Wind farm efficiency assessed by WRF with a statistical-dynamical approach

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Motivation

Adams and Keith, *Environ Res Lett*, 2013

"The results suggest that the maximum energy that can be extracted by turbine arrays at these scales is about $1\,\mathrm{W\,m^{-2}}$."

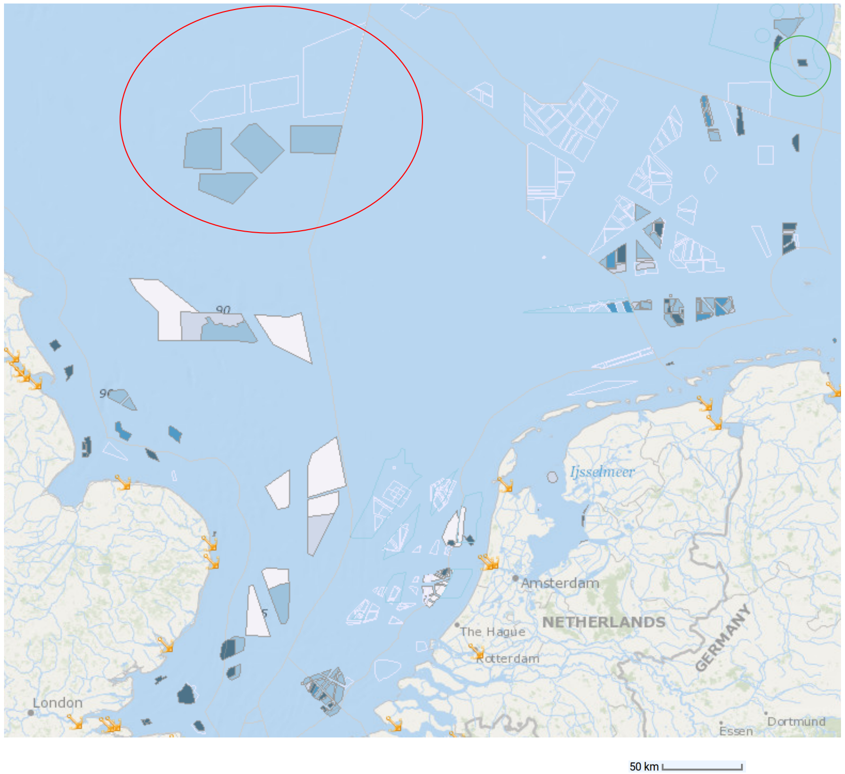
Miller et al., *Proc Natl Acad Sci*, 2015

"Our results suggest that expanding wind farms to large scales will limit generation rates by the vertical kinetic energy flux, thereby constraining mean large-scale generation rates to about $1\,\mathrm{W\,m^{-2}}$ even in windy regions."

Large scale $10^4 - 10^5\,\mathrm{km}^2$

Consequence

Current: the offshore wind farm Horns Rev I $(20\,\mathrm{km}^2)$ has a power density of up-to $3.98\,\mathrm{W\,m^{-2}}$.



Future: very large $(10^4$- $10^5\,\mathrm{km}^2 \sim$ Dogger Bank$)$ wind farms would have a power production per area of 25% compared to Horns Rev I.

