DTU

Jake Badger, Andrea N Hahmann, Xiaoli G Larsén, Jana Fischereit, Marc Imberger, Oscar M.G. Santiago, Nicolas G. Alonso-De-Linaje

DTU Wind and Energy Systems

What is a realistic annual energy yield from very large wind farm clusters and energy islands?

Declarations setting ambitious political ambitions

THE ESBJERG DECLARATION

on The North Sea as a Green Power Plant of Europe

Energy security and the fight against climate change are crucial to the future of the European Union. Recalling the Versailles conclusions on energy, the European Commission's communication on Joint European Action for more affordable, secure and sustainable energy, and the most recent IPCC report and taking note of the European Commission's REPowerEU announcement of 18 May, we aim to take urgent and immediate action. The recent geopolitical events will accelerate our efforts to reduce fossil fuel consumption and promote the deployment of renewable energy for more energy resilience in Europe.

Therefore, we will increasingly **replace fossil fuels, including Russian oil, coal and gas, with European renewable energy from the North Sea,** including offshore wind and green hydrogen, contributing to both EU climate neutrality and energy security.

To achieve this and to pave the way for the further expansion of offshore wind, we have **decided to jointly develop The North Sea as a Green Power Plant of Europe, an offshore renewable energy system** connecting Belgium, Denmark, Germany and the Netherlands and possibly other North Sea partners, including the members of the North Seas Energy Cooperation (NSEC). As Members of NSEC, we will build on the work already accomplished and will implement strategies to achieve our goals in close cooperation with the other regional countries and the European Commission. In doing so, we will strive for a balanced coexistence of econ... needs.

The North Sea as a Green Power Plant ... **offshore energy projects and h**... ty and green hydrogen interc... t will harvest the potential of th... ntries and the

Together, we have ... **W by 2030.** Based on the North S... **n double** our total capacity of offs... **f capacity needed to reach EU cli**... Strategy on Offshore

This will contribute to la... onshore and offshore production of **green hydrogen. We have set combined targets of about 20 GW production capacity already by 2030** and look to expand our production even further for 2050.

65 GW by 2030
150 GW by 2050

THE BALTIC SEA Energy Security Summit

THE MARIENBORG DECLARATION

The Baltic Sea Energy Security Summit

THE PRIME MINISTER

Republic of Estonia Prime Minister

Prime Minister of the Republic of Latvia

MATEUSZ MORAWIECKI
PRIME MINISTER OF POLAND

PRIME MINISTER'S OFFICE FINLAND

Government Offices of Sweden
Prime Minister's Office

19.6 GW by 2030

OSTEND DECLARATION OF ENERGY MINISTERS

ON

THE NORTH SEAS AS EUROPE'S GREEN POWER PLANT

DELIVERING CROSS-BORDER PROJECTS

AND ANCHORING THE RENEWABLE OFFSHORE INDUSTRY IN EUROPE

Recalling the declaration on the North Seas as a Green Power Plant of Europe in Esbjerg signed by the energy ministers of Belgium, Denmark, Germany and the Netherlands on 18 May 2022.

The energy ministers of France, Ireland, Luxembourg, Norway and the United Kingdom are joining this Ostend declaration.

Underlining that energy security and the fight against climate change are crucial to the future of Europe, we need to strengthen our cooperation to ensure affordable, secure and sustainable energy, while at the same time, continuing our efforts to protect the marine ecosystem. In response to Russia's aggression against Ukraine and attempts of energy blackmail against Europe we will accelerate our efforts to reduce fossil fuel consumption as well as dependence on fossil fuel imports and promote the rapid upscaling and deployment of renewable energy for an energy resilient Europe.

Further underlining that the goal of the development of infrastructure, production of offshore renewables and market design for the North Seas, is to accelerate the energy transition and maximise the benefits for households, industry and society as a whole.

Together, we have set ambitious combined targets for offshore wind of about 120 GW by 2030 in the North Seas. Based on the North Seas as a Green Power Plant of Europe, together we aim to more than double our total 2030-capacity of offshore wind to at least 300 GW by 2050.

We acknowledge the progress made since the last summit including through the conclusion of both bilateral agreements on offshore renewable generation and non-binding agreements to cooperate on goals for offshore renewable... tion for the North Seas, under the revised framework for trans-Eu... s (TEN-E). We fully support the ongoing work to devel... offshore network development plan f... der coordination of grid and...

In that resp... tem Operators (TSO's) from... rtaken to develop a mes... tion. We invite them to cont... countries that have joined t...

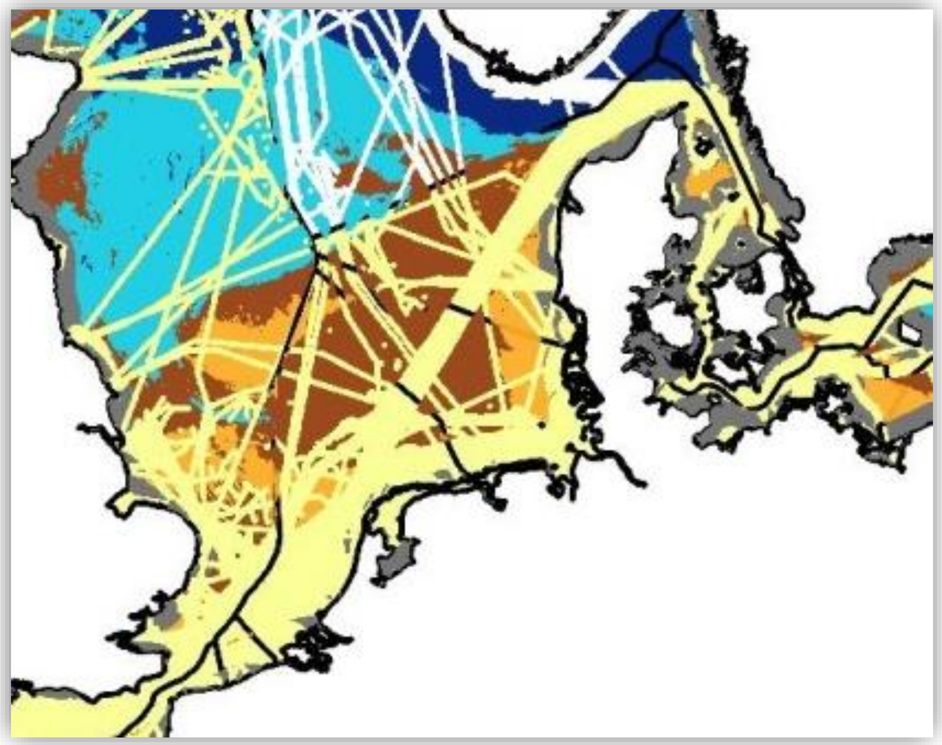
This will contr... wable hydrogen. Germany... have set combined targets of abou... and look to expand their production even further fo...

120 GW by 2030
300 GW by 2050

Ambitions consistent with published data

From Ruiz Castello et al (2019),

– Calculate area available for wind installation
  - Installation capacity density 5 MW/km**2
  - Capacity factors from Global Wind Atlas (v1)



For the case of the Esbjerg Declaration countries,

...and inferring from Ruiz Castello et al (2019)

