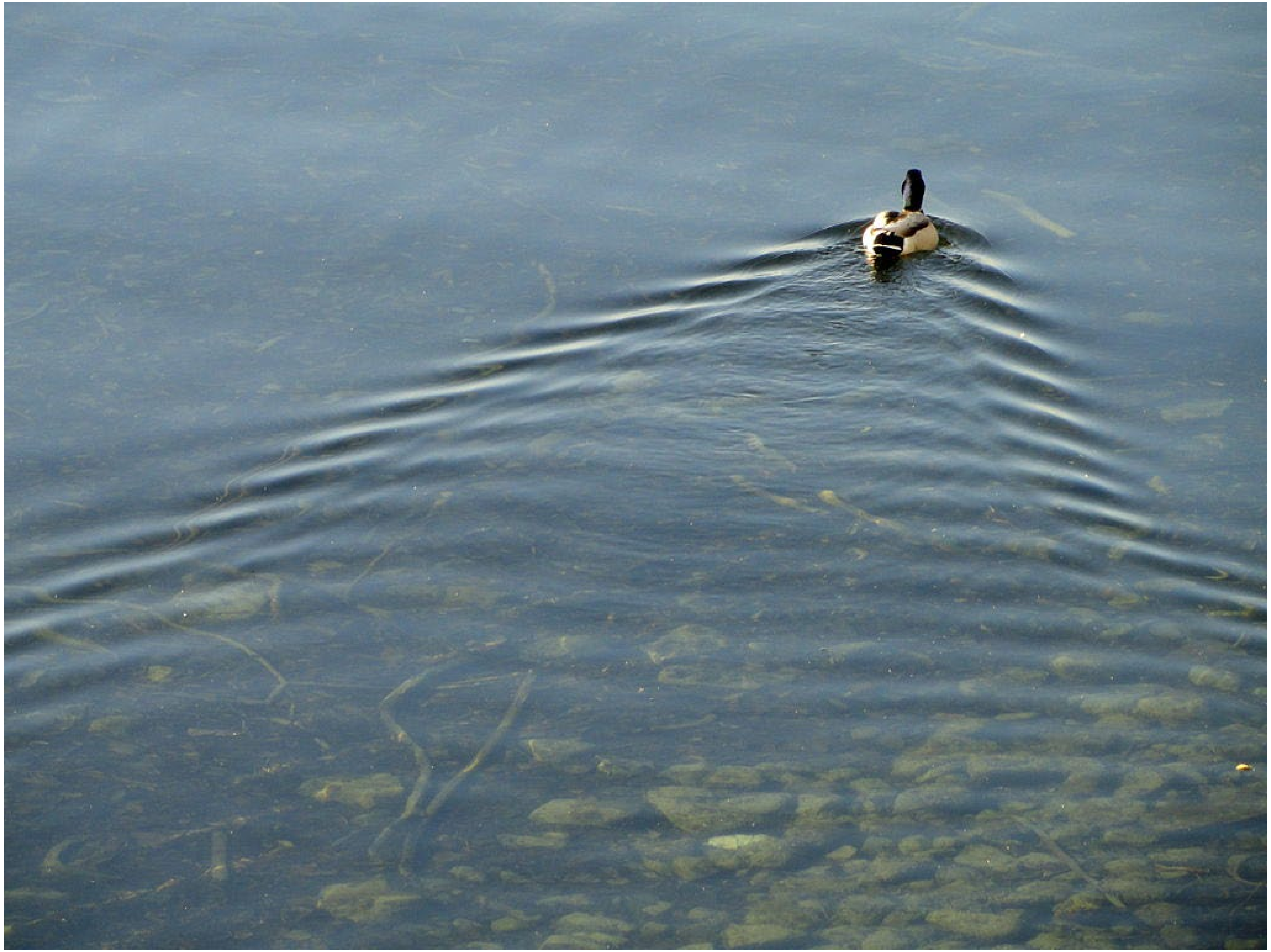
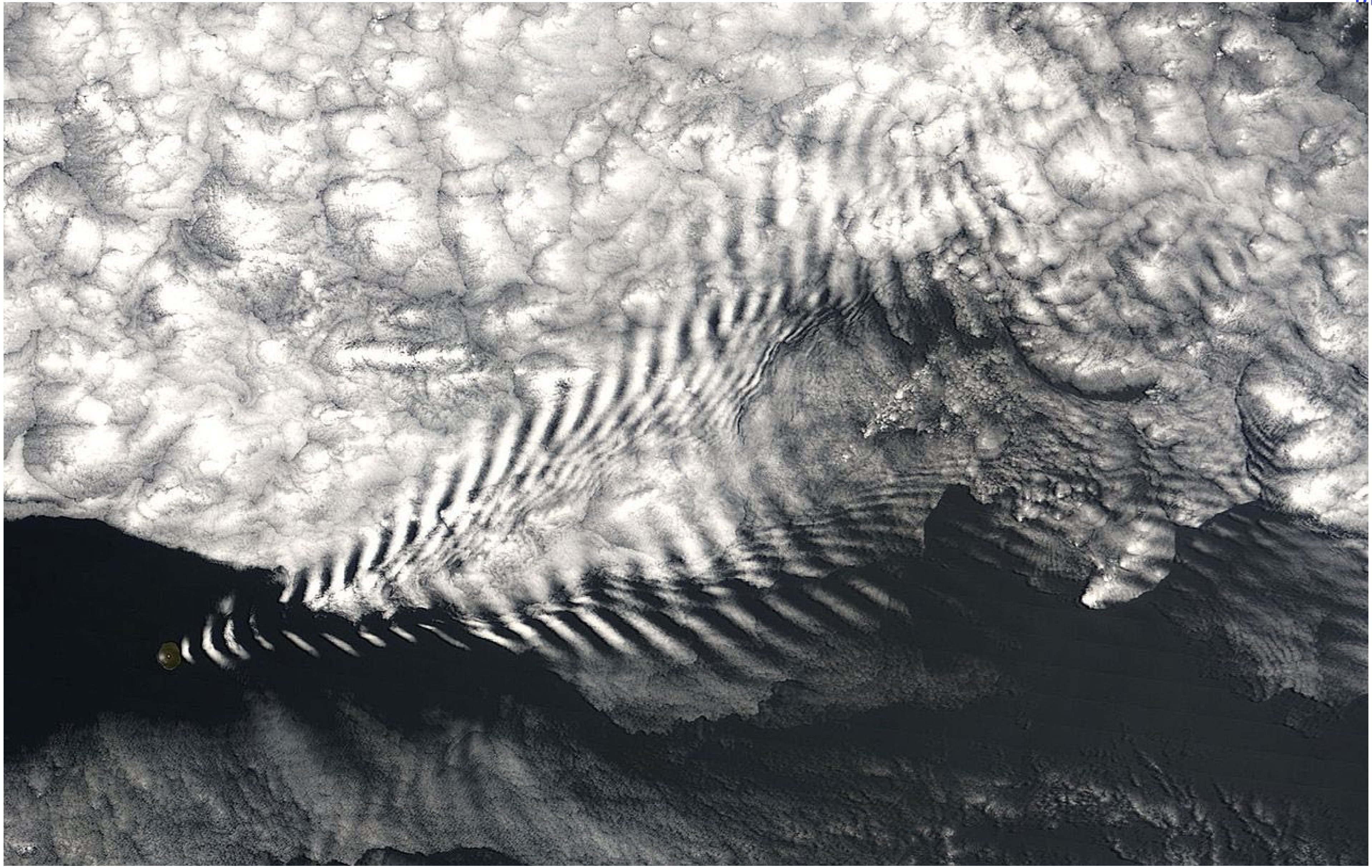
Modelling and analysis methods and the need for mesoscale modelling