Method of Adams and Keith 2013

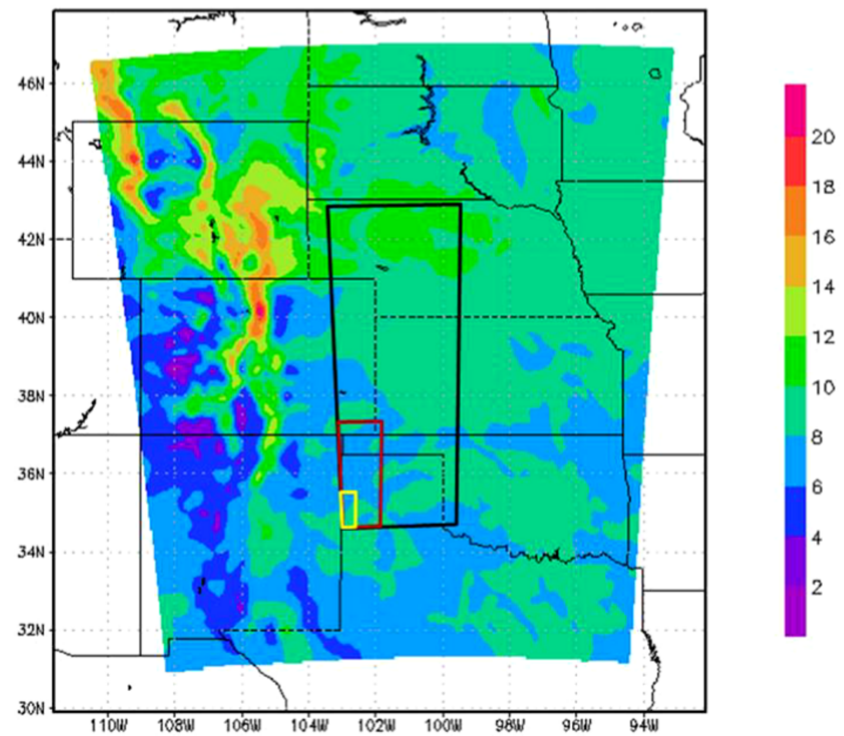
Use WRF model to simulate:

- Actual Power Density (APD) (wake effects with wind farm parametrisation)
- Ideal Power Density (IPD) (no wake effects)

Simulations over the Great plains in winter/summer 2006

The Power Density (PD) is a function of:

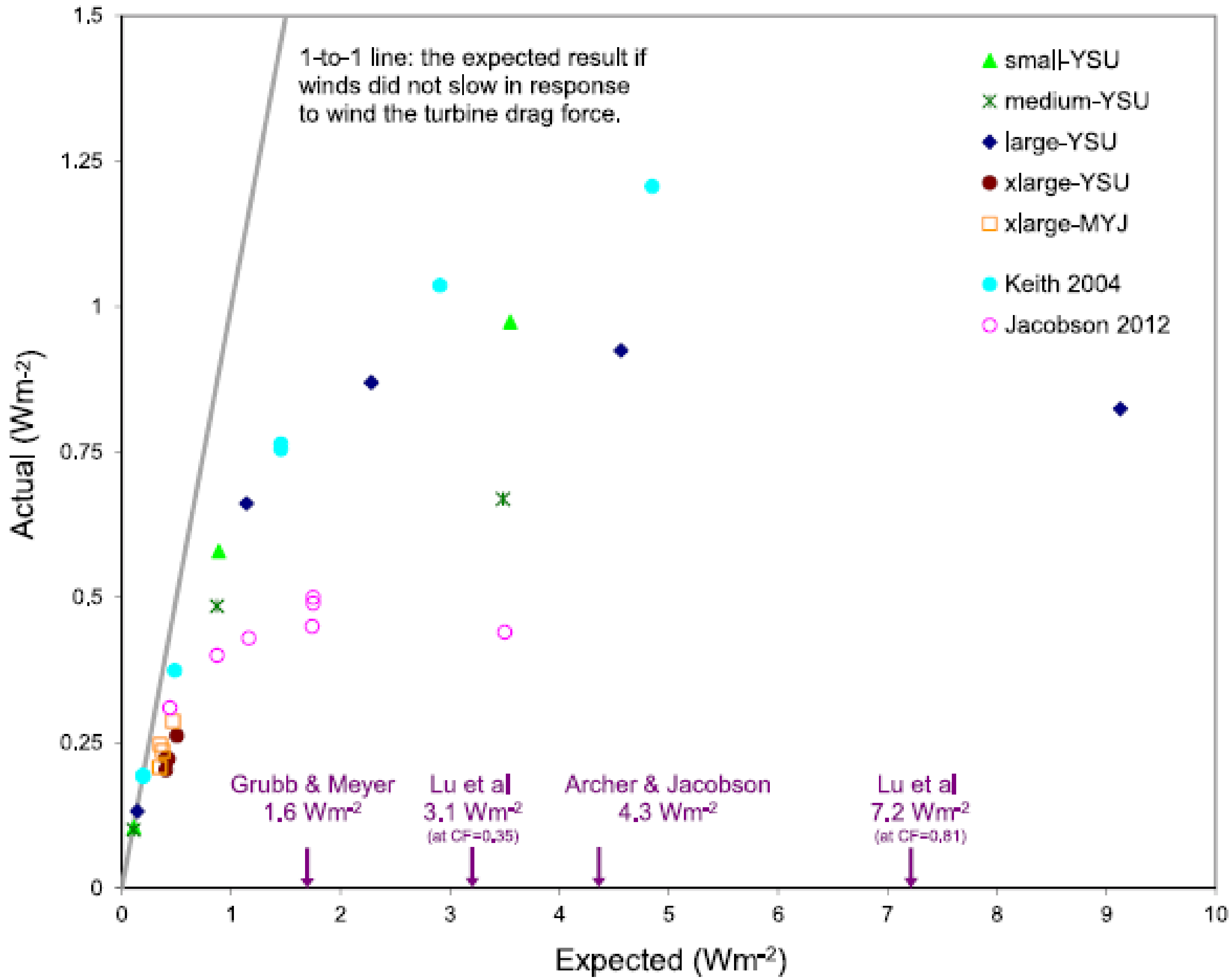
- Wind farm size $10^3 – 10^5\,\mathrm{km}^2$
- Turbine density $0.25 – 16\,\mathrm{km}^{-2}$