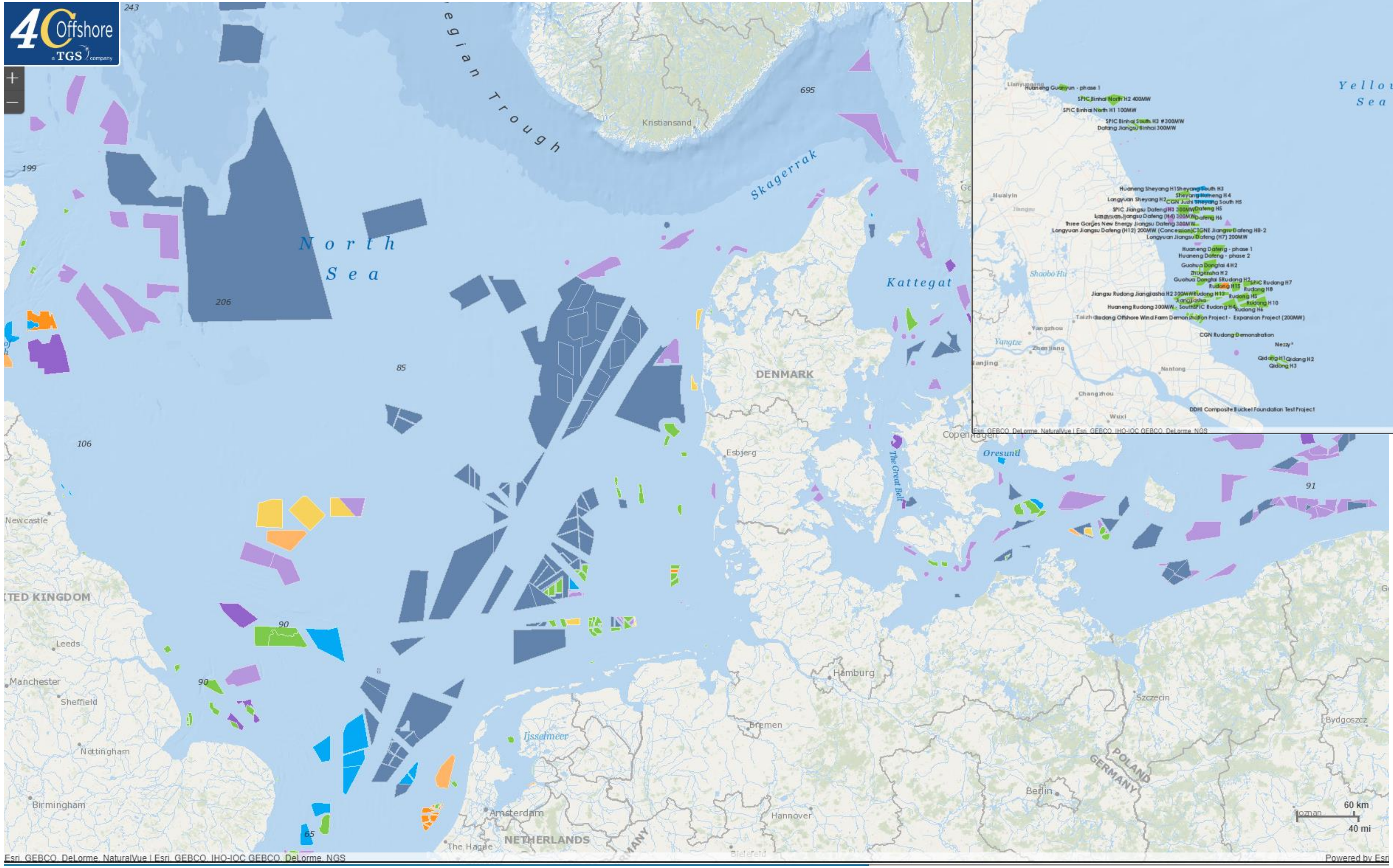
– Capacity range
  - DK 27-226 GW
  - DE 28-106 GW
  - NL 48-97 GW
  - BE 2-2 GW

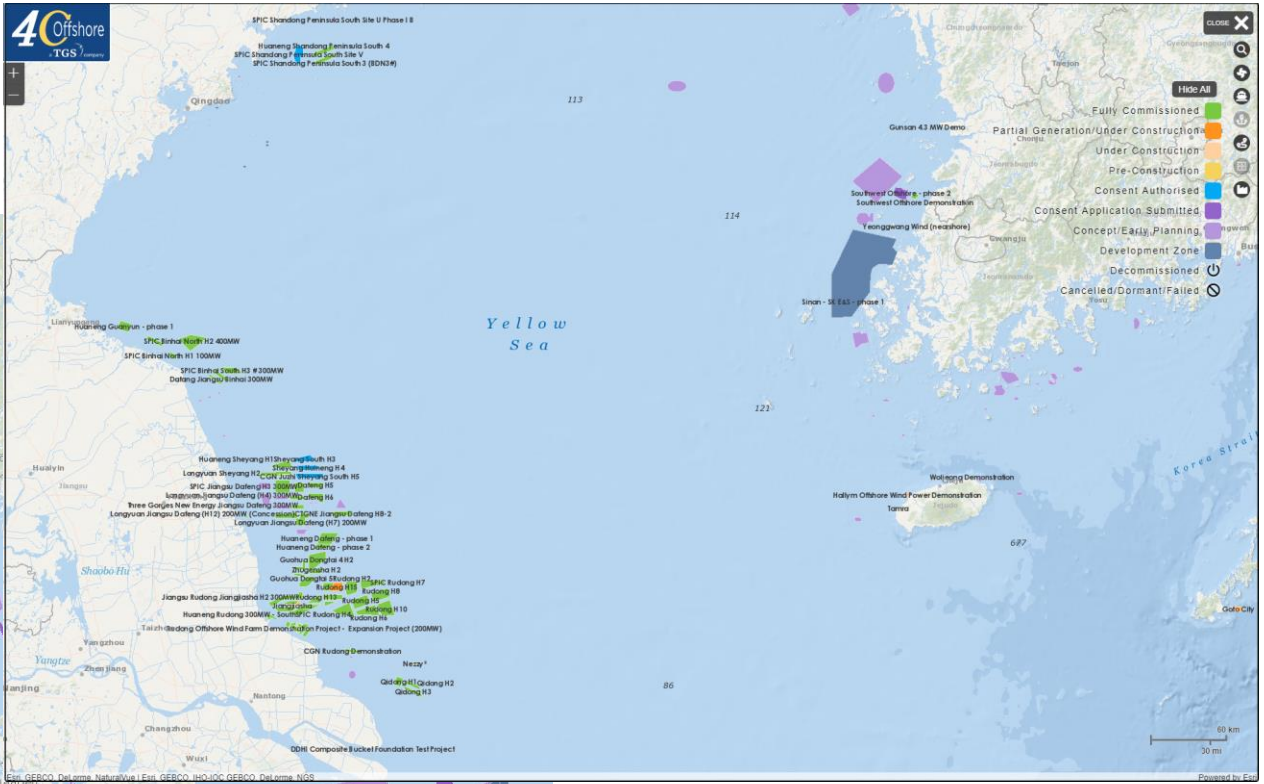
  - **Total 105-431GW**

Esbjerg Declaration:
65 GW by 2030
150 GW by 2050

Ruiz Castello, P., Nijs, W., Tarvydas, D., Sgobbi, A., Zucker, A., Pilli, R., Jonsson, K., Camia, A., Thiel, C., Hoyer-Klick, C., Dalla Longa, F., Kober, T., Badger, J., Volker, P., Elbersen, B., Brosowski, A. and ThrÃ¤n, D., ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials, ENERGY STRATEGY REVIEWS, 2019, ISSN 2211-467X, 26, p. 100379, JRC112858.

How might this look?