Jake Badger



Picture: Daderot

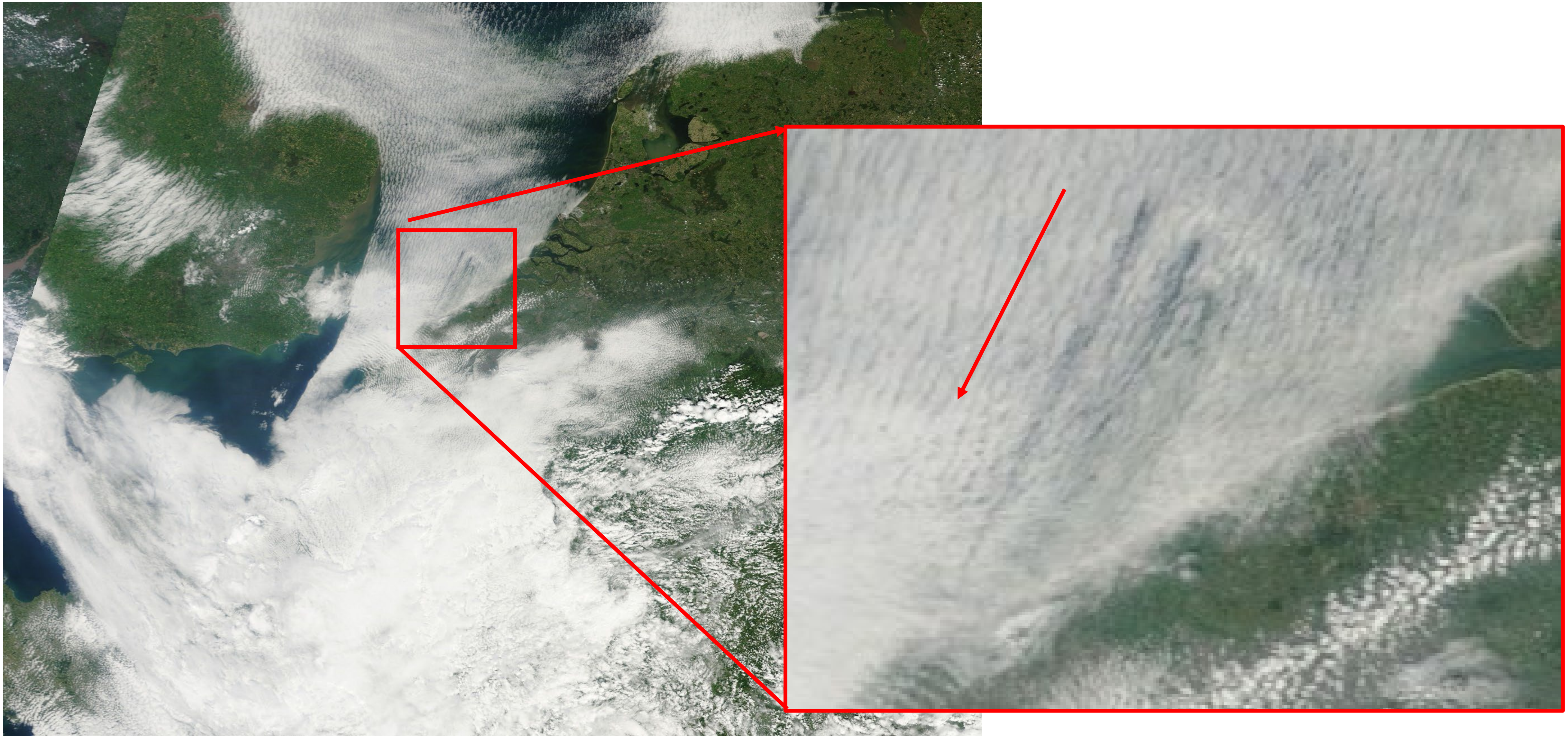


Île Amsterdam, Indian Ocean

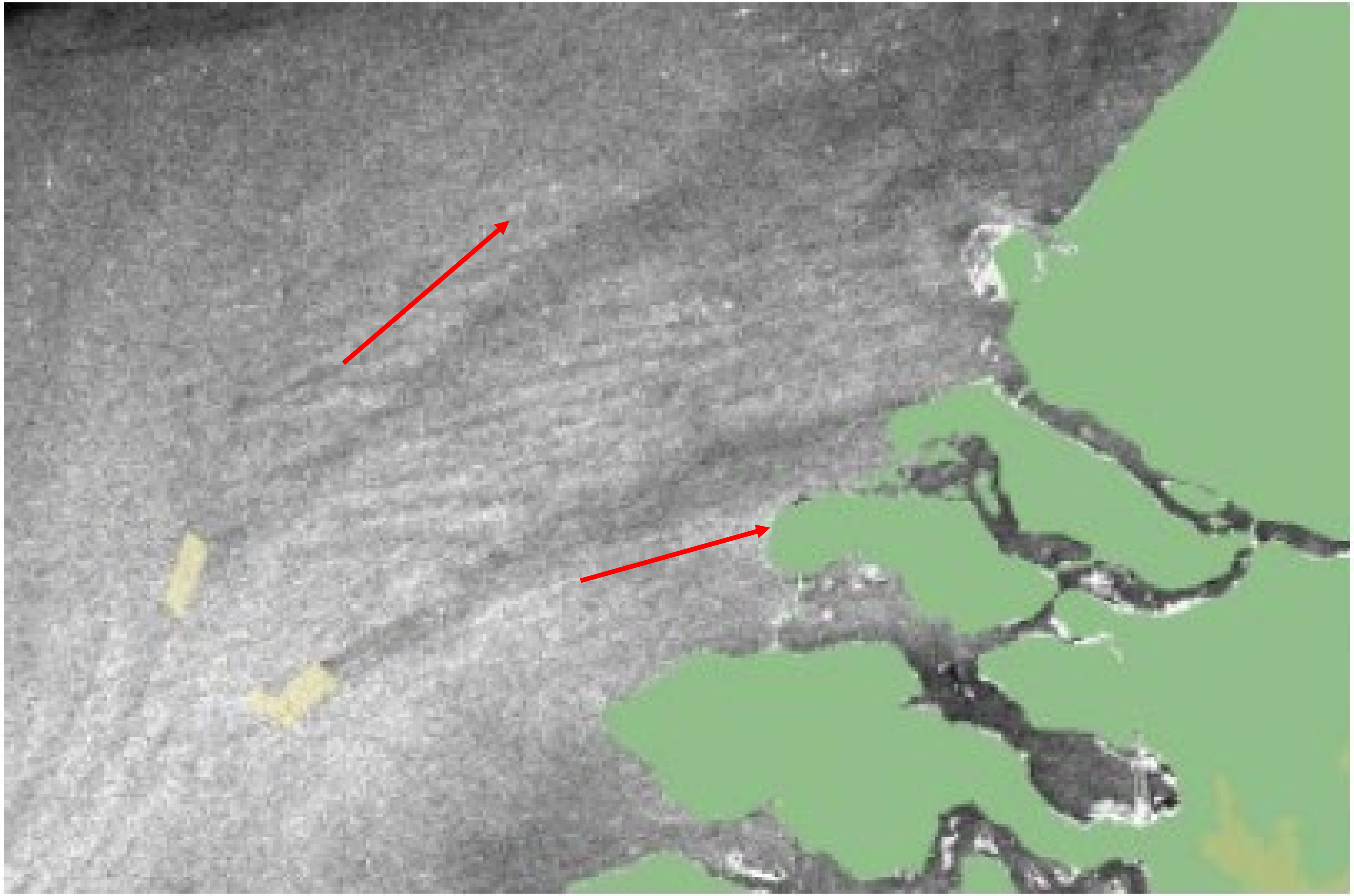
Indications of turbine wakes

Photo Bel Air Aviation, Denmark

Indications of wind farm wakes



Indications of wind farm wakes



~50 km

Synthetic Aperture Radar
Satellite scene

Review papers of interest (1)

- Porté-Agel, F., Bastankhah, M. and Shamsoddin, S., 2020. Wind-turbine and wind-farm flows: a review. *Boundary-layer meteorology*, *174*(1), pp.1-59.

