CARNEGIE SCIENCE

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Geophysical constraints to large wind farm development

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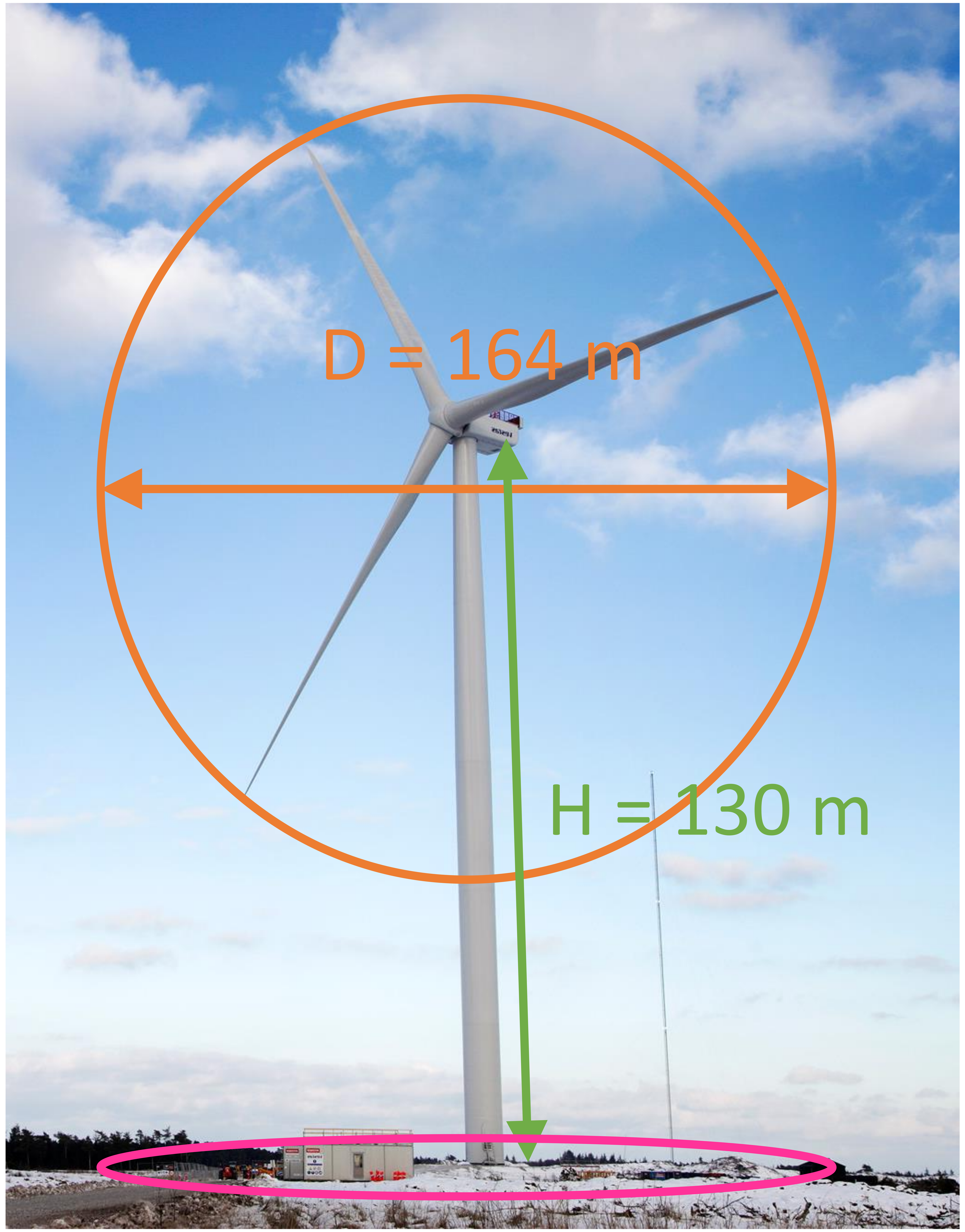
As wind farm size increases,
mean generation per unit area decreases