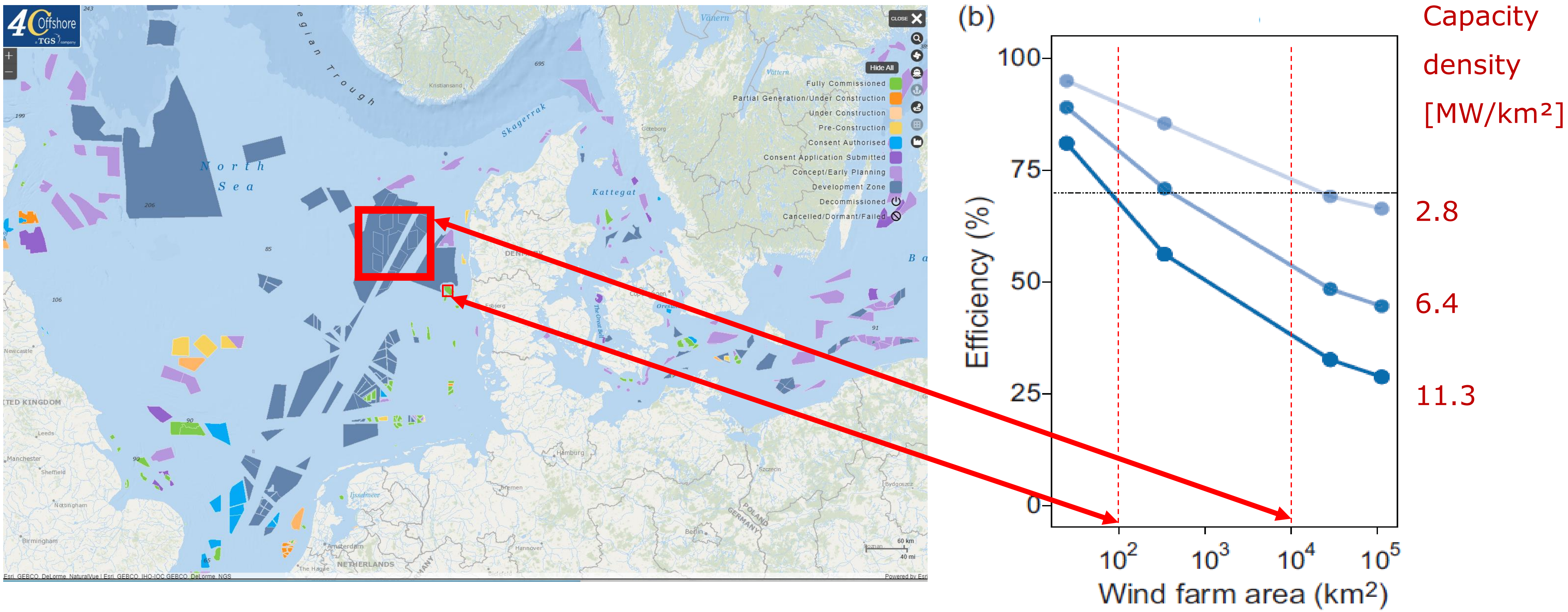


This scale of wind energy deployment is completely new.

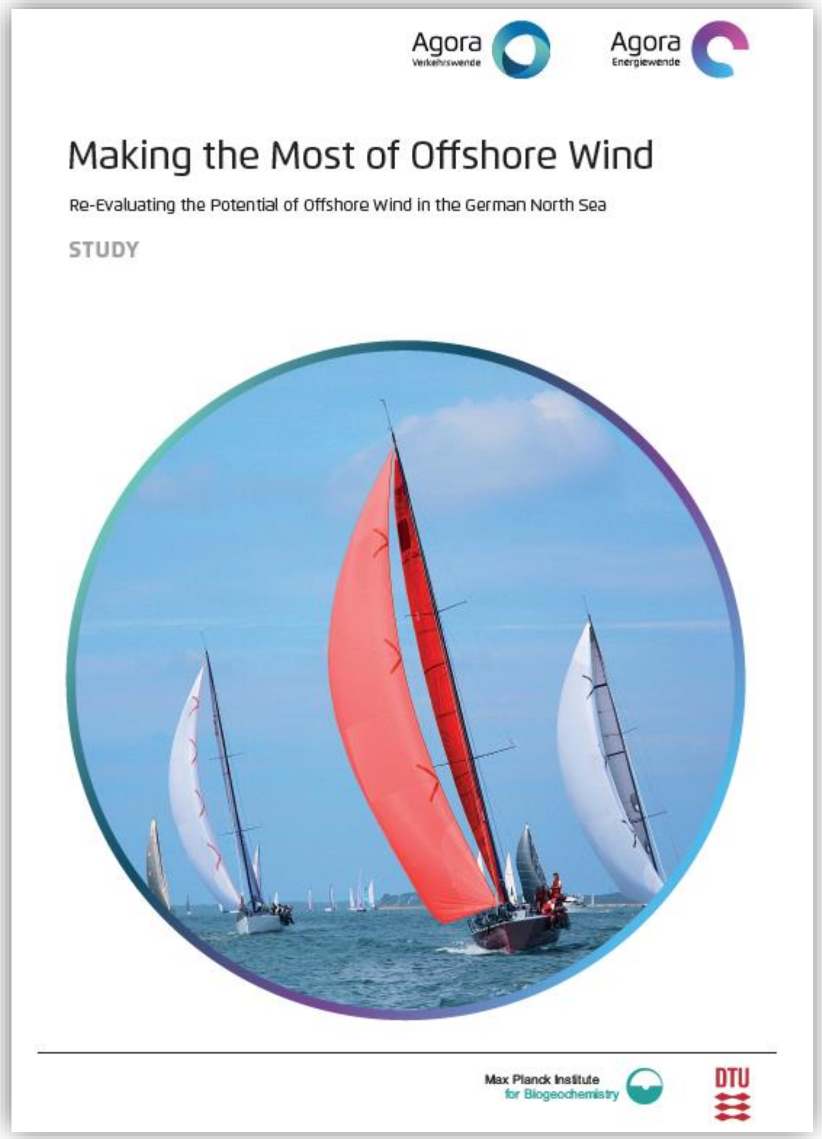
No or limited experience of such development in the real world.

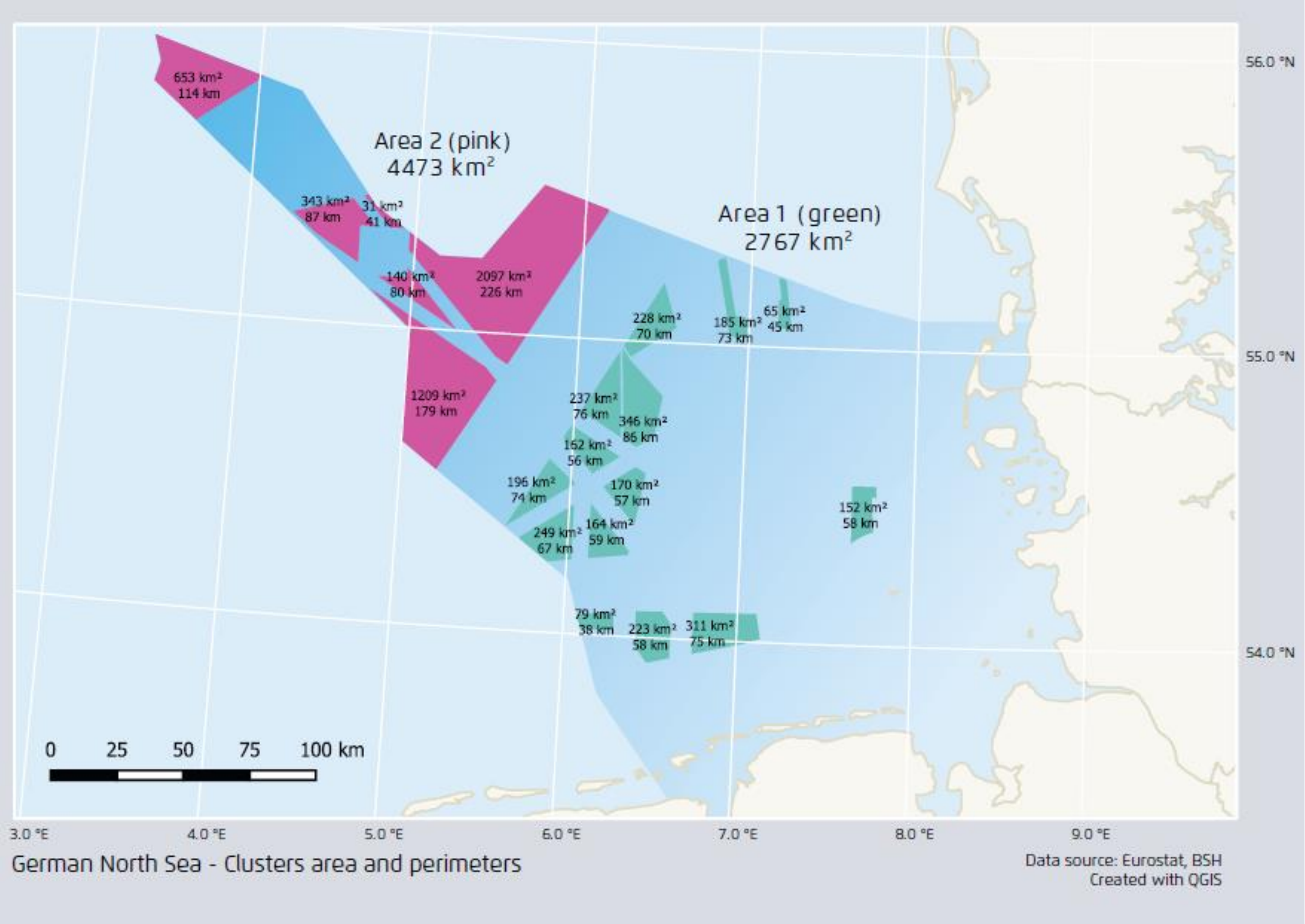
We need, and have models to guide us.