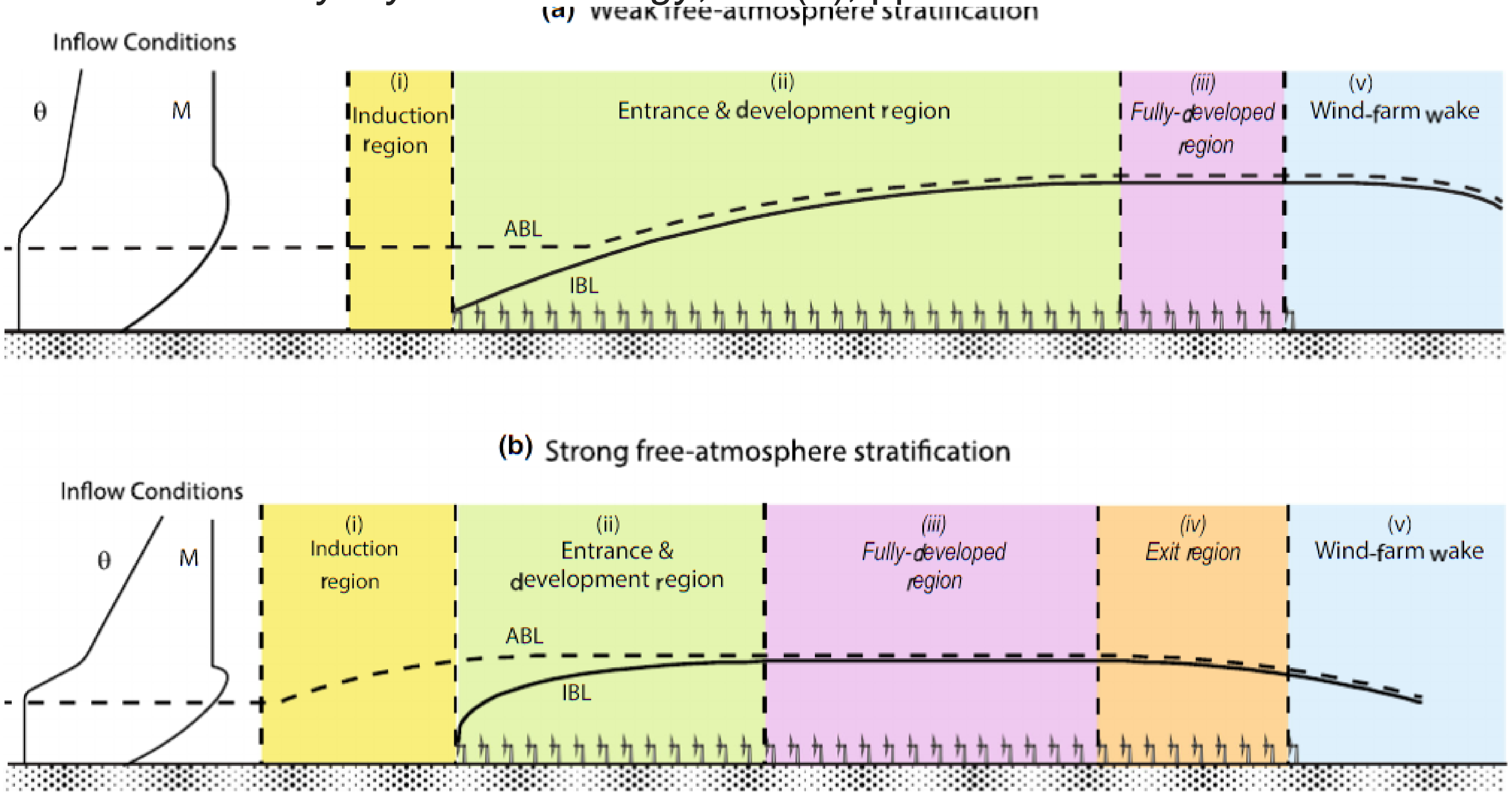
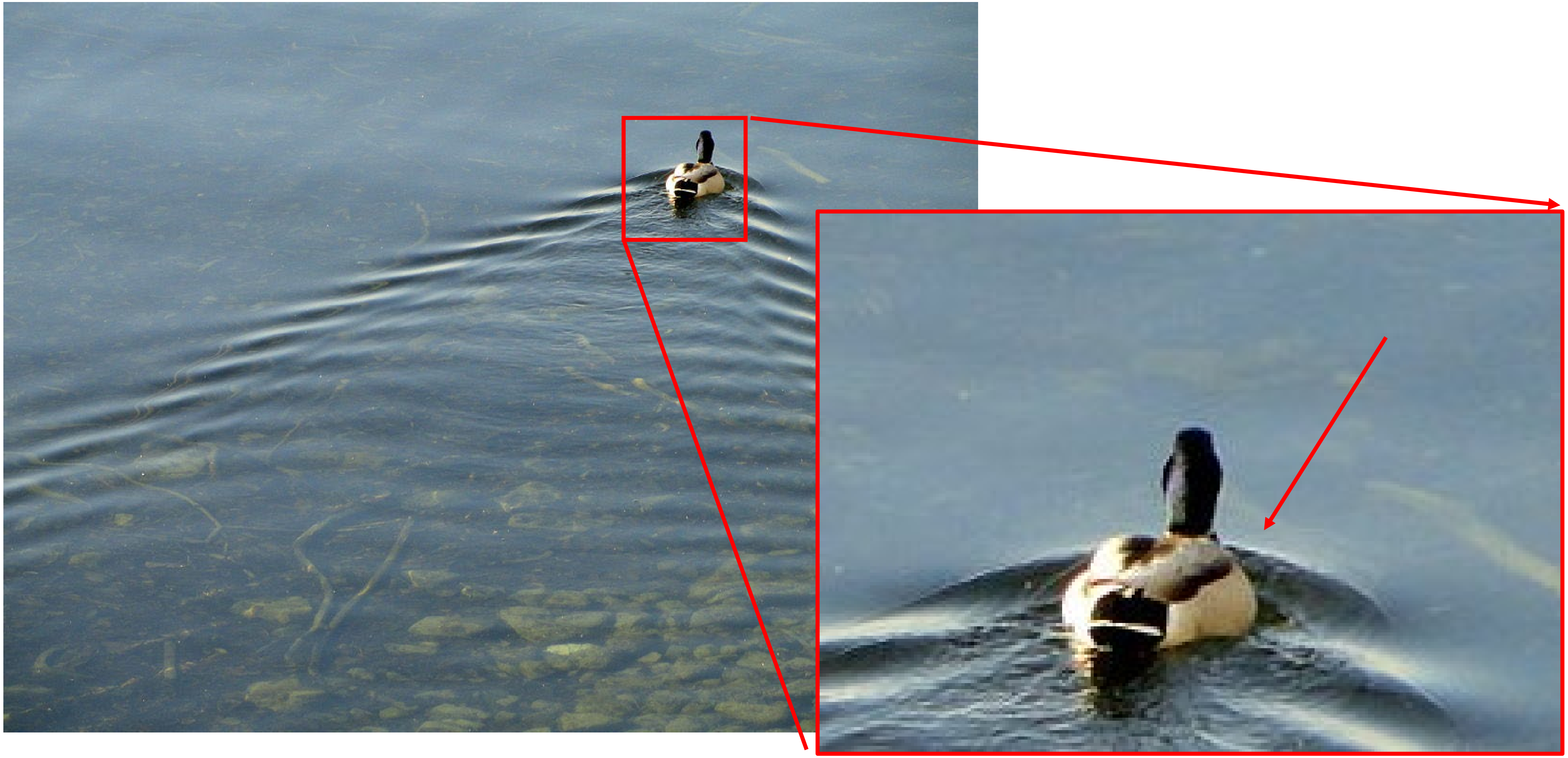
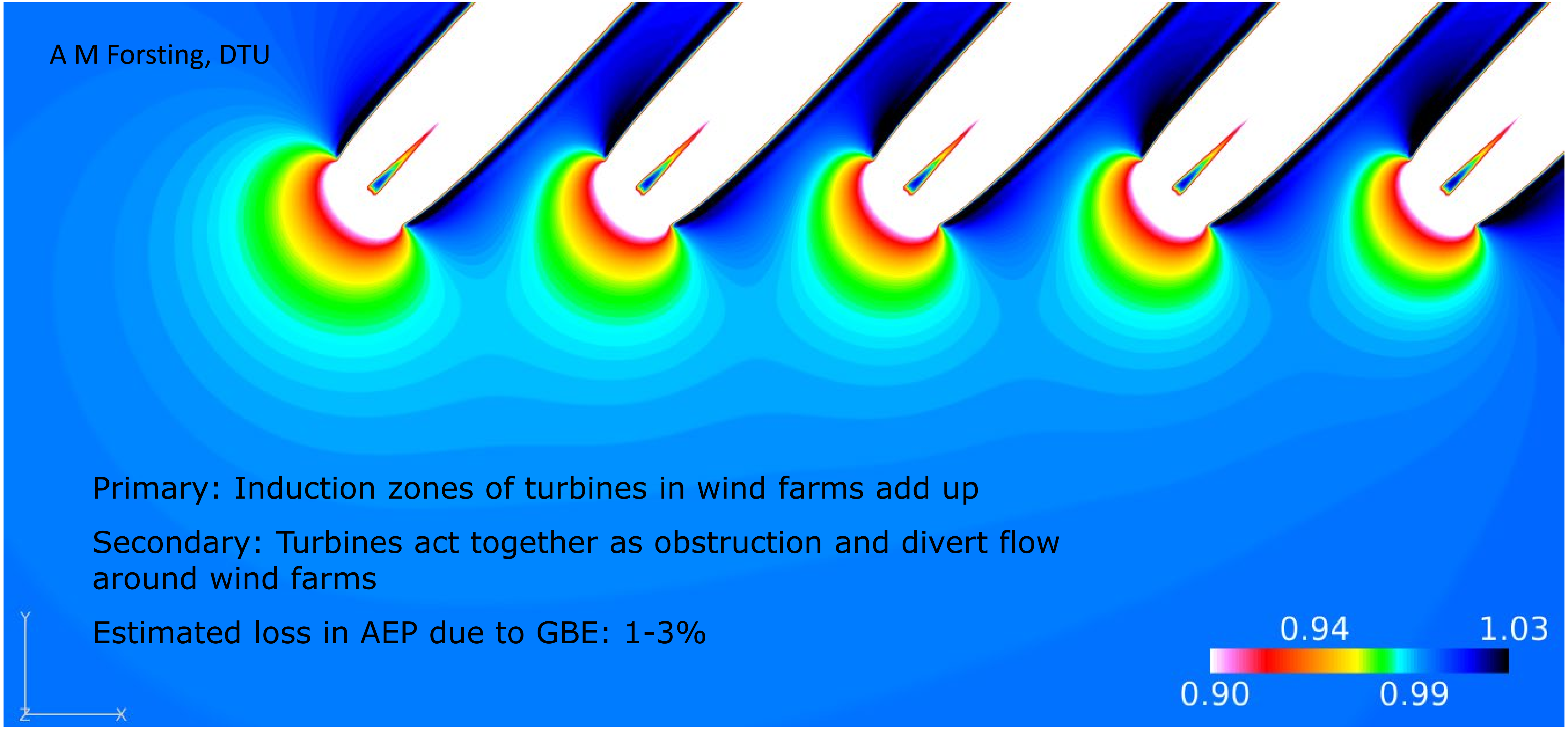


Fig. 10 Schematic showing different flow regions caused by the interaction of a very large wind farm with a conventionally-neutral ABL under weak free-atmosphere stratification (**a**) and strong free-atmosphere stratification (**b**). The dashed and continuous lines represent the top of the ABL and the farm-induced IBL, respectively. Inflow conditions are represented by vertical profiles of the mean potential temperature (θ) and mean wind speed (M). In italics: regions that might or might not be present in a wind farm, depending on the wind-farm size and the free-atmosphere stratification. Figure modified from Wu and Porté-Agel (2017)



Picture: Daderot

Global blockage effect (GBE)



Modelled winds by EllipSys3D, RANS-CFD with actuator disks

Meyer Forsting, AR 2017, *Modelling Wind Turbine Inflow: The Induction Zone*. DTU Wind Energy. https://doi.org/10.11581/DTU:00000022

Main types of wake modelling

- Engineering wake models
  - Gaussian wake model
  - Park model
  - … mainly go under “family” of Wake Deficit Models
    https://topfarm.pages.windenergy.dtu.dk/PyWake/notebooks/WakeDeficitModels.html

- Higher fidelity wake models
  - Large Eddy Simulation (LES) – computational fluid dynamics (CFD)
  - Reynolds-averaged Navier-Stokes (RANS) simulations – computational fluid dynamics (CFD)
  - …

- Mesoscale modelling of wind farm wakes
  - Running Weather and Research Forecasting (WRF) Model with
    - Fitch Scheme
    - Explicit Wake Parameterization (EWP)
    - …