Result of Adams and Keith 2013

Actual (wakes) versus Ideal or expected (no wakes) Power Density (PD):

APD/IPD is the degree to which the turbine drag reduces the wind speed



Our experiments

We want to analyse if the power density of very large wind farms is **generally** limited to $1\,\mathrm{W\,m^{-2}}$.

12 different wind farm configurations:

- 4 wind farm sizes (**small** (Horns Rev I), **medium** (London Array), **large** (Dogger Bank), and **very large** (Iowa))
- 3 turbine densities (5.25 Do, 7 Do, and 10.5 Do) (V80 2 MW)

Wind farm size and turbine spacing

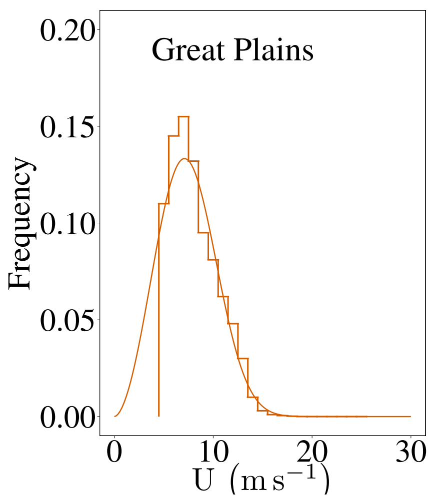
	Small ($25\,\mathrm{km^2}$)	Medium ($342\,\mathrm{km^2}$)	Large ($2.9 \cdot 10^4\,\mathrm{km^2}$)	Very Large ($1.1 \cdot 10^5\,\mathrm{km^2}$)
	Total number of turbines			
Wide	36	484	40.804	161.604
Intermediate	81	1089	91.809	363.609
Narrow	144	1936	163.216	646.416