Farm efficiency… using WRF wind farm parameterization



Volker, P, Hahmann, AN, Badger, J & Ejsing Jørgensen, H 2017, 'Prospects for generating electricity by large onshore and offshore wind farms: Letter', *Environmental Research Letters*, vol. 12, no. 3, 034022 . https://doi.org/10.1088/1748-9326/aa5d86





https://www.agora-energiewende.de/en/publications/making-the-most-of-offshore-wind/

Agora (2020):

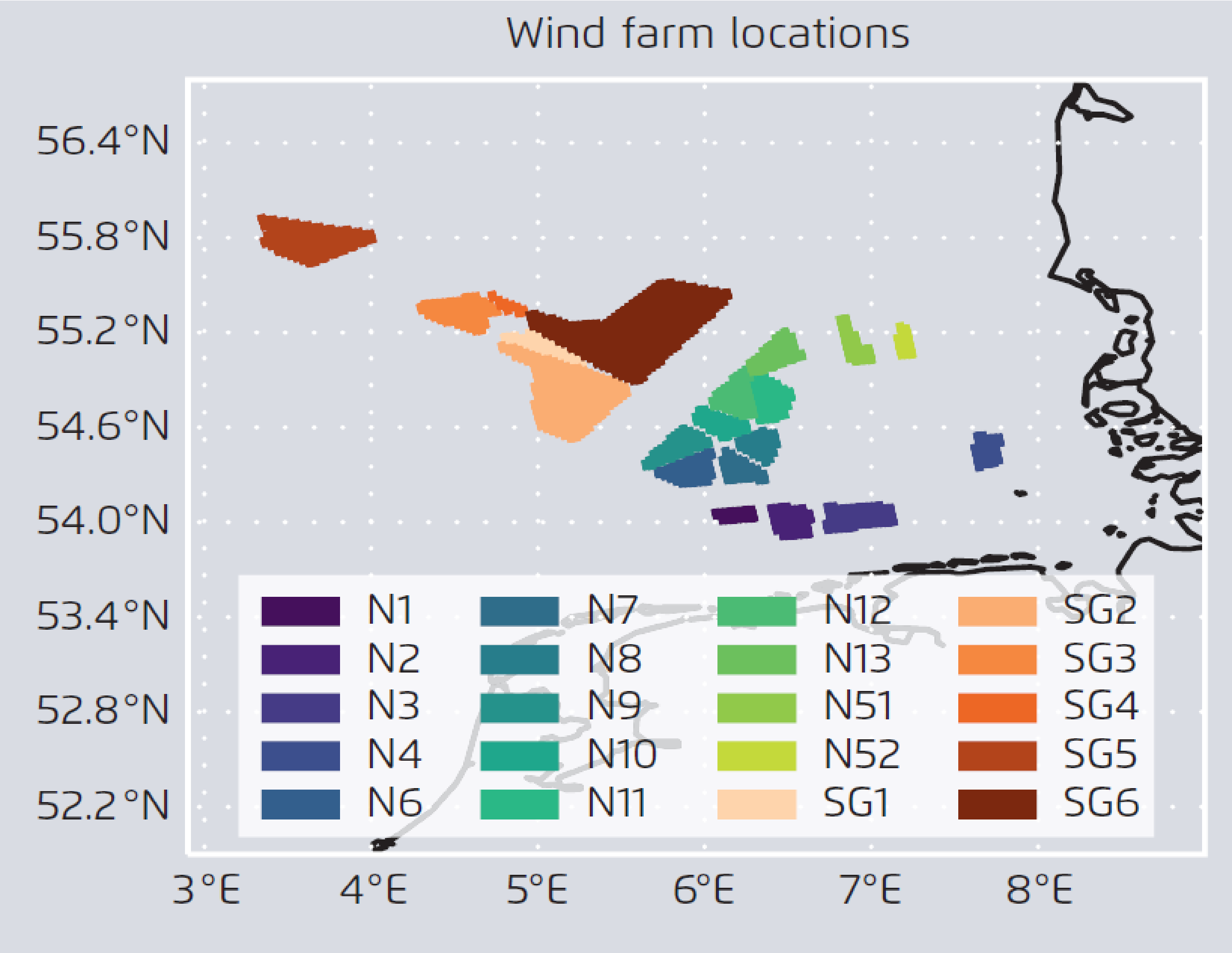
Technical University of Denmark and Max-Planck Institute (2020): Making the Most of Offshore Wind: Re-Evaluating the Potential of Offshore Wind in the German North Sea. Study commissioned by Agora Energiewende and Agora Verkehrswende.