Lillgrund Wind Farm PyWake Validation

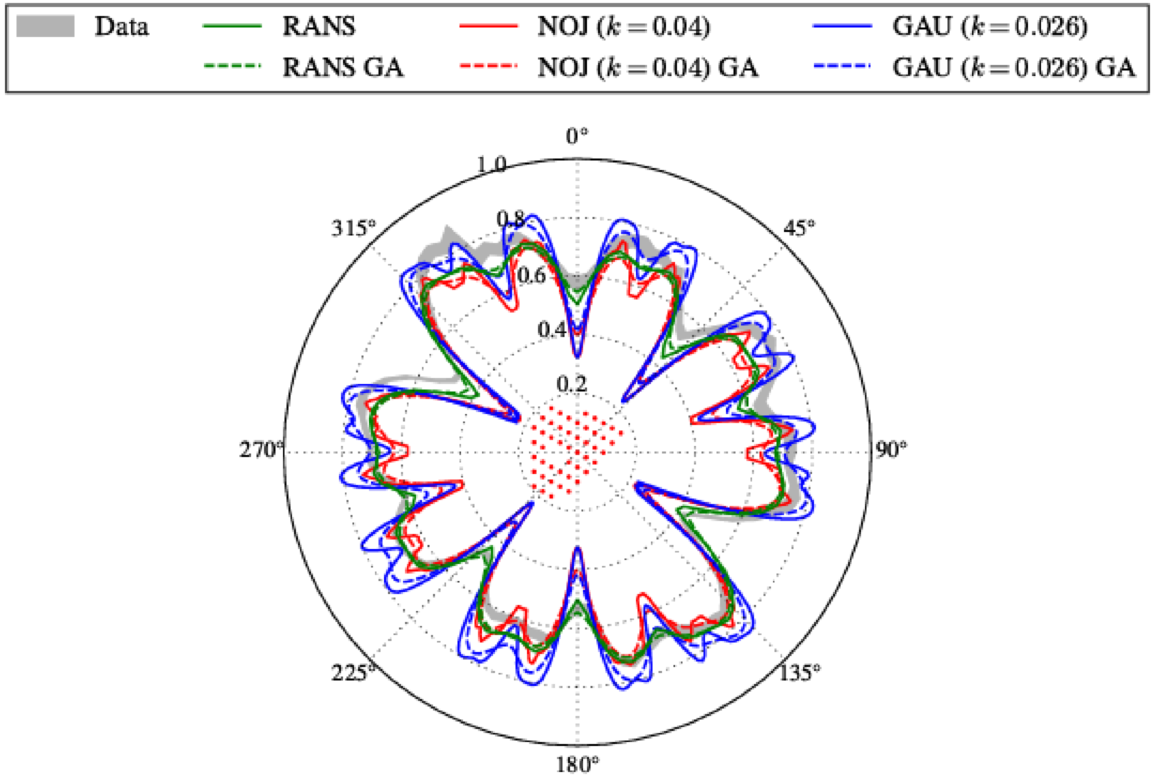
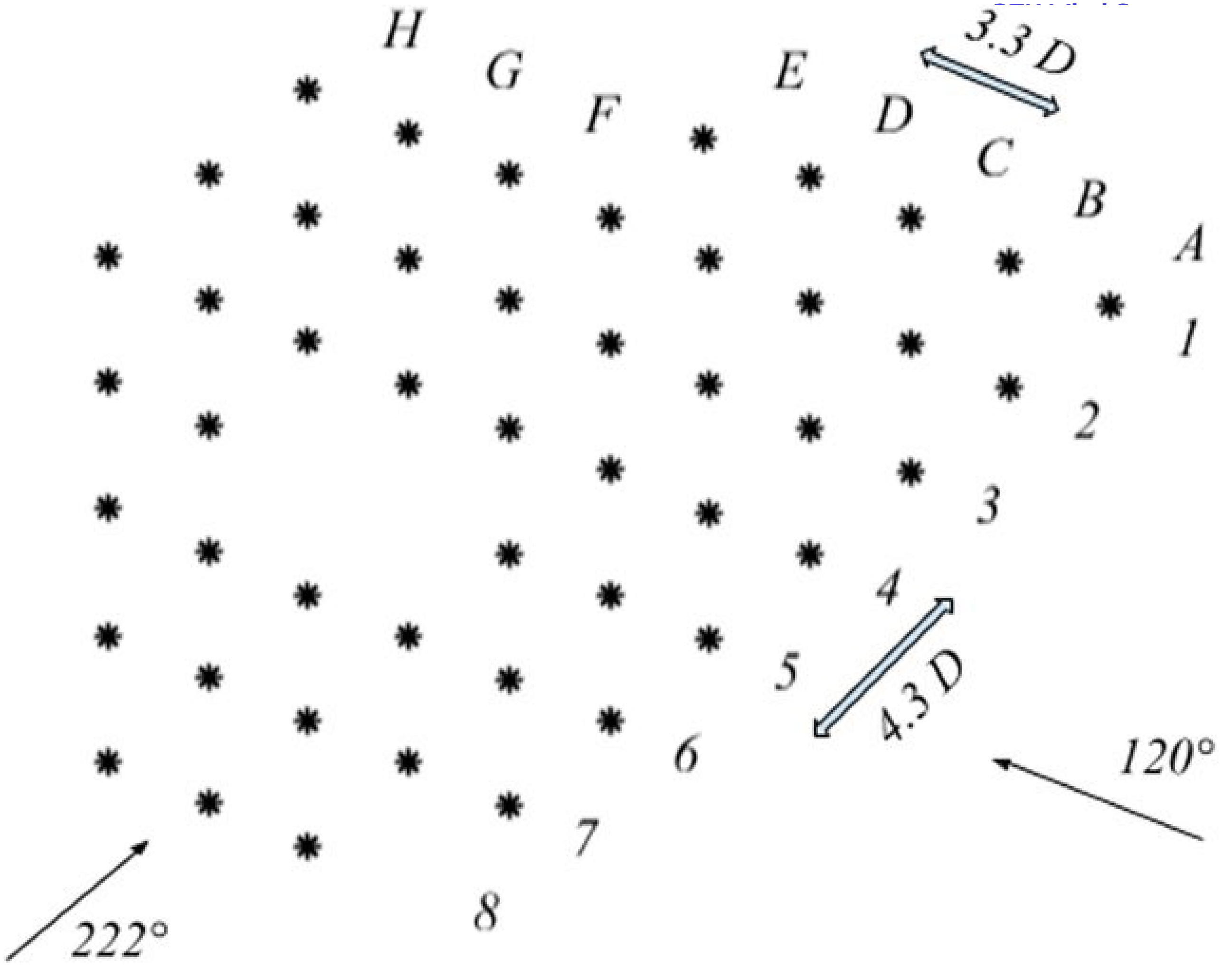


Figure 17: Case 12: Lillgrund wind farm efficiency.

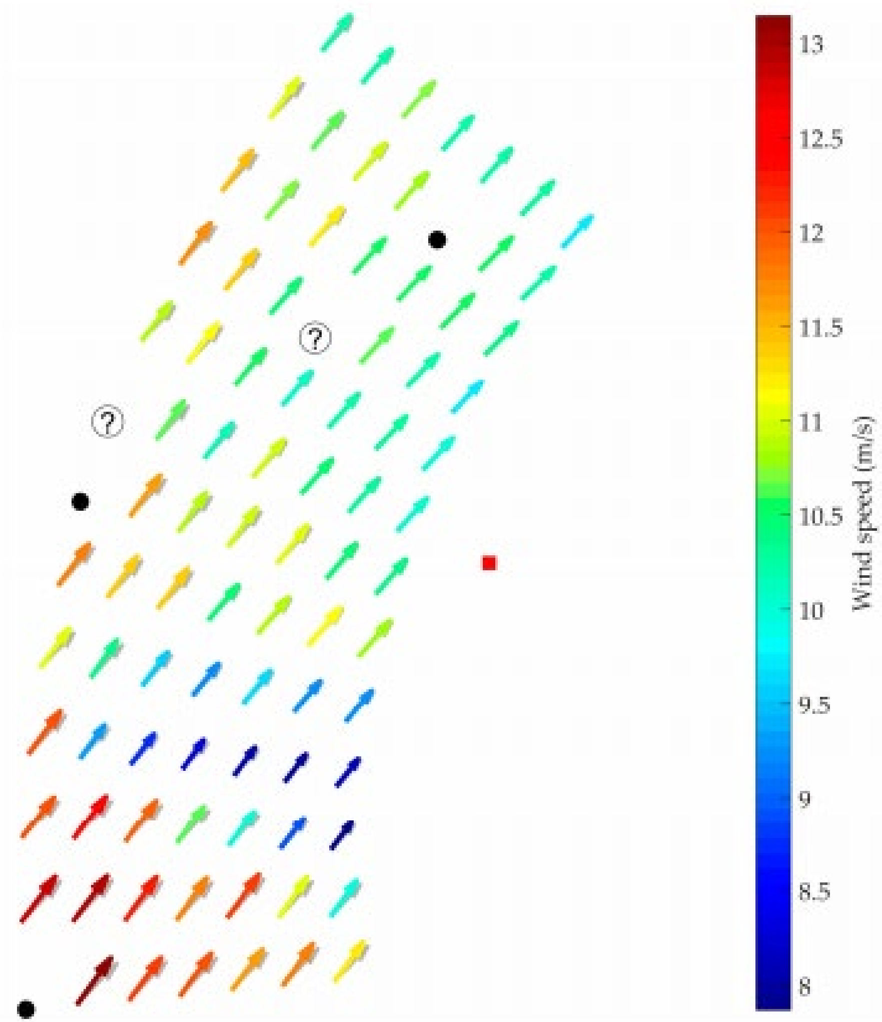
https://topfarm.pages.windenergy.dtu.dk/PyWake/validation.html



Sebastiani, Alessandro & Castellani, Francesco & Crasto, Giorgio & Segalini, Antonio. (2021). Data analysis and simulation of the Lillgrund wind farm. Wind Energy. 24. 10.1002/we.2594.