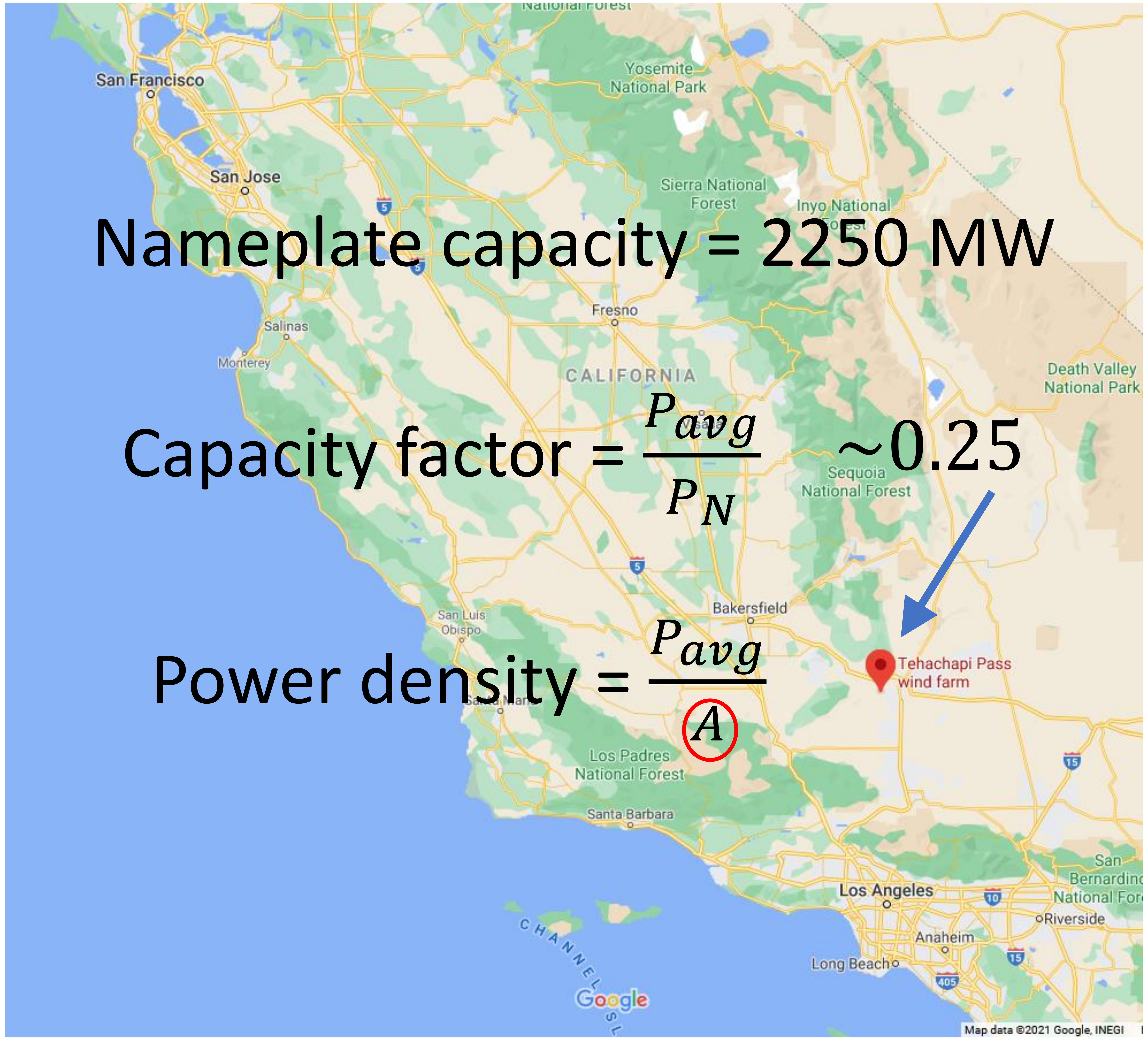
Vestas V164-9.0MW

Nameplate capacity = 9 MW

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

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

Tehachapi Wind Resource Area