Wind Conditions

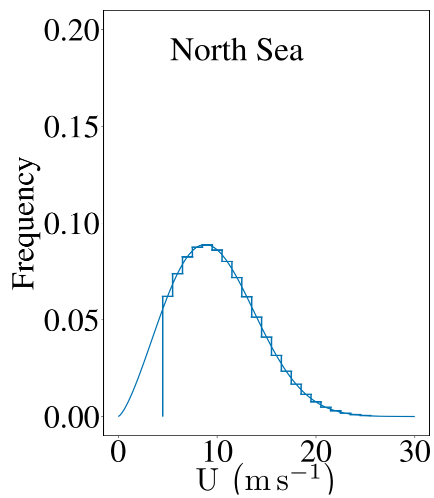
For each wind farm we simulated a range of idealised case experiments between the turbine cut-in and cut-out wind speed.

From the set of simulations we define 3 wind conditions (1 Land, 2 Sea).

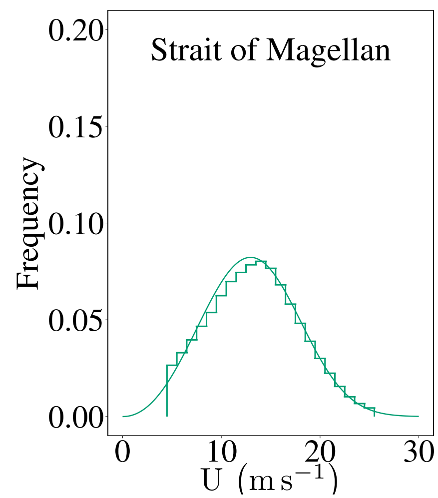
Great Plains:
High roughness
Moderate winds



North Sea:
Low roughness
Strong winds



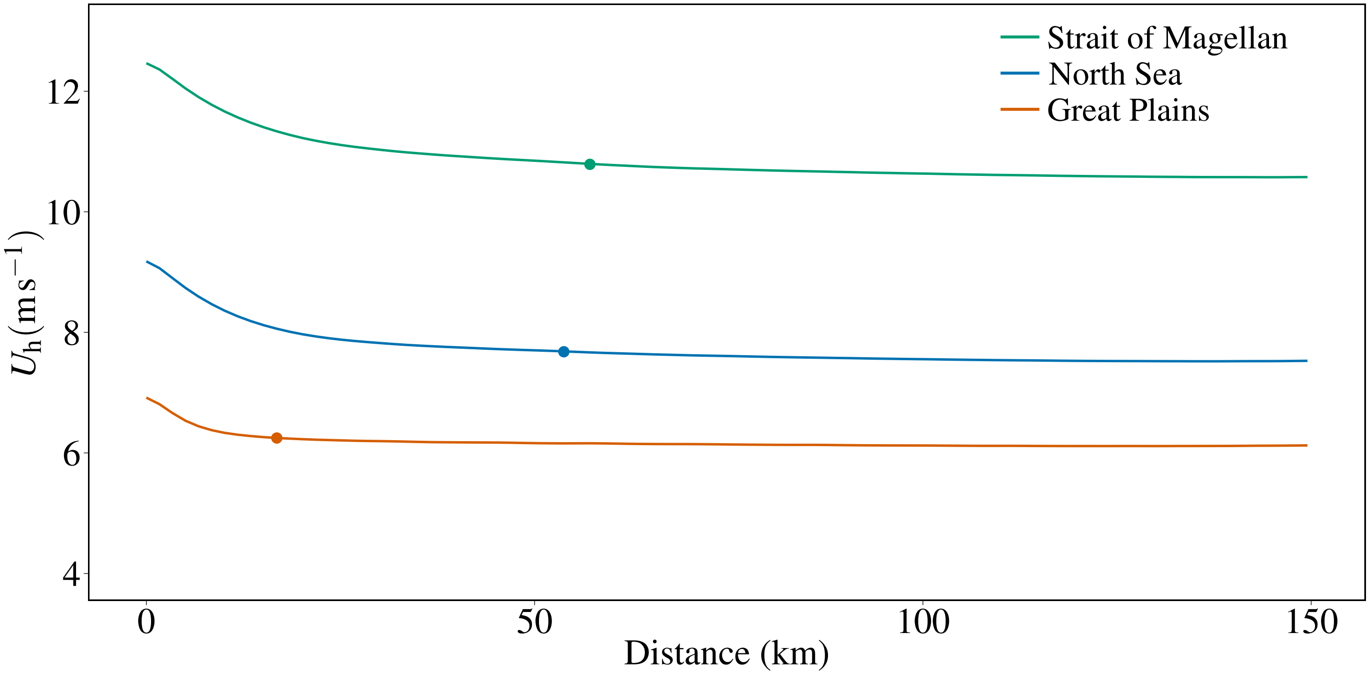
Strait of Magellan:
Low roughness
Very strong winds