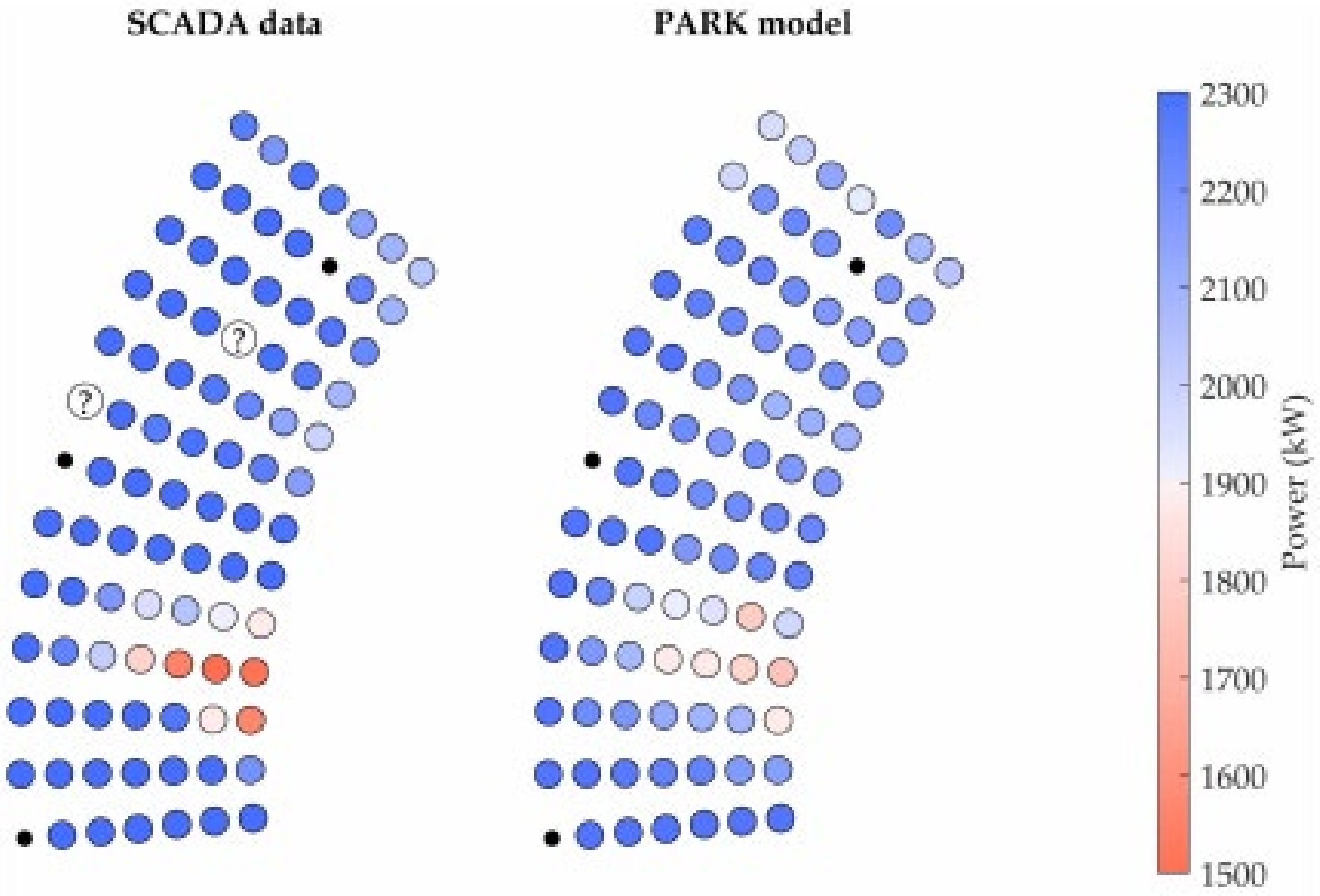
Horns Rev 2 wind speed from nacelle anemometers

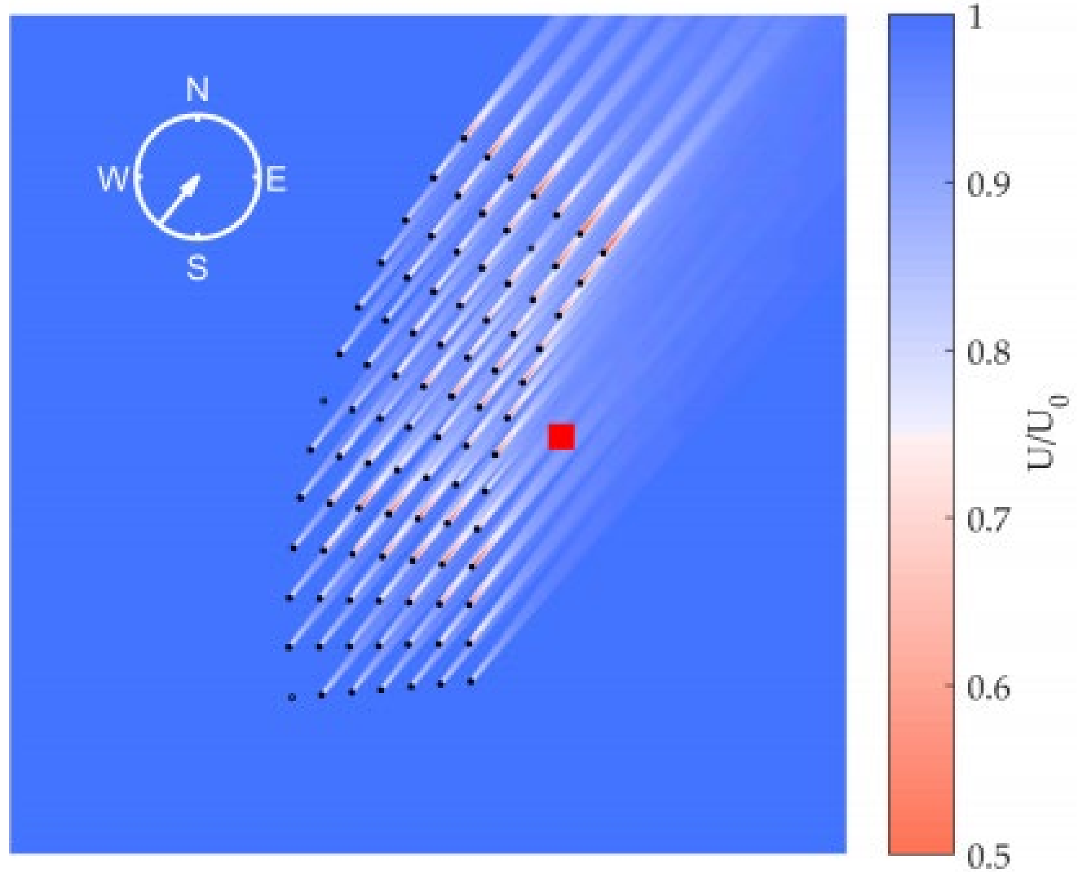
Photo Bel Air Aviation, Denmark



Hasager, CB, Nygaard, NG, Volker, P, Karagali, I, Andersen, SJ & Badger, J 2017, 'Wind Farm Wake: The 2016 Horns Rev Photo Case', *Energies*, vol. 10, no. 3, 317. https://doi.org/10.3390/en10030317

Wake modelling: fast engineering models

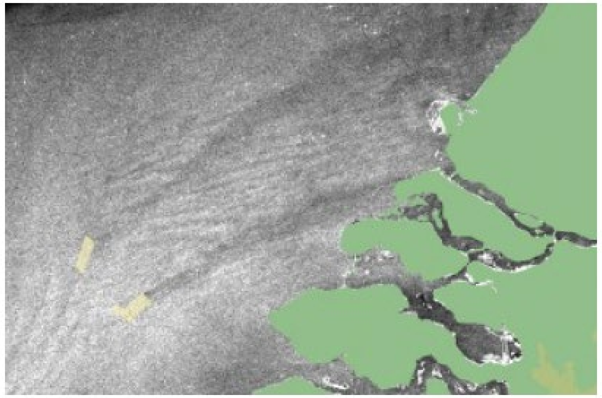




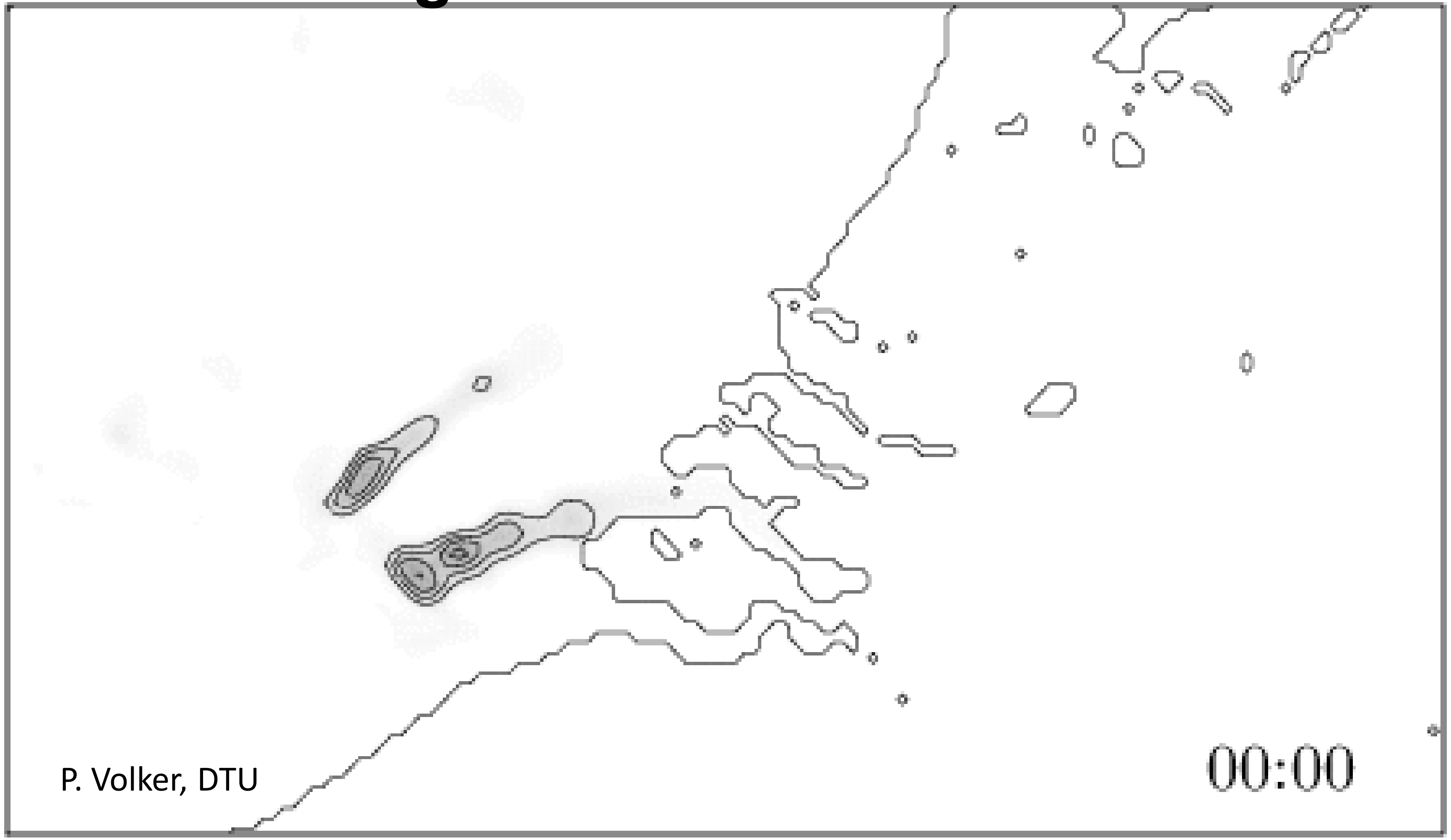
Horns Rev 2 power production on 25/1/2016 13:00 UTC

Hasager, CB, Nygaard, NG, Volker, P, Karagali, I, Andersen, SJ & Badger, J 2017, 'Wind Farm Wake: The 2016 Horns Rev Photo Case', *Energies*, vol. 10, no. 3, 317. https://doi.org/10.3390/en10030317

Mesoscale modelling of wind farm wake



Flow is complex, changing in time and space (t,x,y,z)
Other properties of flow matter too.