Nameplate capacity = 2250 MW

Capacity factor = $\frac{P_{avg}}{P_N}$ ~ 0.25

Power density = $\frac{P_{avg}}{A}$

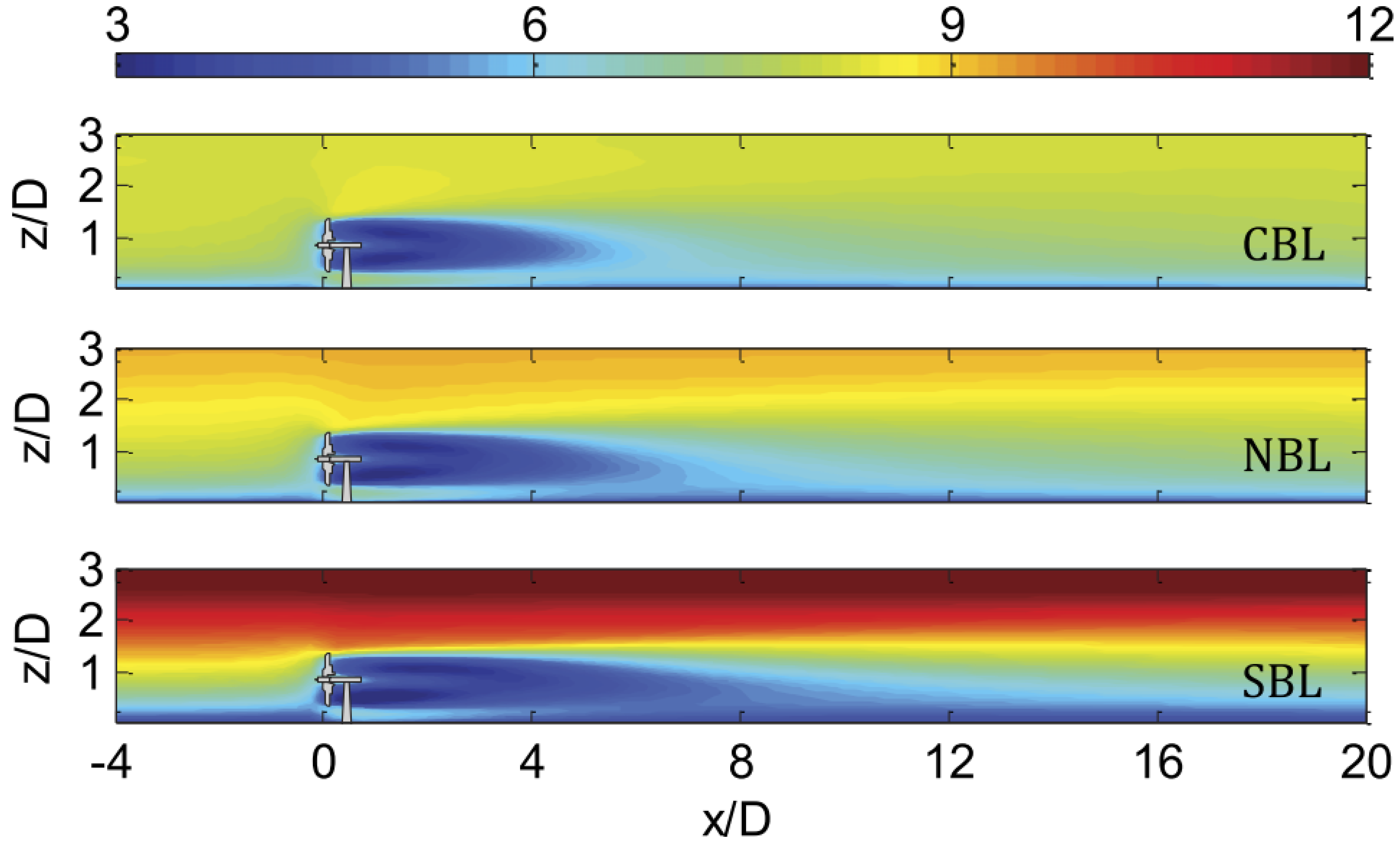
$$\text{Power density} = \frac{P_{avg}}{A} \quad \sim 2\ \frac{\mathrm{W}}{\mathrm{m}^2}$$