Power Density: $PD = \frac{1}{2}\frac{\rho\,\pi\,R_0^2}{A_{\mathrm{WF}}} \sum_{i=1}^{N_{\mathrm{ws}}} f_i \sum_{j=1}^{N_{\mathrm{turbine}}} C_p(U)\,U_j^3$

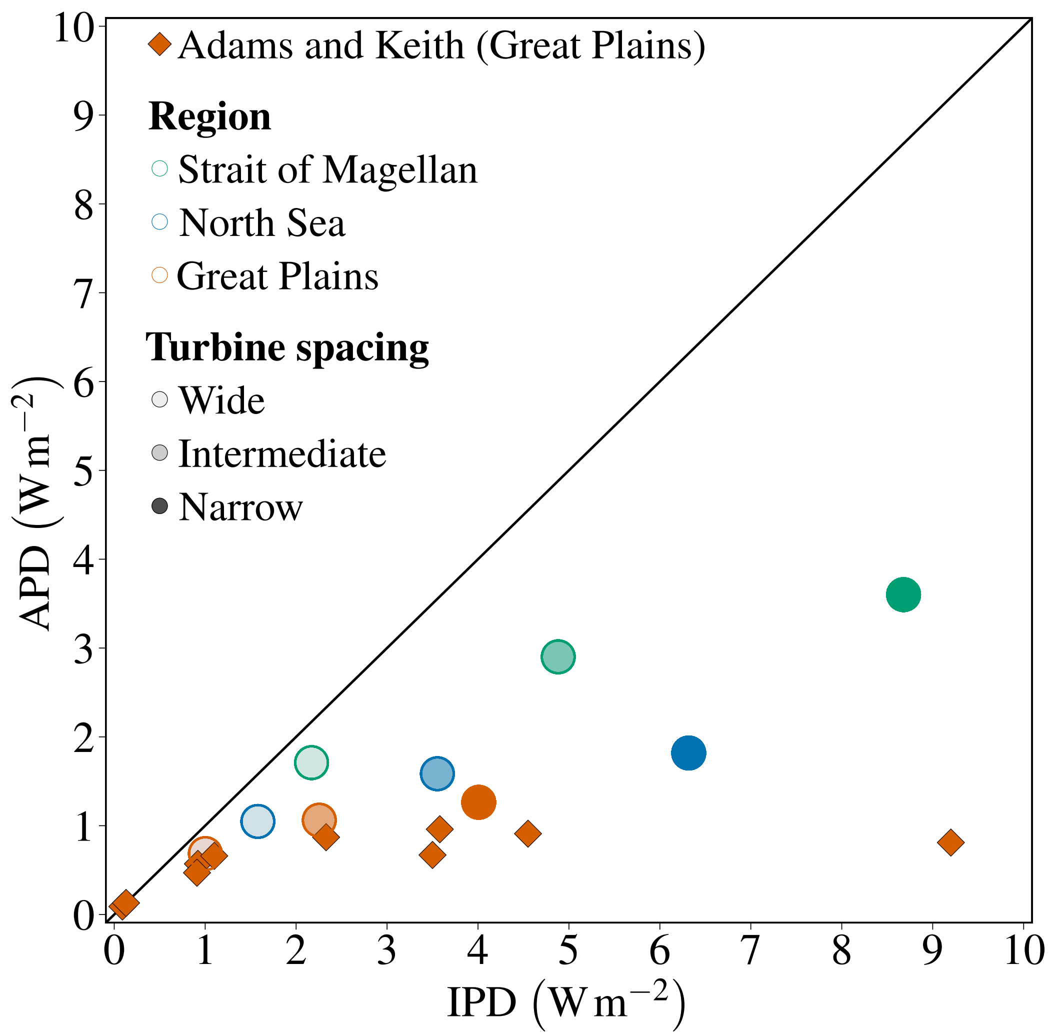
Wind speed reduction in very large wind farms