Wind farms as increased surface roughness

Keith, D.W., DeCarolis, J.F., Denkenberger, D.C., Lenschow, D.H., Malyshev, S.L., Pacala, S. and Rasch, P.J., 2004. The influence of large-scale wind power on global climate. *Proceedings of the National Academy of Sciences*, *101*(46), pp.16115-16120.

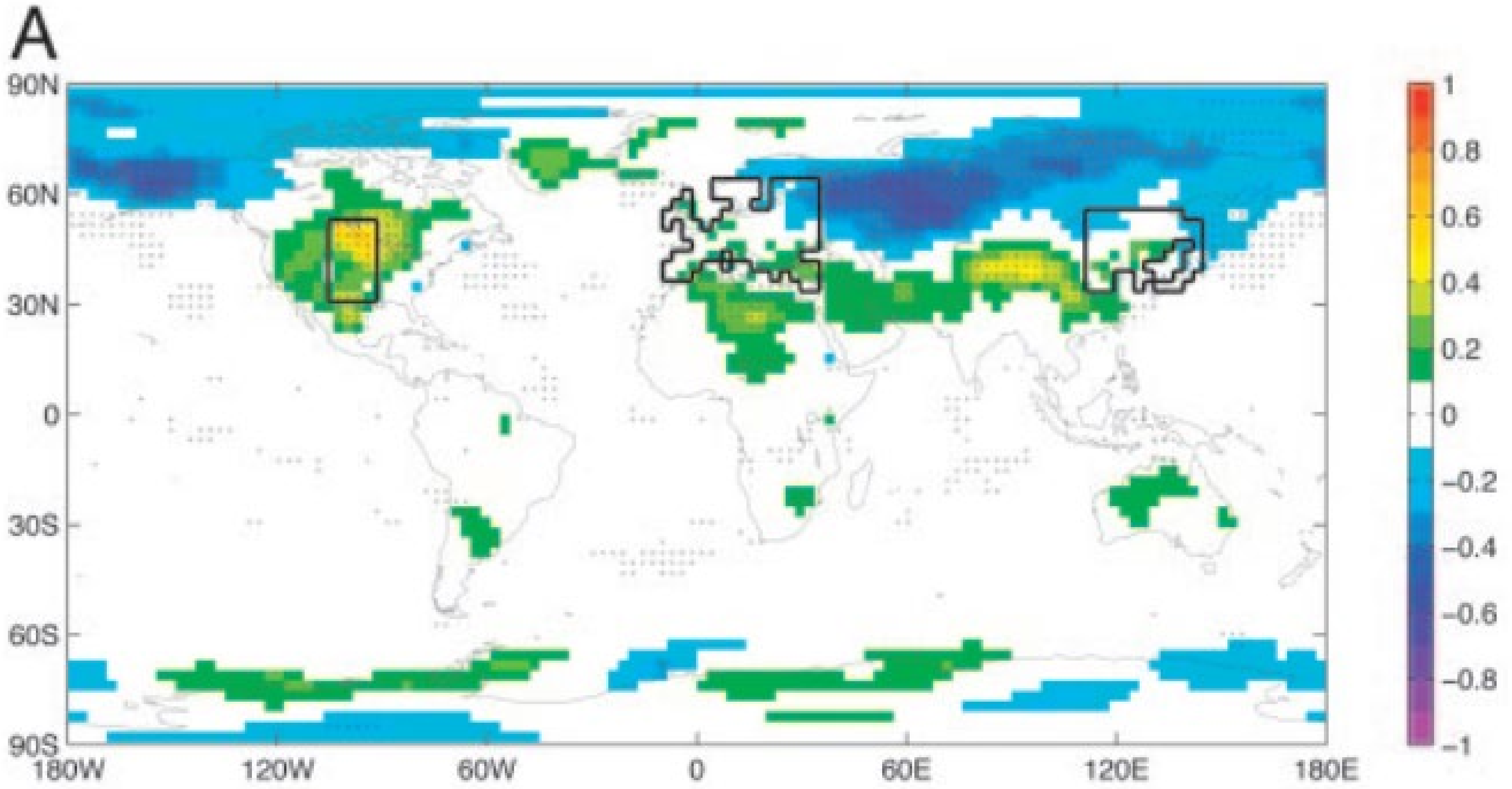


Fig. 1. Wind-farm array and temperature response. Data are surface (2 m) air temperature, experiment minus control. Drag perturbation, CD, was 0.005 over the A wind-farm array outlined in black.

Wind farms as increased surface roughness

- Frandsen, S.T., Jørgensen, H.E., Barthelmie, R., Rathmann, O., Badger, J., Hansen, K., Ott, S., Rethore, P.E., Larsen, S.E. and Jensen, L.E., 2009. The making of a second-generation wind farm efficiency model complex. *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology*, *12*(5), pp.445-458.

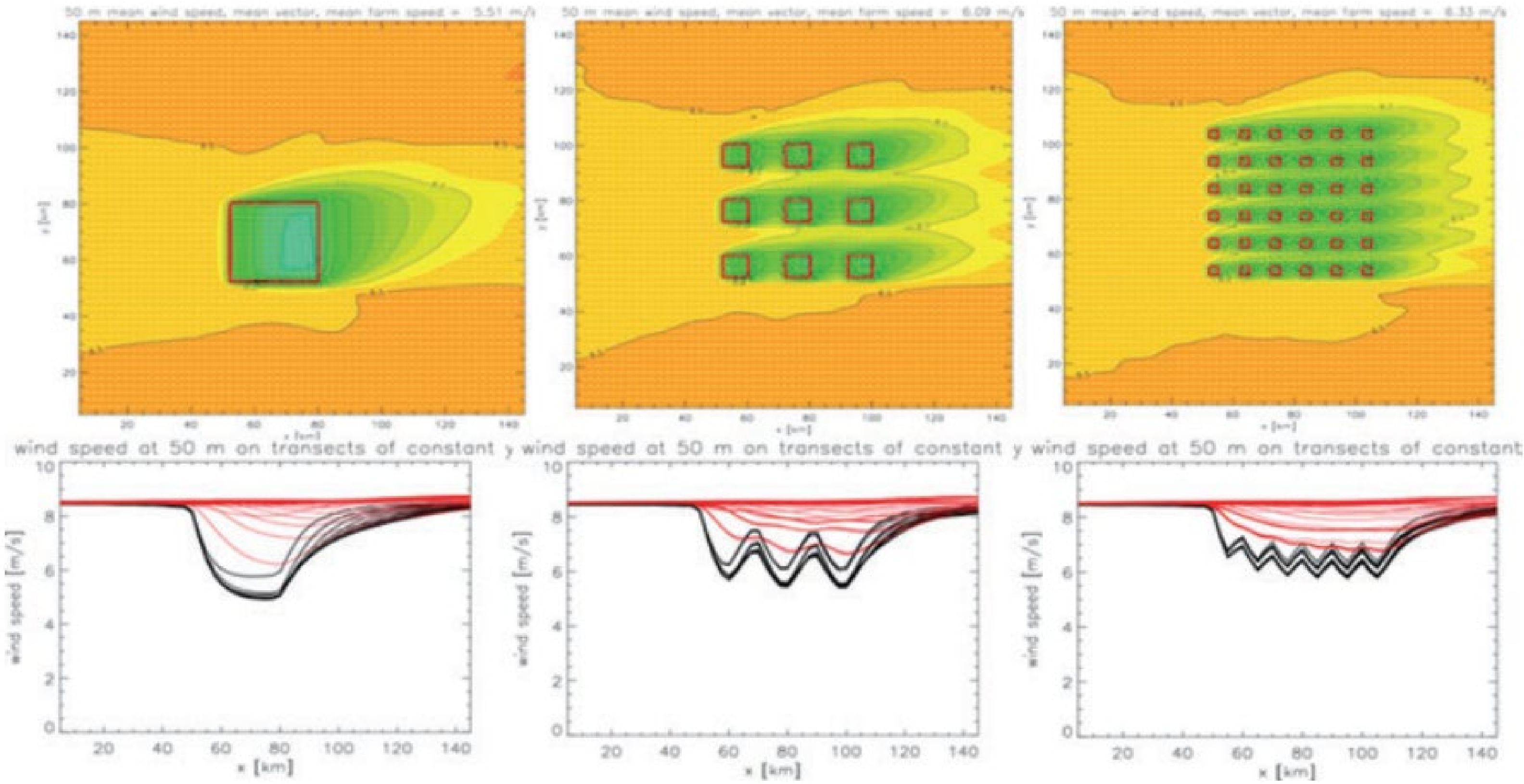


Figure 10. The mean wind speed for the three wind farm configurations.

Black and red lines show transects that do pass and transects that do not pass through the wind farm grid cells, respectively

Wind farms as elevated sink of resolved kinetic energy (KE) and source of turbulent kinetic energy (TKE)

Fitch, A.C., Olson, J.B., Lundquist, J.K., Dudhia, J., Gupta, A.K., Michalakes, J. and Barstad, I., 2012. Local and mesoscale impacts of wind farms as parameterized in a mesoscale NWP model. *Monthly Weather Review*, *140*(9), pp.3017-3038.