$$\sim 100 \frac{\mathrm{W}}{\mathrm{m}^2}$$

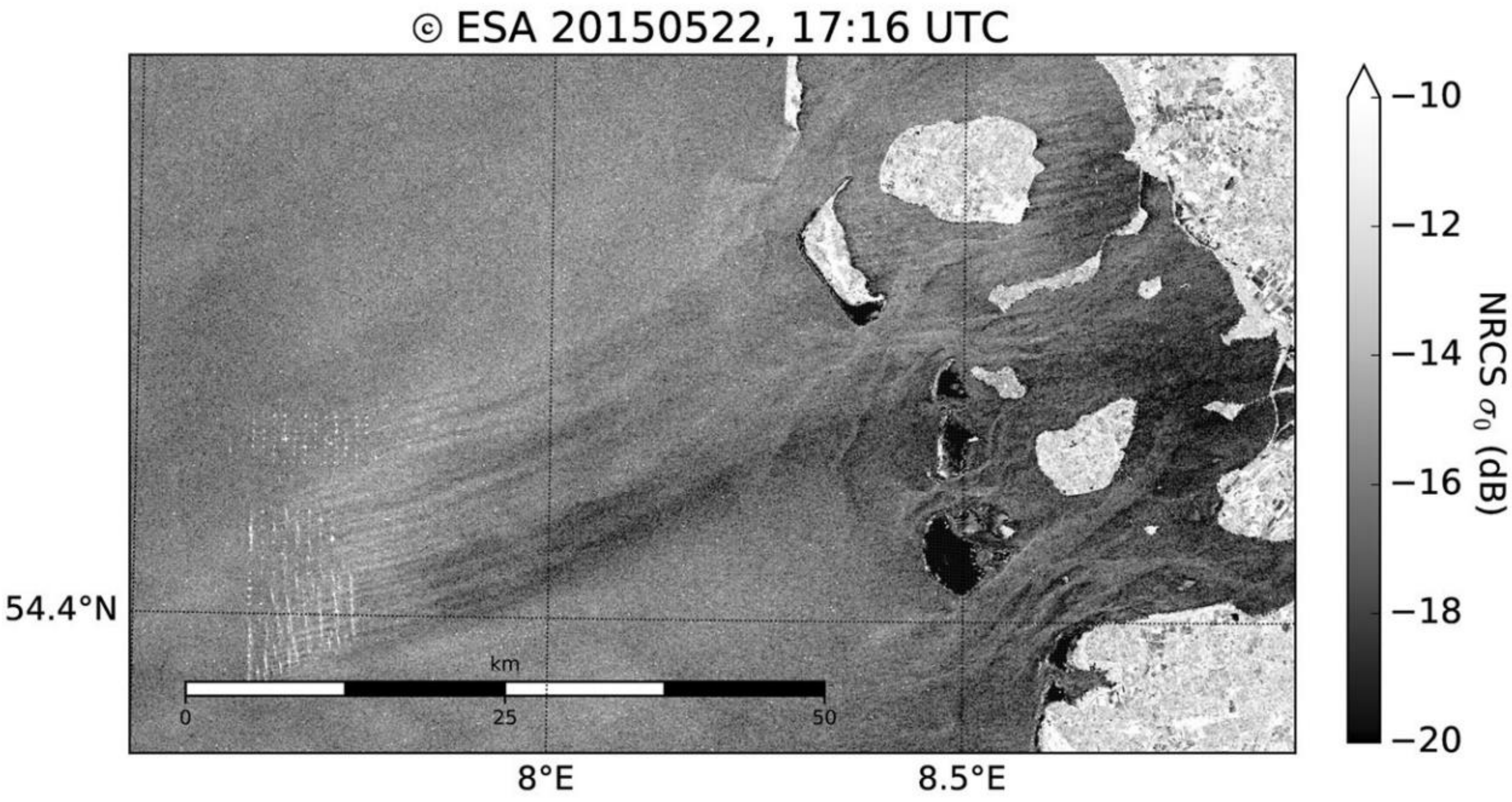
$$\sim 10 \frac{\mathrm{W}}{\mathrm{m}^2}$$