There is at equilibrium wind speed a **balance** between:
the **drag force** $f(Ct, U)$ and vertical **turbulence influx**



- Offshore there is less mixing and equilibrium is reached much later
- Equilibrium wind speed remains higher in offshore regions

APD vs IPD for very large wind farms



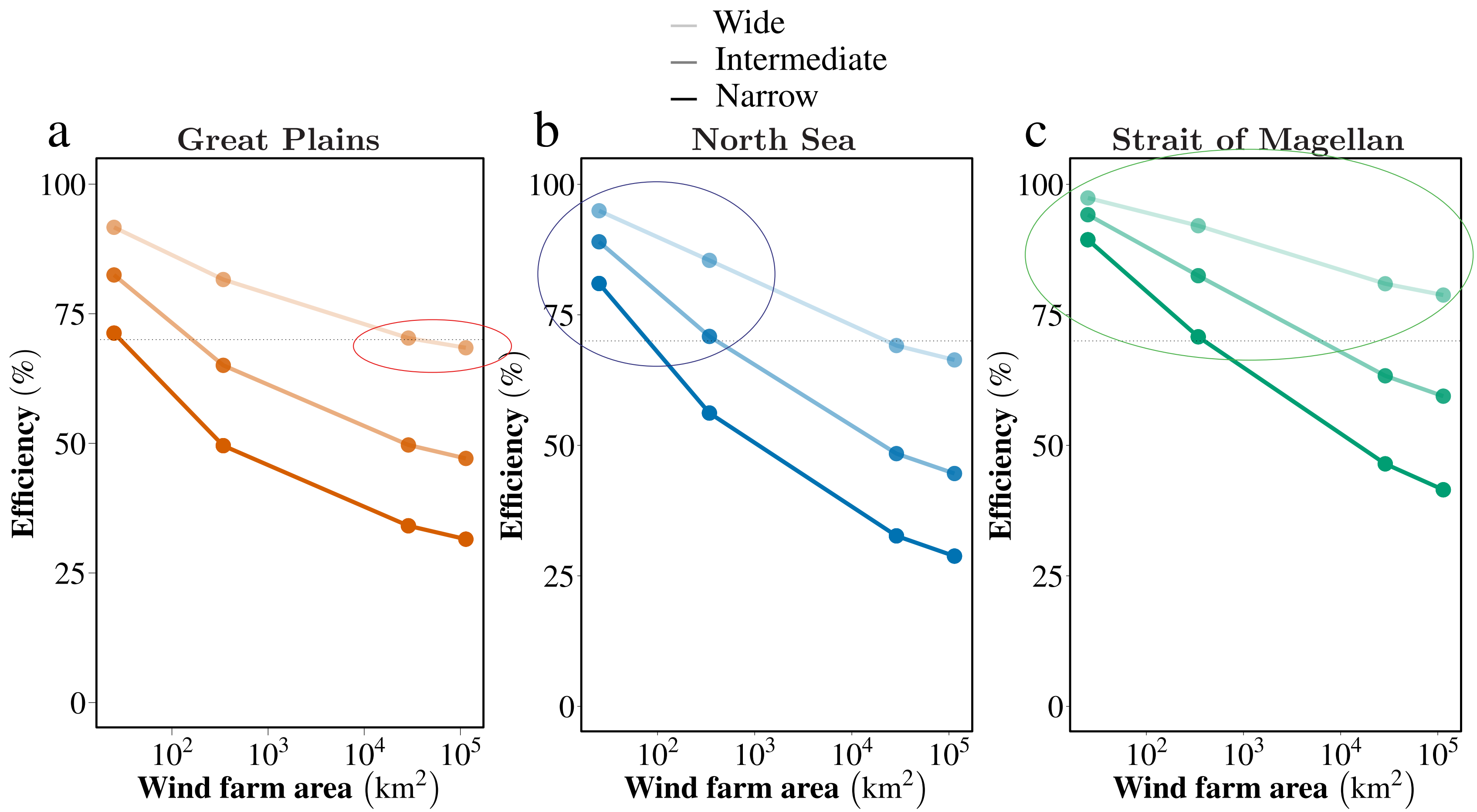
- In the Great Plains also 1 $\mathbf{W\,m^{-2}}$ (differences are due to parametrisation)
- However: In regions with strong winds the APD is almost 3.5 $\mathbf{W\,m^{-2}}$