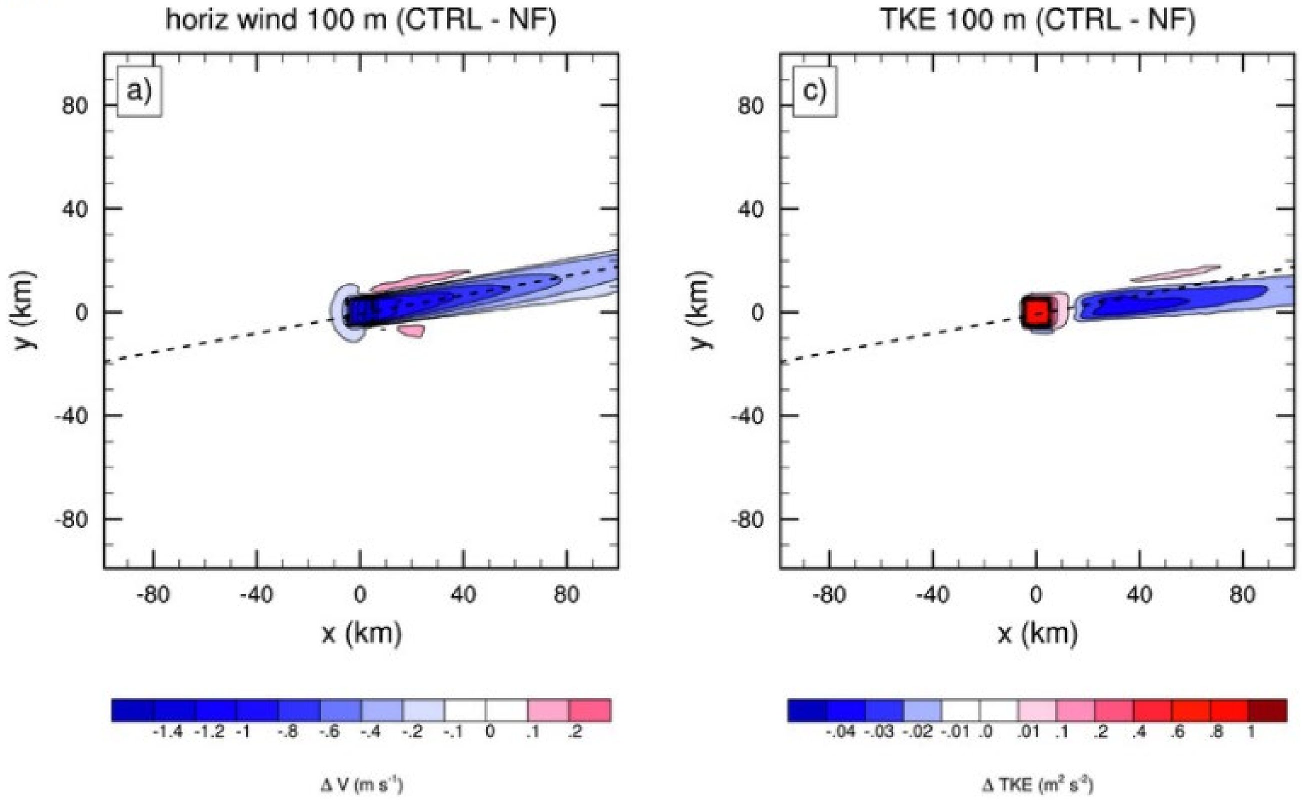
Fitch Scheme

FIG. 2.

$$\frac{\partial|\mathbf{V}|_{ijk}}{\partial t} = -\frac{\frac{1}{2}N_t^{ij}C_T(|\mathbf{V}|_{ijk})|\mathbf{V}|_{ijk}^2A_{ijk}}{(z_{k+1}-z_k)}. \tag{8}$$

$$\frac{\partial P_{ijk}}{\partial t} = \frac{\frac{1}{2}N_t^{ij}C_P(|\mathbf{V}|_{ijk})|\mathbf{V}|_{ijk}^3A_{ijk}}{(z_{k+1}-z_k)}. \tag{11}$$

$$\frac{\partial \mathrm{TKE}_{ijk}}{\partial t} = \frac{\frac{1}{2}N_t^{ij}C_{\mathrm{TKE}}(|\mathbf{V}|_{ijk})|\mathbf{V}|_{ijk}^3A_{ijk}}{(z_{k+1}-z_k)}. \tag{12}$$

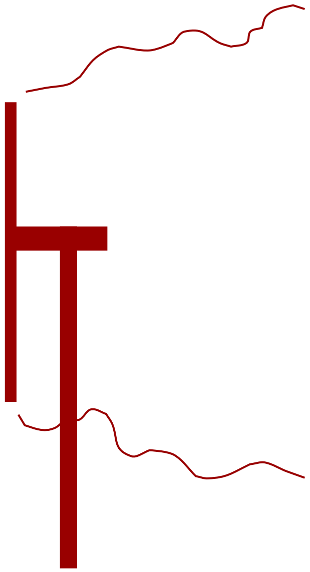


C_{TKE} is then given by $C_T - C_P$

"TKE source is overestimated; although, given that modern turbines have been designed to keep losses to a minimum, this overestimate should be rather small."

TKE treatments

Volker, P.J.H., Badger, J., Hahmann, A.N. and Ott, S., 2015. The Explicit Wake Parametrisation V1. 0: a wind farm parametrisation in the mesoscale model WRF. *Geoscientific Model Development*, *8*(11), pp.3715-3731.

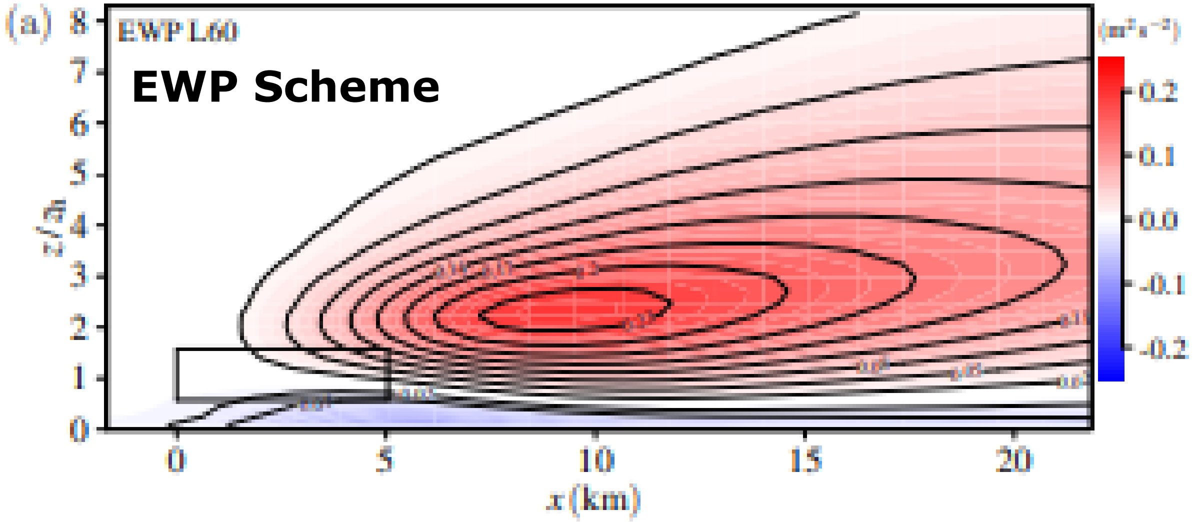


EWP Scheme

Drag force imposed over expanded vertical extent, i.e. larger the rotor extent.

Explicit wake parameterization.

No TKE injection: let the MYNN scheme add this



Fitch Scheme

Drag force imposed only over vertical extent of rotor.

TKE injection

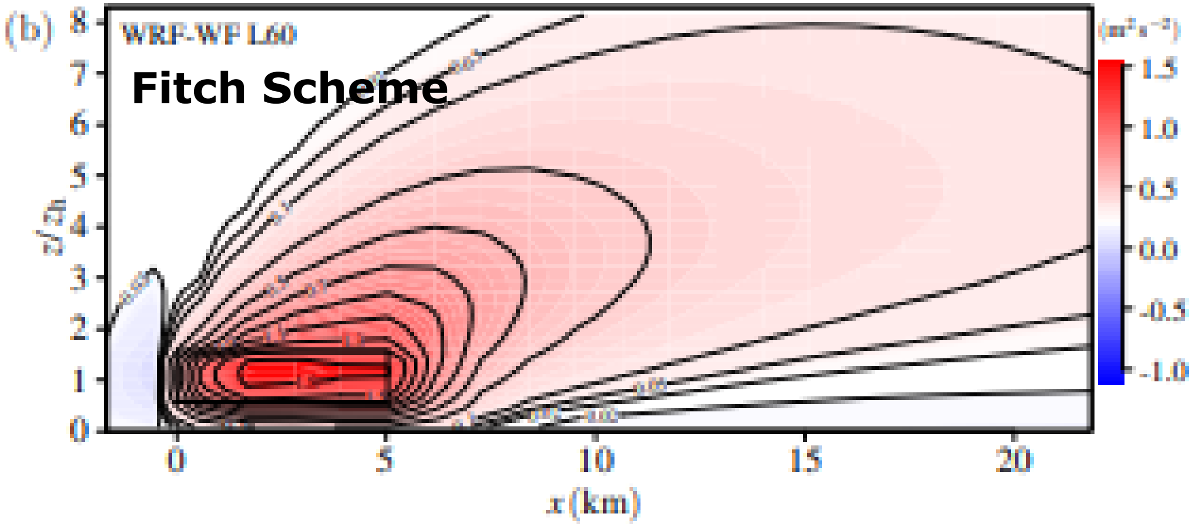


Fig 8: Vertical cross section of the TKE difference for (a) EWP and (b) WRF-WF scheme

Wind farms as elevated sink of resolved kinetic energy (KE) over expanded wake vertical wake extent

DTU Wind Energy

EWP Scheme

Volker, P.J., Hahmann, A.N., Badger, J. and Jørgensen, H.E., 2017. Prospects for generating electricity by large onshore and offshore wind farms. *Environmental Research Letters*, *12*(3), p.034022.