$$\sim 1 \frac{\mathrm{W}}{\mathrm{m}^2}$$

**As wind farm size increases,
wake extension increases**



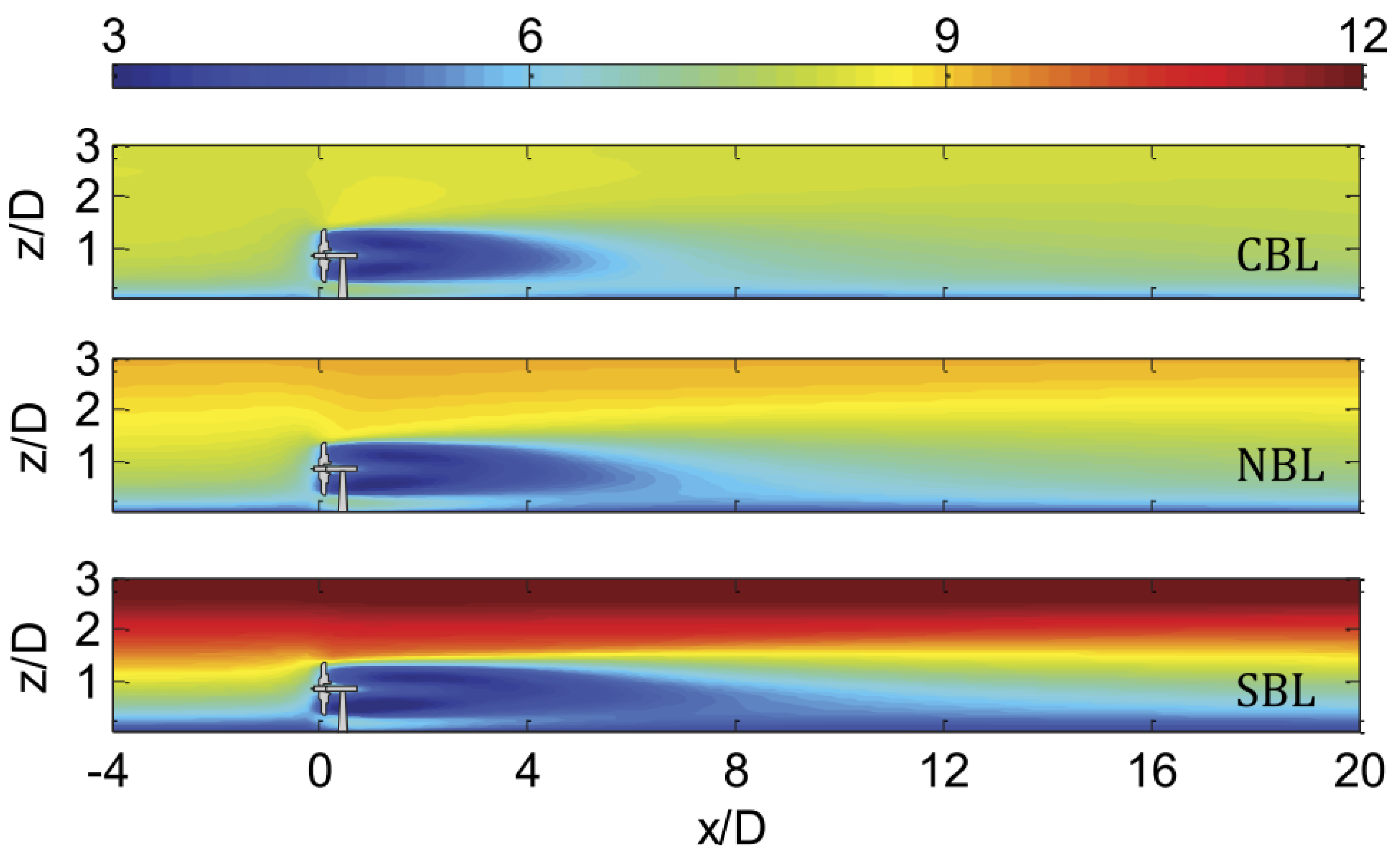
Abkar et al. (2015), Influence of atmospheric stability on wind-turbine wakes: A large-eddy simulation study



