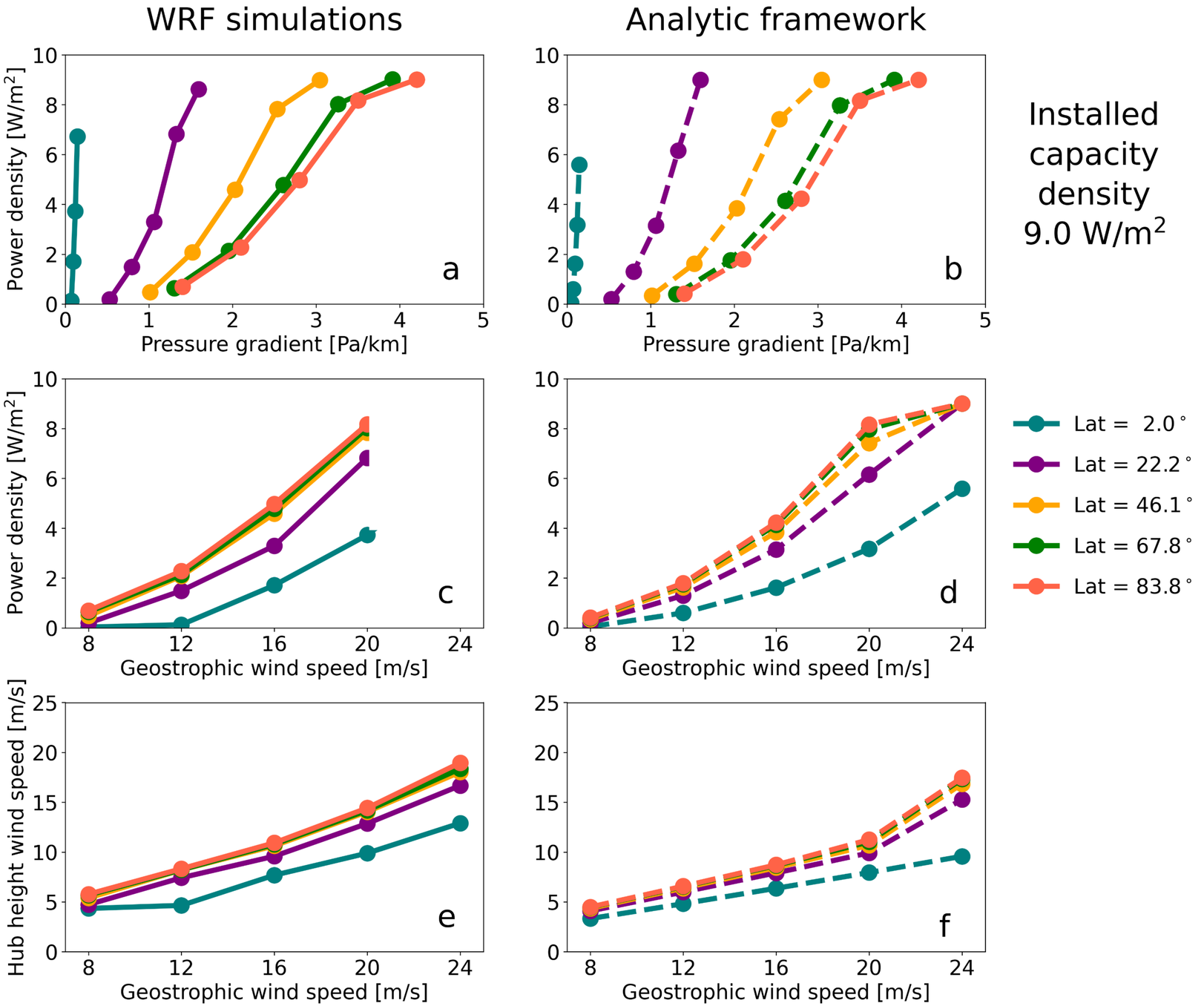
Tehachapi Wind Resource Area

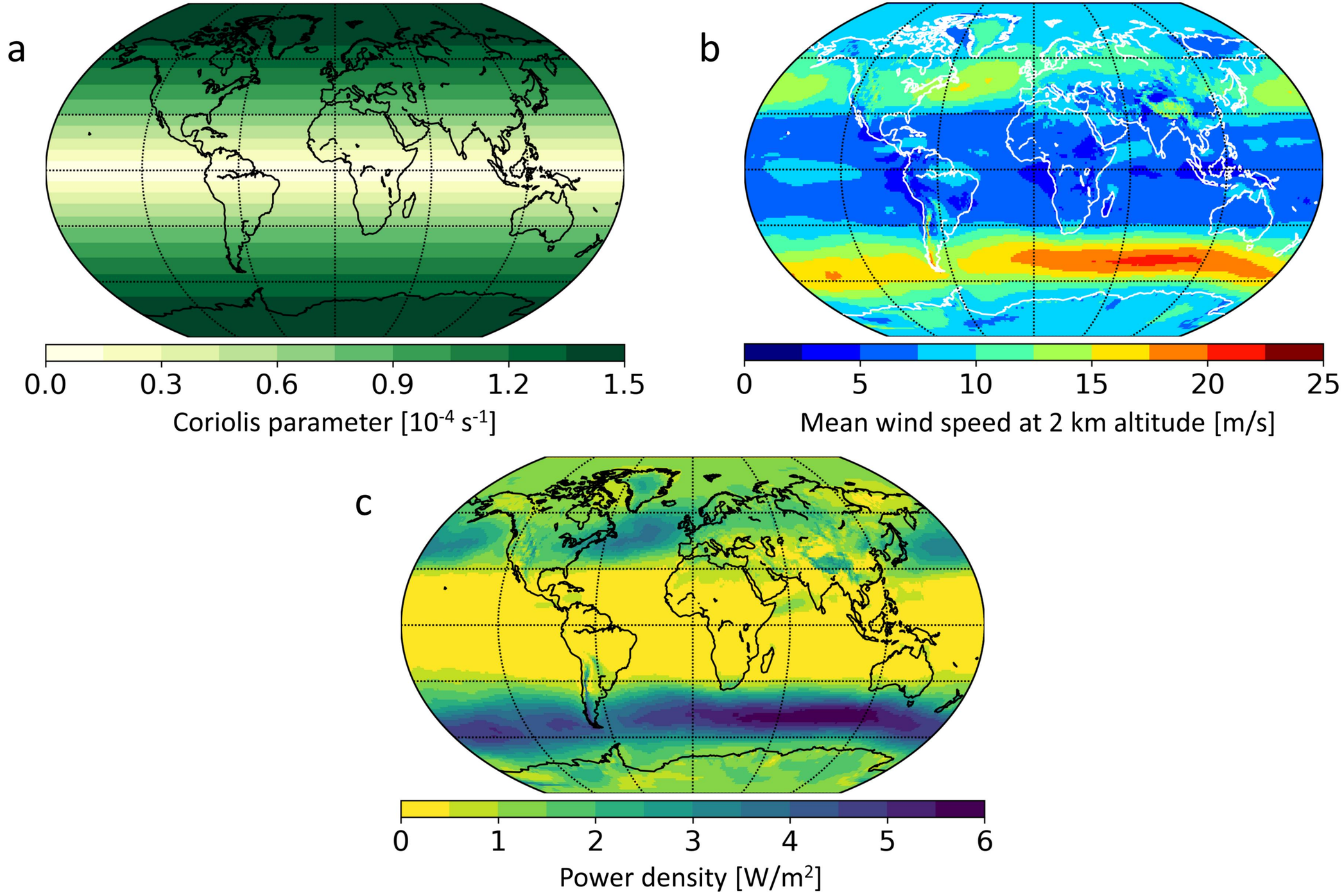


$$\text{Power density} = \frac{P_{avg}}{A} \quad \sim 2\ \frac{\text{W}}{\text{m}^2}$$

What controls and limits the energy extraction in large wind farms?


$-\frac{1}{\rho}\nabla p$
G
fG
Geostrophic flow
Ekman layer
Wind farm
$s_x D$
$s_y D$
D
z
y
x
$\frac{W}{m^2}$


WRF simulations
Analytic framework
Power density [W/m^2]
Pressure gradient [Pa/km]
Geostrophic wind speed [m/s]
Hub height wind speed [m/s]
a
b
c
d
e
f
Installed capacity density 9.0 W/m^2
Lat = 2.0°
Lat = 22.2°
Lat = 46.1°
Lat = 67.8°
Lat = 83.8°


a
0.0
0.3
0.6
0.9
1.2
1.5
Coriolis parameter [10-4 s-1]
b
0
5
10
15
20
25
Mean wind speed at 2 km altitude [m/s]
c
0
1
2
3
4
5
6
Power density [W/m2]

Key takeaways

- We provide a theoretical basis for upper limits of power density in large wind farms
- Interacting pressure-gradient, Coriolis and drag forces control the power density
- Pressure gradients within the Ekman layer supply energy to large wind power plants
- Energy does not originate from the overlying free troposphere
- The power density of regional-scale wind farms is resource- and location-dependent

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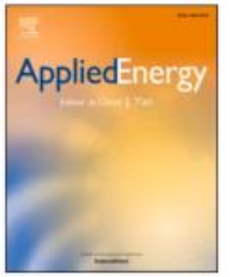

Atmospheric pressure gradients and Coriolis forces provide geophysical limits to power density of large wind farms

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HIGHLIGHTS

- We provide a theoretical basis for upper limits of power density in large wind farms.
- Pressure gradients within the Ekman layer supply energy to large wind power plants.
- Interacting pressure-gradient, Coriolis and drag forces control the power density.
- The power density of regional-scale wind farms is resource- and geographic-dependent.

Thanks for your attention!

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