12 MW turbine
Hub height 140 m
Rotor Diameter 200 m

20 colour coded wind farms
Total area is 7249 km^2

5, 7.5, 10, 12.5, 20 MW/ km^2

14 - 144 GW



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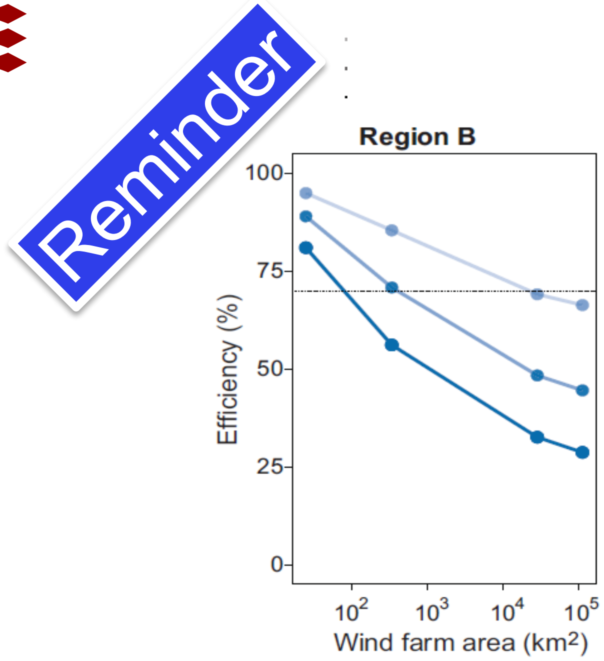
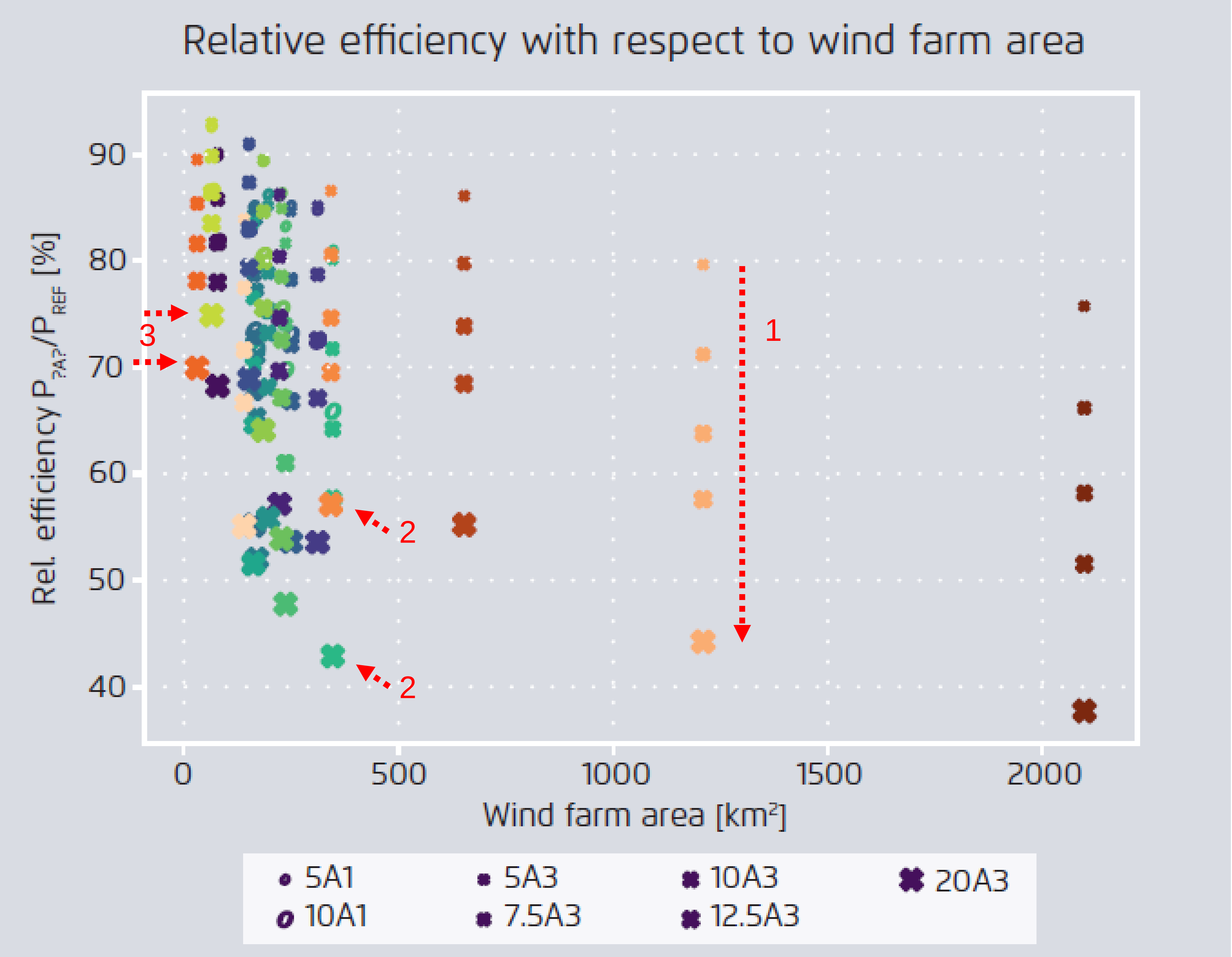
WRF results



- Efficiency drops for higher installed capacity densities (1)
- Efficiency also depends on wind farm location and climate. (2)
- Efficiency depends on farm size and proximity of large expanse of neighbouring wind farms (3)

Agora (2020)



Apply to the 10 GW North Sea Energy Island

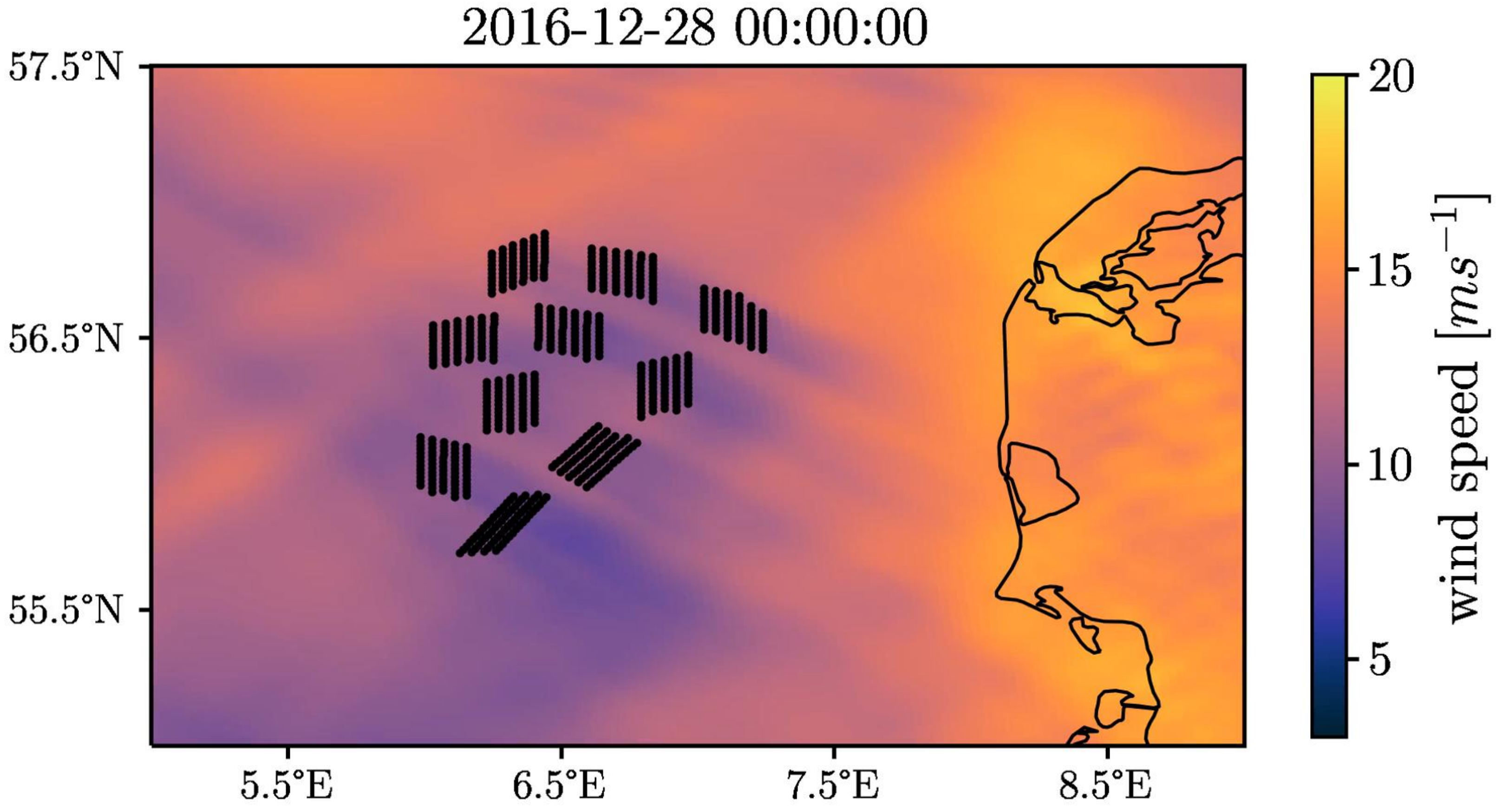
Inferring results from Volker et al (2017) and Agora (2020) suggest Energy Island losses between 10 – 20 %.

Dedicated Mesoscale simulations in van der Laan (2023) predict a wake loss between 9.3 - 10.1%.

Total area and capacity density:

6.4 * 10^3 km^2

1.6 MW / km^2



van der Laan, M.P., García-Santiago, O., Sørensen, N.N., Troldborg, N., Risco, J.C. and Badger, J., 2023, May. Simulating wake losses of the Danish Energy Island wind farm cluster. In *Journal of Physics: Conference Series* (Vol. 2505, No. 1, p. 012015). IOP Publishing.