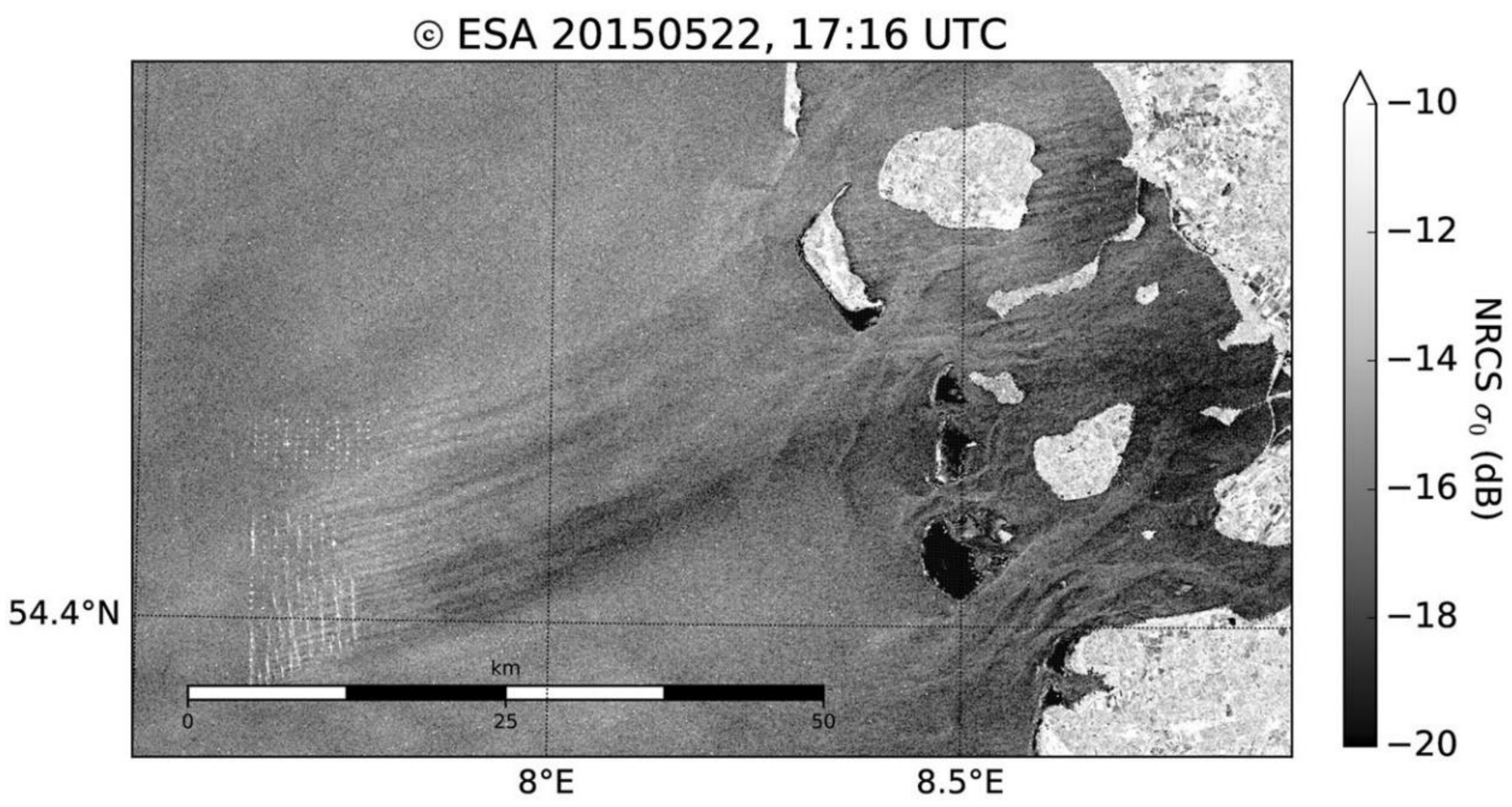
Platis et al. (2018), First in situ evidence of wakes in the far field behind offshore wind farms