$\Rightarrow$ APD is not limited, but depends strongly on wind (and roughness) conditions

Wind farm Performance

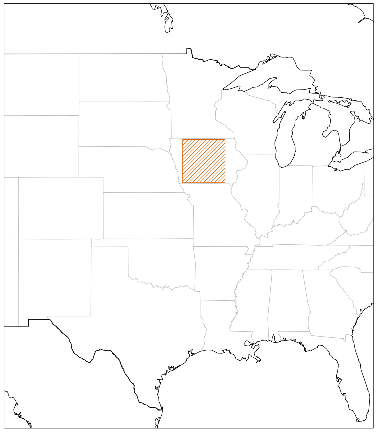
For wind farm developers the **efficiency** (APD/IPD) is more relevant

All wind farms in three regions (70% threshold)

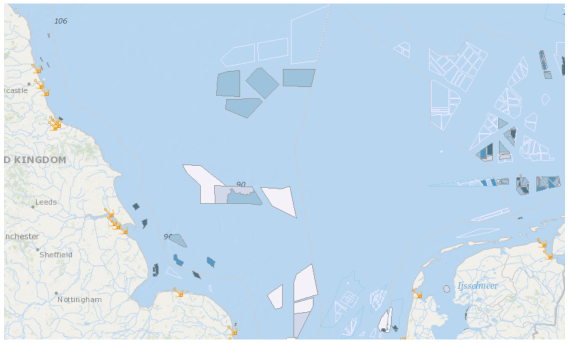


Examples of efficient wind farms

Great Plains A Very large wind farm (160.000 turbines) with wide (10.5 Do) spacing produces 700 TWh (around 17% of to U.S. electricity consumption)



North Sea In the Dogger Bank a cluster of nine medium wind farms (total 9.801 turbines) with intermediate (7 Do) turbine spacing would produce 77 TWh (more then 20% of U.K. electricity consumption)



Strait of Magellan A small wind farm with intermediate spacing produces 1 TWh (50% more than Horns Rev I in Denmark). A very large wind farm (160.000 turbines) would produce 1.7 PWh, 7% of global electricity consumption.

Conclusion

Power Density

- The power density is not limited to $1\,\mathrm{W\,m^{-2}}$ as previously assumed
- Instead it depends also for very large wind farms on the local up-stream wind conditions

Wind farm efficiency/production

- Even in land regions with moderate wind conditions wind energy have potential to significantly contribute to the electricity production
- Generally offshore, clusters of smaller wind farms are more efficient
- Wind farms in regions with very strong wind speeds seem to be very productive