Research on wind farm modelling wakes

See poster 4 for more details

One object is to reduce grid choice dependency when using wind farm parameterizations

- using microscale models to provide thrust
- using anti-aliasing methods

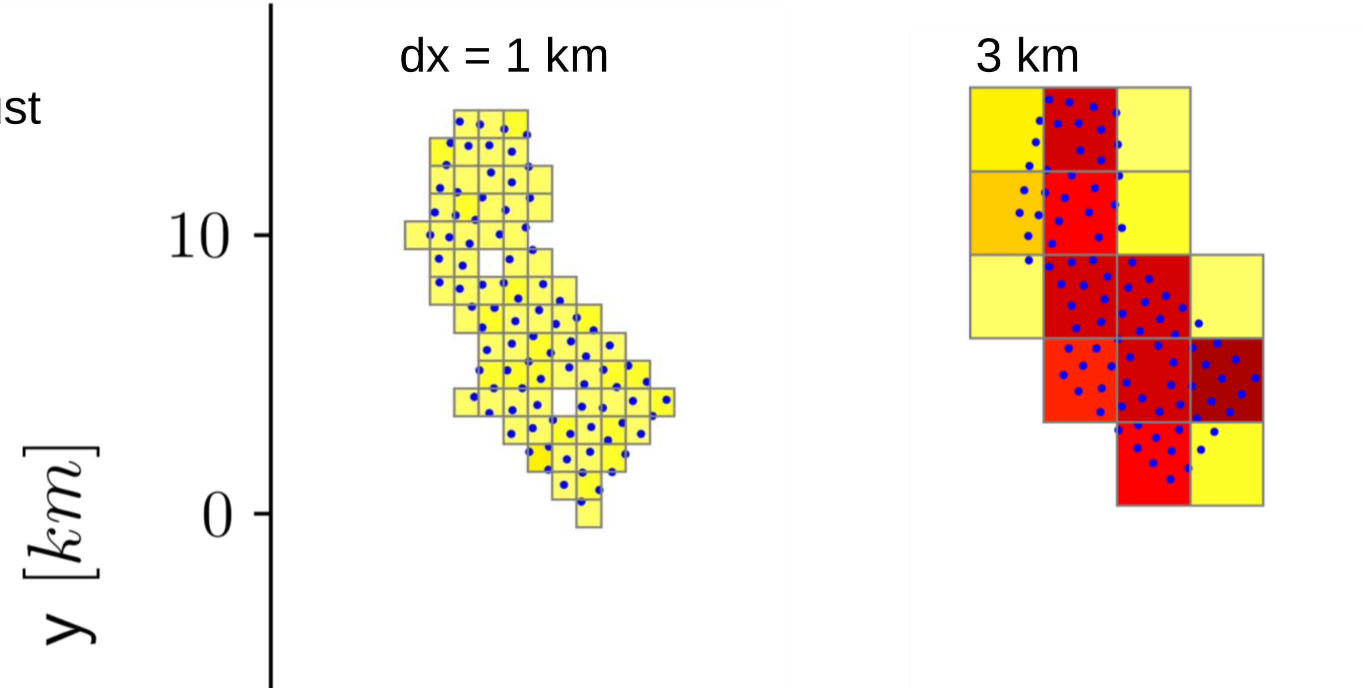
Race Bank (UK)

Turbine 91 * 6 MW

Total Capacity 546 MW

Area 75 km^2

Capacity density 7.3 MW / km^2



	dx = 1 km	3 km
Efficiency	0.73	0.76
Normalized Wake Area Size	5.1	3.1

Scaling-up within capacity density limits

Use Volker et al (2017) to guide capacity density as function of area available.

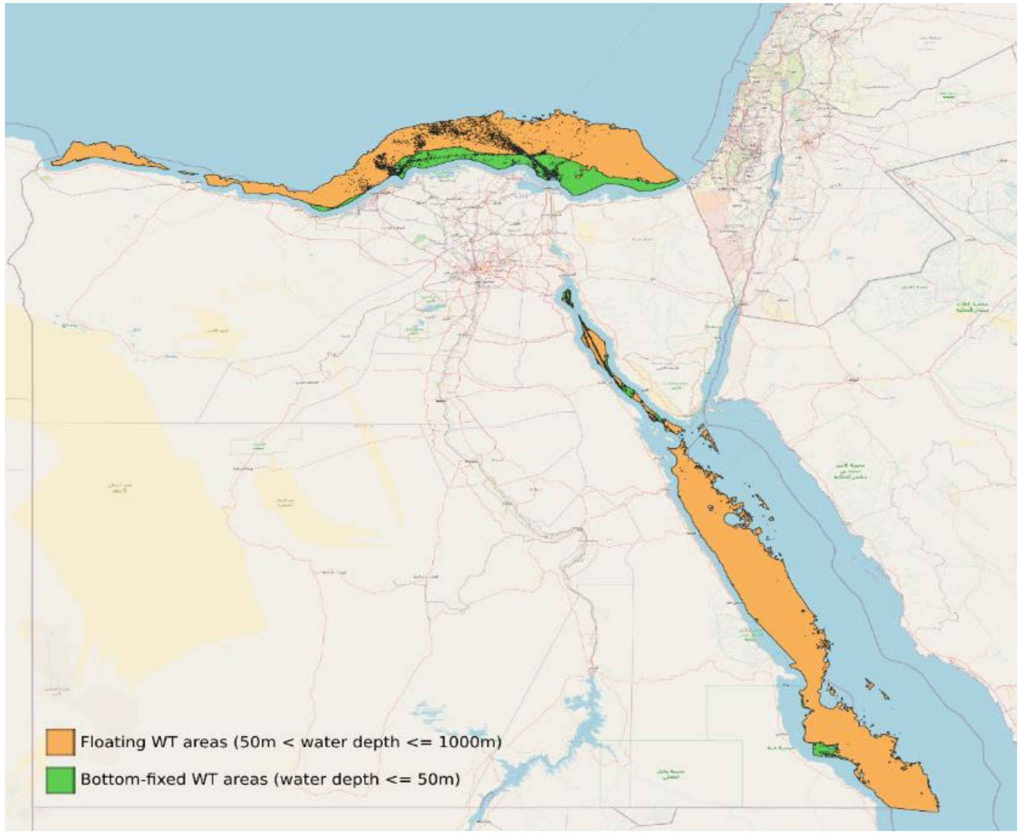
i.e. to keep large scale wind farm wake losses small (5 – 10 %) limit aggregated installed capacity density to

- 2 MW/km^2 in Gulf of Suez
- 2 MW/km^2 for bottom-fixed in Red Sea
- 1 MW/km^2 for floating in Red Sea

A guiding estimate of capacity and production is

51.5 GW generating 176 TWh per year:

	Bottom-fixed capacity	Floating capacity	Bottom-fixed annual yield	Floating annual yield
	GW	GW	GWh/year	GWh/year
Mediterranean	3	-	5740	-
Gulf of Suez	1	4	4910	15500
Red Sea	1.5	42	5440	144000
Total	5.5	46	16000	160000



Badger, J., Hansen, B.O., Mitsakou, A., Blagojevic, S.S., Hansen, T. and Clausen, N.E., 2022. Case Study-based Prefeasibility Assessment of Offshore Wind Resources in Egypt.

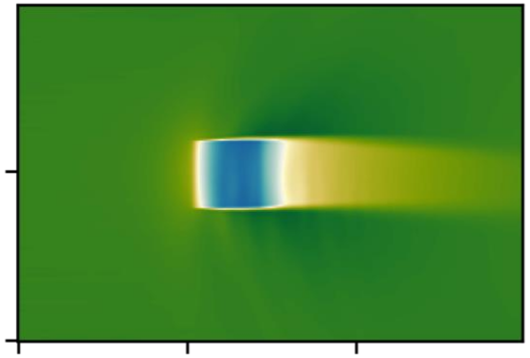
https://orbit.dtu.dk/en/publications/case-study-based-prefeasibility-assessment-of-offshore-wind-resou