~1 km

~10 km



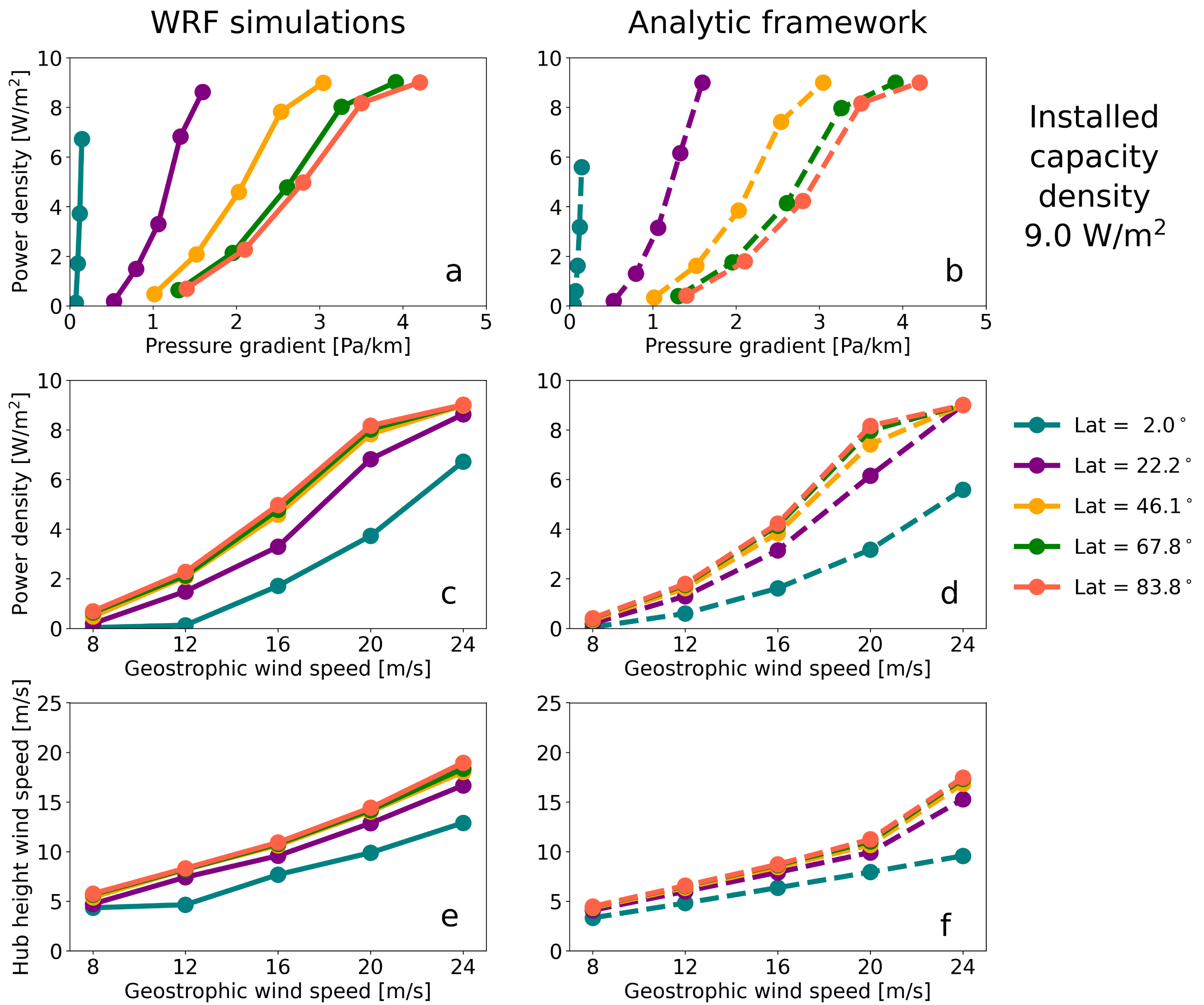
3
6
9
12
z/D
CBL
NBL
SBL
-4
0
4
8
12
16
20
x/D