Calculated wind farm power curves including farm efficiency

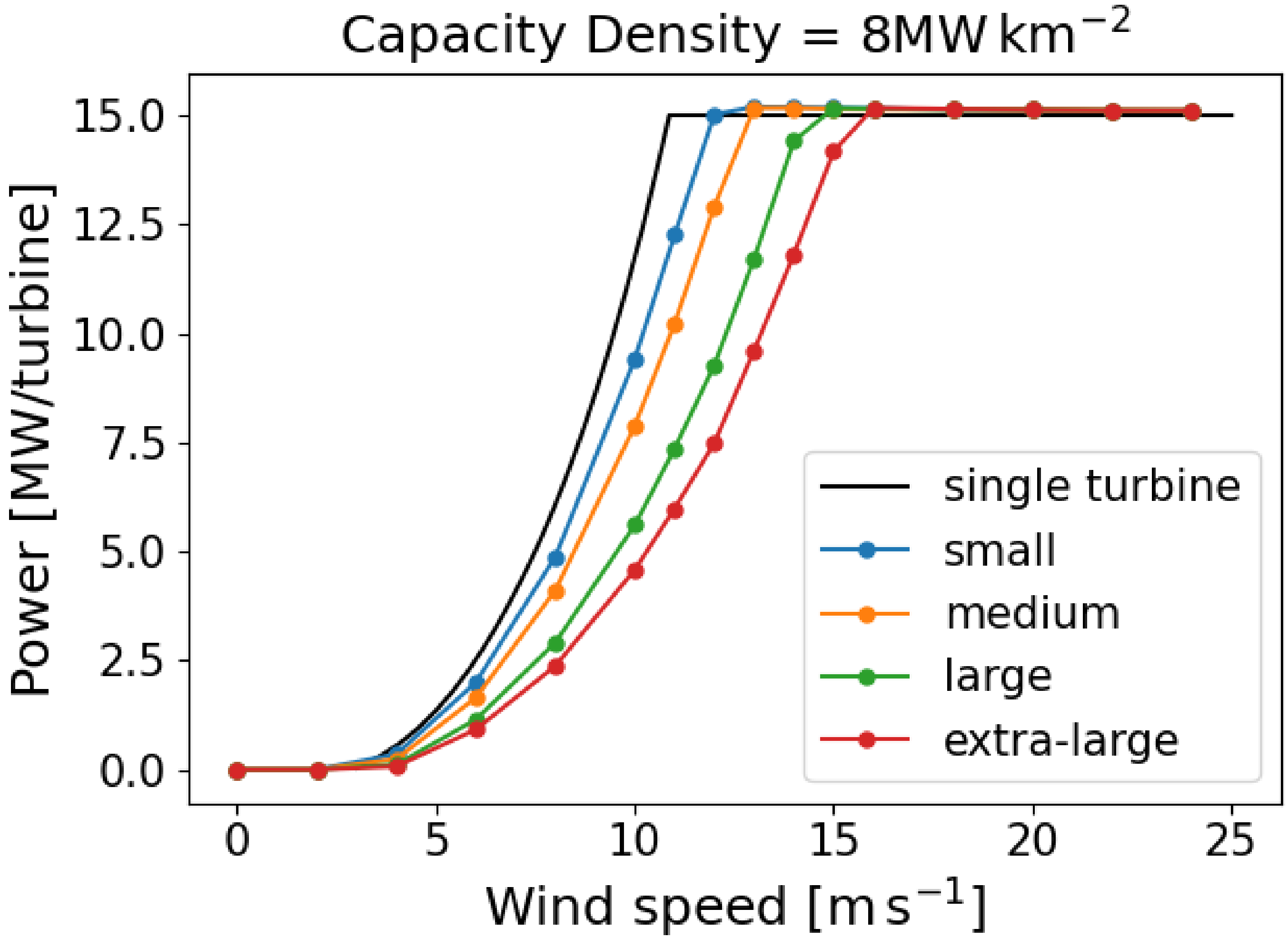
Useful for power time series studies…

Mesoscale wake (WRF ideal)

- Wind farm power curve derived for various sizes:
  - 4 x 4 (small) 0.24 GW
  - 8 x 8 (medium) 0.96 GW
  - 20 x 20 (large) 6 GW
  - 40 x 40 (x-large) 24 GW



Oscar Garcia (2023)



Hahmann, A.N., De Linaje, N.G.A. and Mitsakou, A., 2023. Assessing the wind energy technical potential of the North Sea—Final Project Report.

https://backend.orbit.dtu.dk/ws/portalfiles/portal/322712205/TennetProjectReport2023_final.pdf

Other studies

Maas and Raasch (2022):
LES study using,
Parallelized Large-eddy Simulation Model (PALM)

Turbine: 15 MW, D=240 m, z_h = 150 m
10.4 W/m*2   (efficiency down to 0.41)

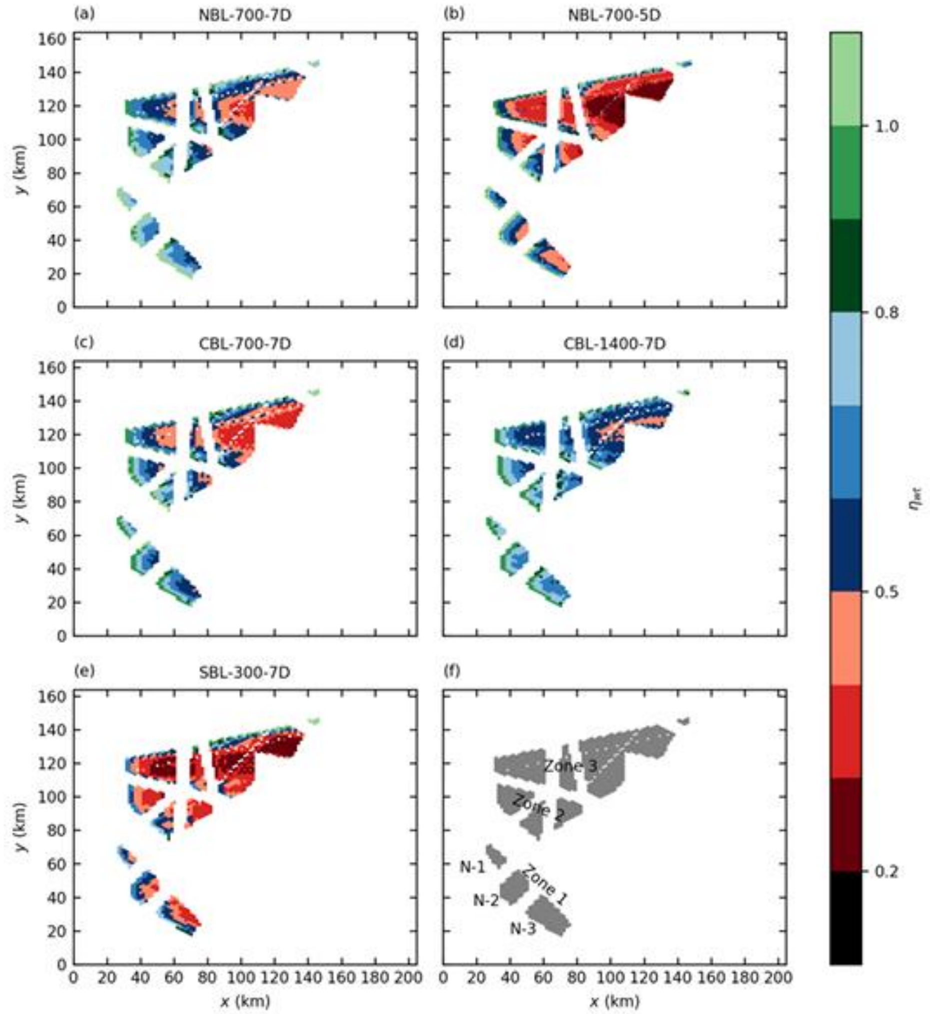


Figure 10. Wind turbine efficiencies η_{wt} for all five cases (**a–e**) and overview of wind farm names (**f**).

- X-wakes project
  - Recent workshop 26/6/2023
  - Flight data, Lidar data, SAR scenes, flow modelling at different scales

Maas, O. and Raasch, S., 2022. Wake properties and power output of very large wind farms for different meteorological conditions and turbine spacings: A large-eddy simulation case study for the German Bight. *Wind Energy Science*, *7*(2), pp.715-739.