© ESA 20150522, 17:16 UTC
54.4°N
8°E
8.5°E
NRCS σ_0 (dB)
−10
−12
−14
−16
−18
−20

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

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

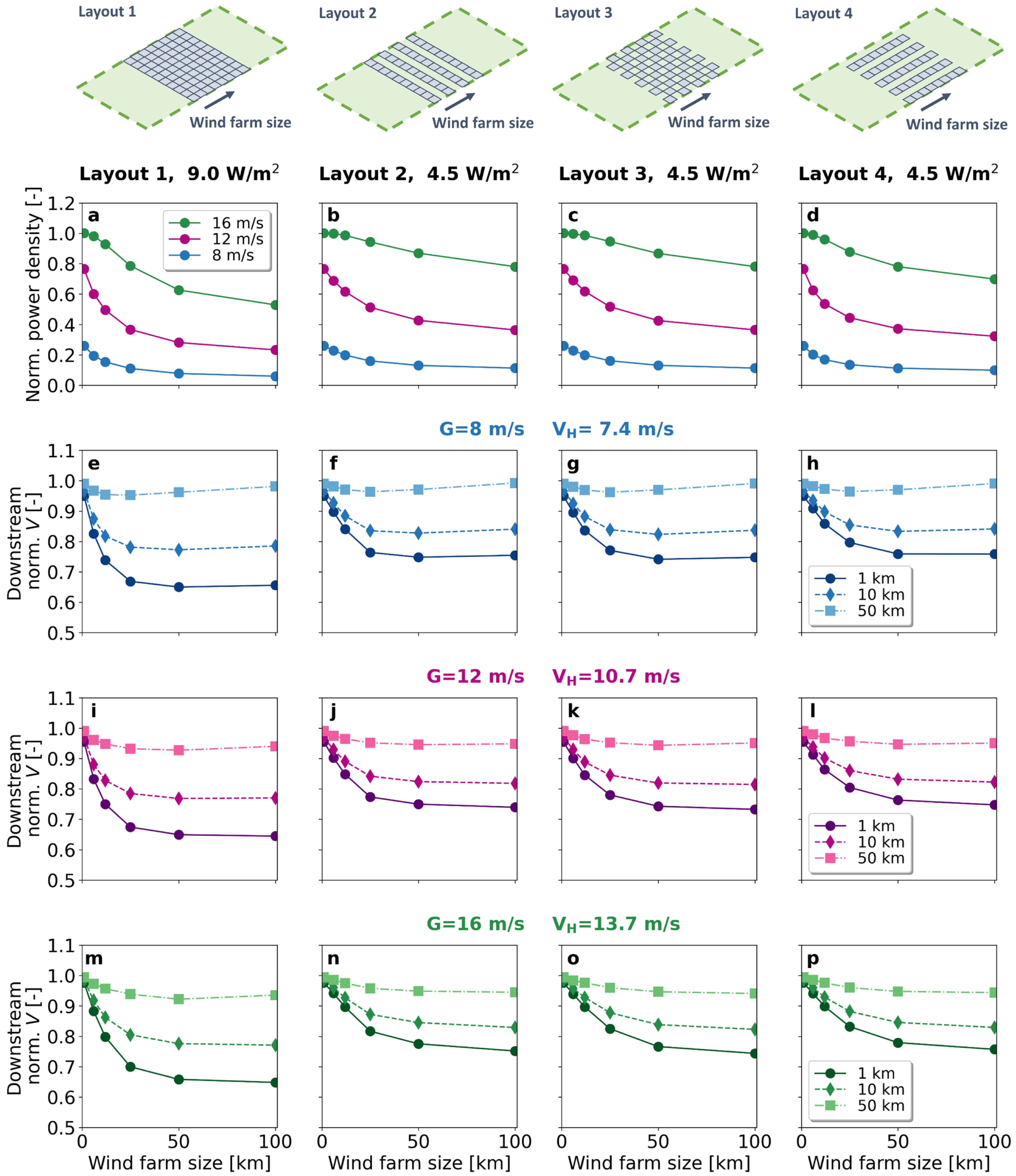


WRF simulations
Analytic framework
Installed capacity density 9.0 W/m²
Power density [W/m²]
Pressure gradient [Pa/km]
Geostrophic wind speed [m/s]
Hub height wind speed [m/s]
a
b
c
d
e
f
Lat = 2.0 °
Lat = 22.2 °
Lat = 46.1 °
Lat = 67.8 °
Lat = 83.8 °

Transitional scales in wind farm performance and wake characteristics

F_p
G
F_c
Geostrophic layer
$L_c = G\tau_c$
L_c
F_p
Ekman layer
V
$L_t = G\tau_t$
L_t
F_t
F_c
Upstream flow
Developed flow over wind farm
Recovery of downstream flow

f=0.55·10⁻⁴ rad/s
f=1.05·10⁻⁴ rad/s
L_t=58.2 km, L_c=145.5 km
L_t=30.5 km, L_c=76.2 km
L_t=87.3 km, L_c=218.2 km
L_t=45.7 km, L_c=114.3 km
L_t=116.4 km, L_c=290.9 km
L_t=61.0 km, L_c=152.4 km
L_t
L_c
G=8 m/s
G=12 m/s
G=16 m/s
Altitude [km]
Length [km]
Normalized wind speed [-]



Layout 1
Layout 2
Layout 3
Layout 4
Wind farm size
Layout 1, 9.0 W/m2
Layout 2, 4.5 W/m2
Layout 3, 4.5 W/m2
Layout 4, 4.5 W/m2
Norm. power density [-]
16 m/s
12 m/s
8 m/s
G=8 m/s
VH= 7.4 m/s
G=12 m/s
VH=10.7 m/s
G=16 m/s
VH=13.7 m/s
Downstream norm. V [-]
1 km
10 km
50 km
Wind farm size [km]

Key takeaways

- 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
- We characterized transitional scales in wind farm performance and wake characteristics
- Timescales related to the forces at play give a physical explanation to such a transition
- Wind farms smaller than the characteristic length scale result in higher power densities and shorter wakes
- Increasingly larger wind farms result instead in power densities that asymptotically reach their minimum and wakes that reach their maximum extent

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REVIEW

Grand challenges in the science of wind energy

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First grand challenge: Improved understanding of atmospheric and wind power plant flow physics

What's next?

- Are many small, highly packed wind farms better than a single large, sparse wind farm?
- Can we validate these numerical and analytical solutions with experimental observations?
- Can we design better engineering wake models for inter-wind farm interaction?
- Can we define a power coefficient for large wind farms?

Thanks for you attention!

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