X-wakes project webpage: https://www.iwes.fraunhofer.de/en/research-projects/current-projects/x-wakes-.html

Research on wind farm: broader environmental impacts

- Wind-Wake-Wave modelling
- waves affect the momentum transport into the ocean and thus mixing in the ocean.
  - mixing has important consequences for the ecosystem

30-year worth wind and wave statistics

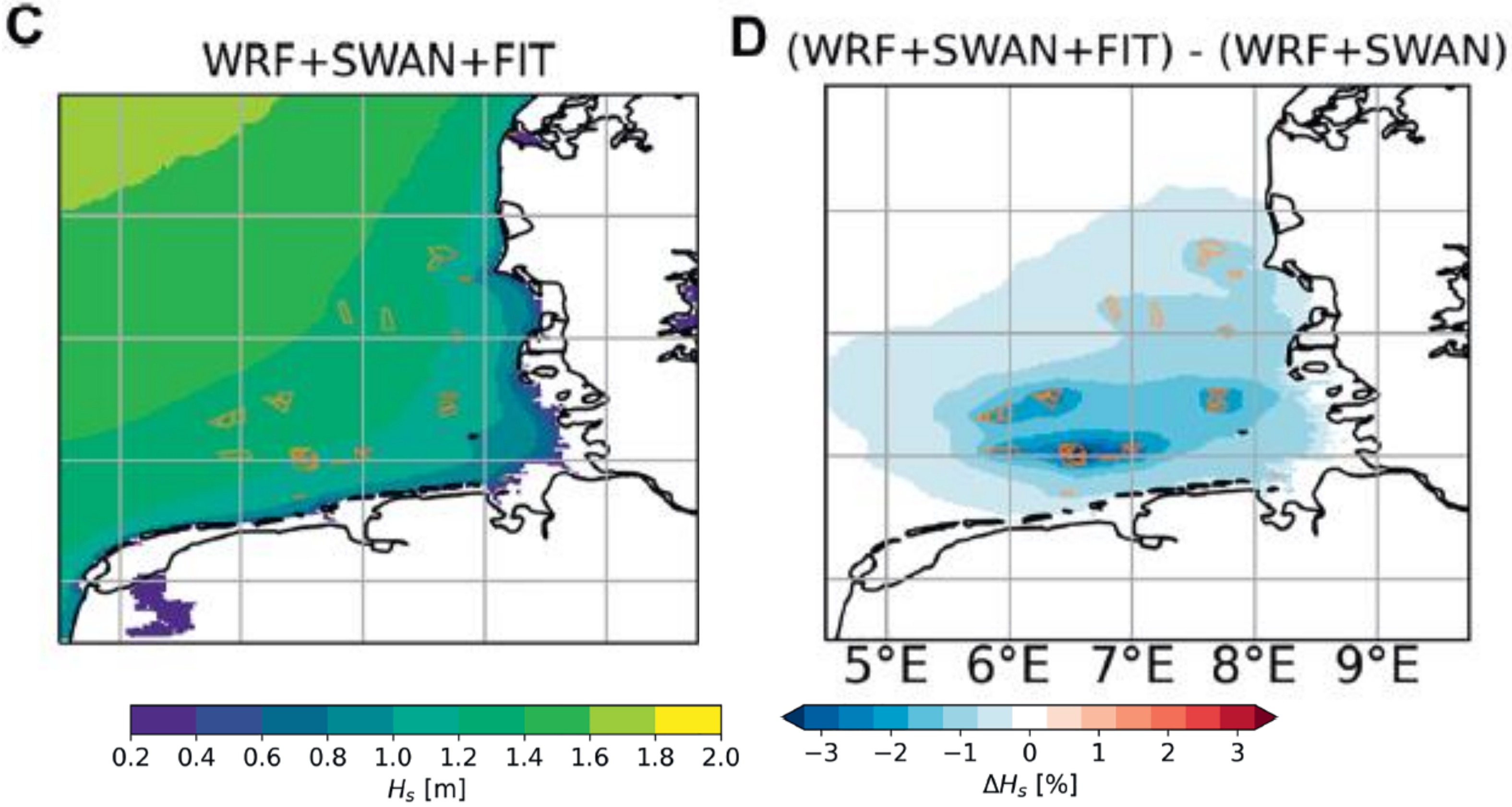


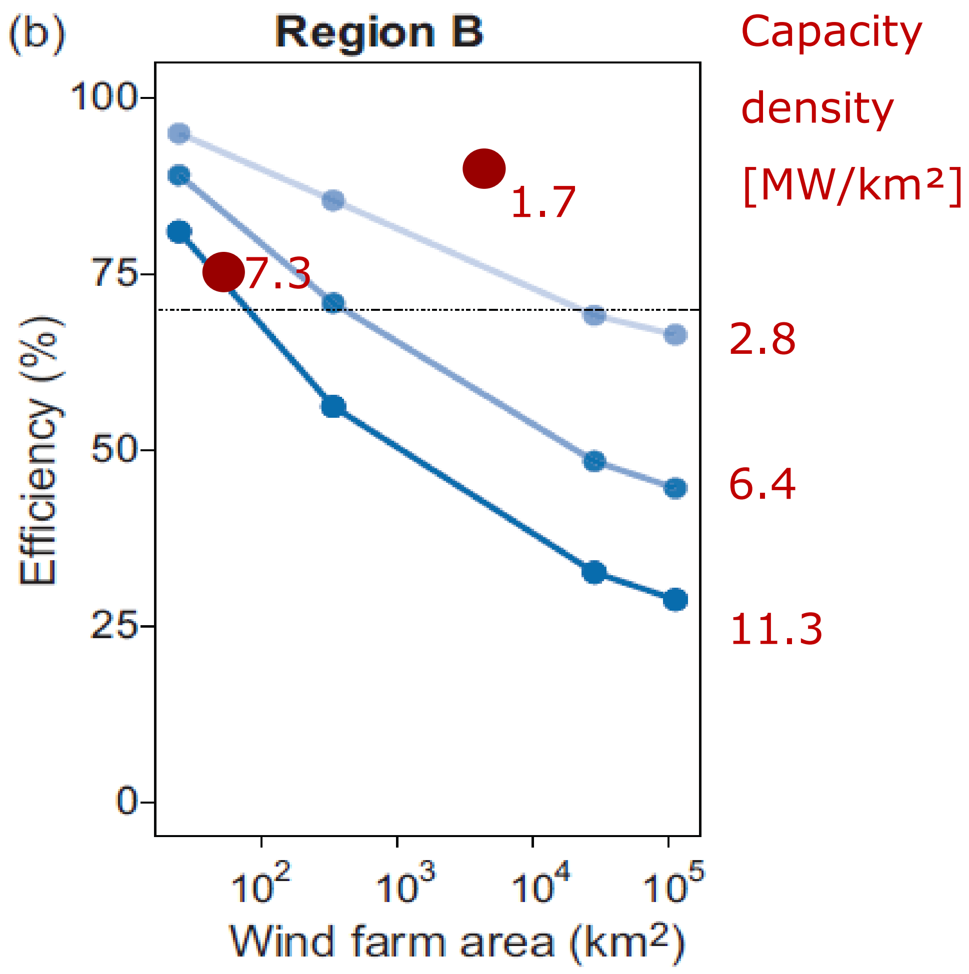
FIGURE 13 | (A) Long-term significant wave height (H_s) from ERA5 and simulated by **(B)** WRF + SWAN and **(C)** WRF + SWAN + FIT. **(D)** Relative reduction on significant wave height from (WRF + SWAN + FIT)-(WRF + SWAN) normalized by (WRF + SWAN).

Fischereit, J., Larsen, X.G. and Hahmann, A.N., 2022. Climatic Impacts of Wind-Wave-Wake Interactions in Offshore Wind Farms. *Frontiers in Energy Research*, *10*, p.881459.

Conclusions

My unofficial production estimate for 150 GW in North Sea is 507 – 570 TWh

- Capacity goals are ambitions and grounded in data
- Estimating yield for these installed capacities must consider wind farm wake impacts
  – different approaches have been presented
- Uncertainty estimation is needed
  – Validation is a challenge given the scale of installations does not yet exist
- Modelling approaches show promise
  – Broader impacts on environment can also to be assessed



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Thank you for your attention

Contact: jaba@dtu.dk

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