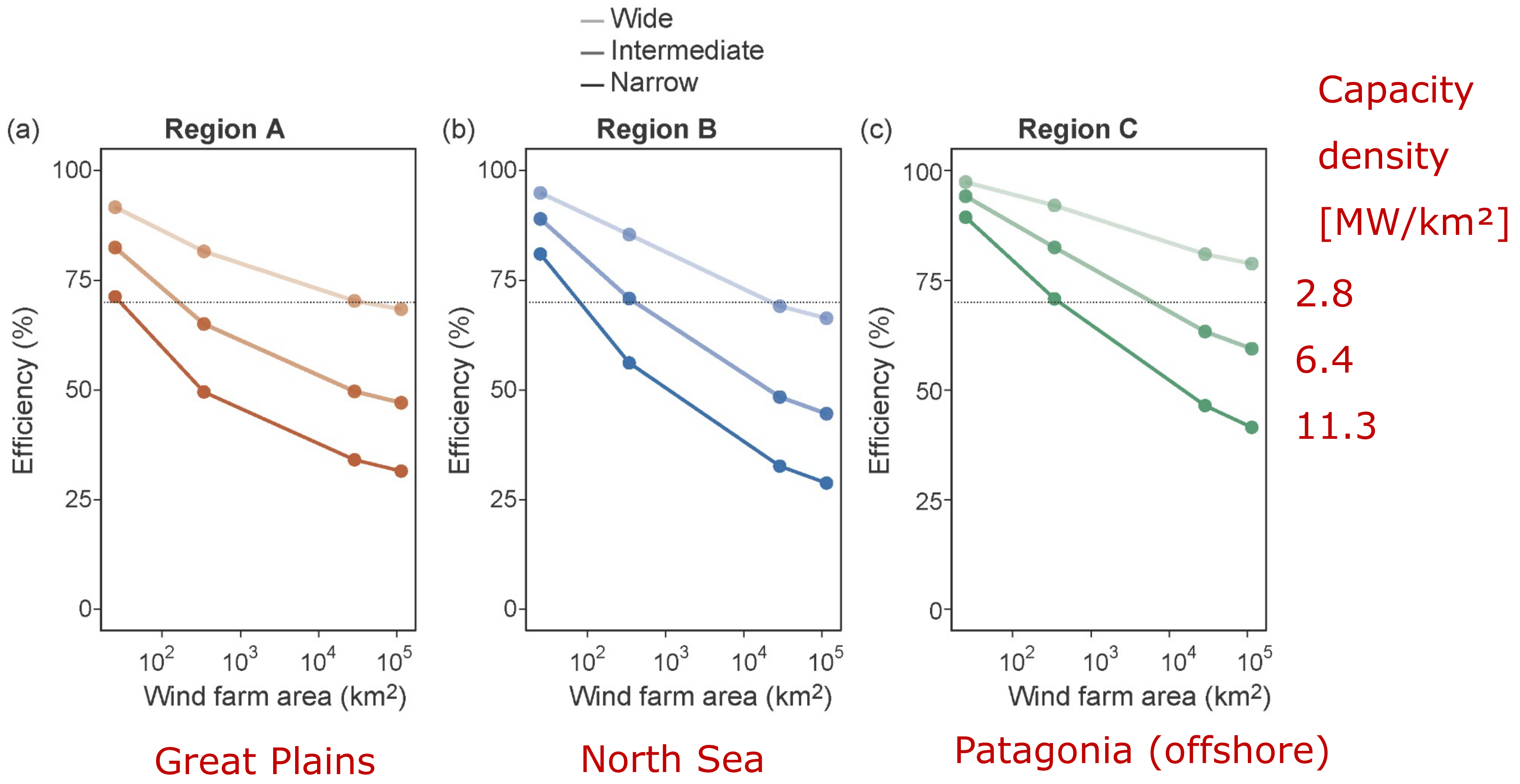
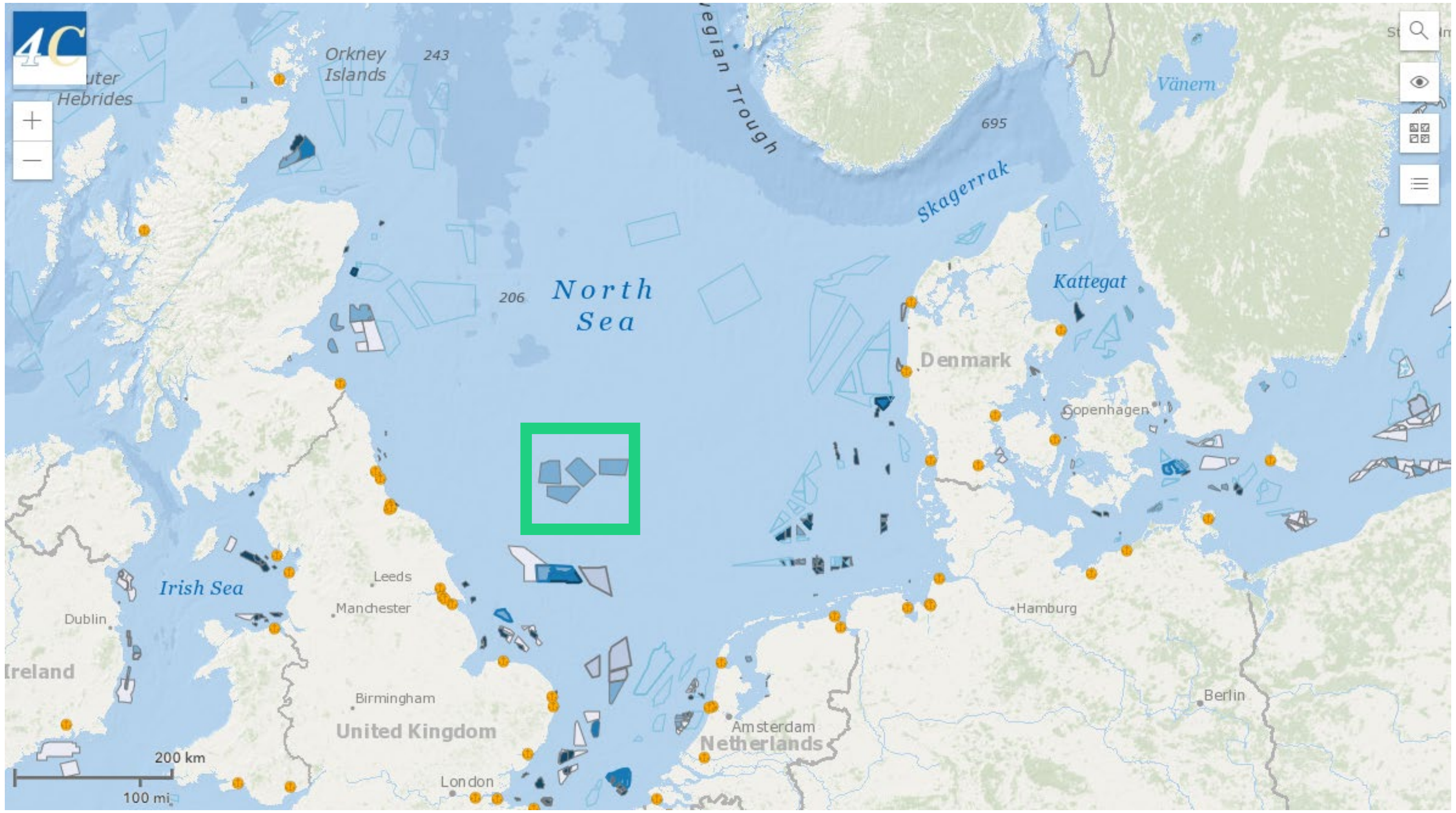
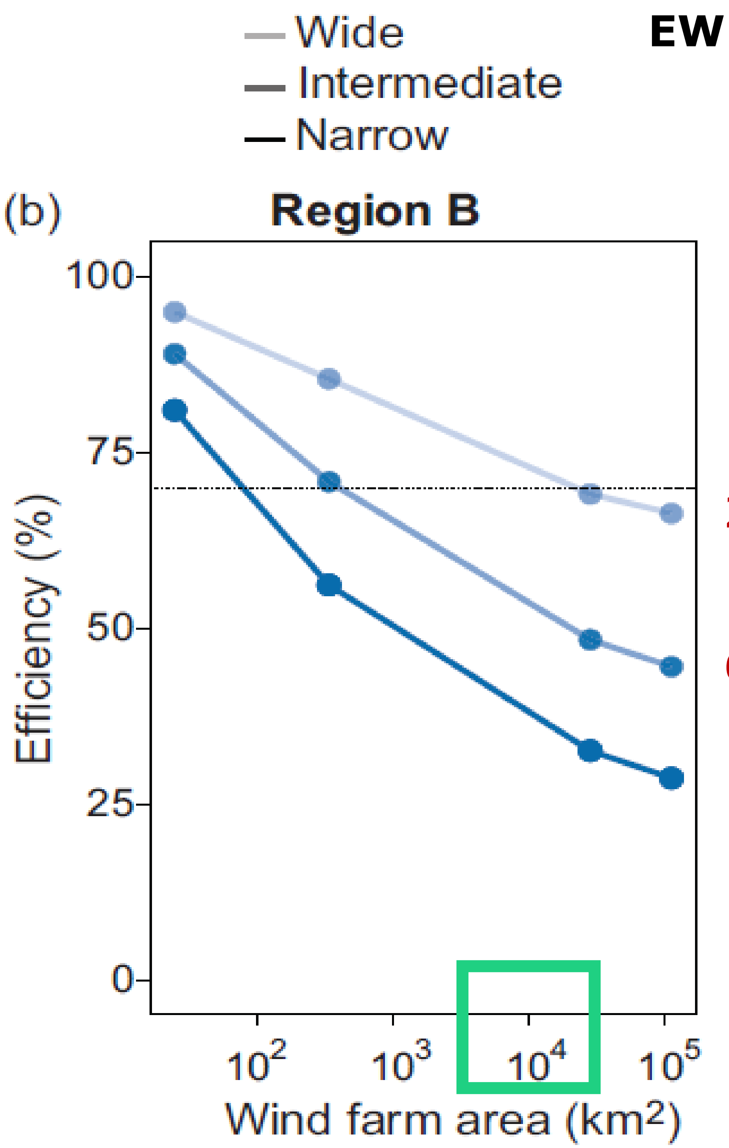


Figure 5 Wind farm efficiency for the EWP parametrisation as a function of the wind farm area in the: (*a*) onshore Region A, (*b*) the offshore Region B, and (*c*) the offshore Region C for the wide (10.5 D_0), intermediate (7 D_0), and narrow (5.25 D_0) turbine spacings (transparency). The efficiency of 70% is indicated with a dotted line.

Very large wind farm clusters





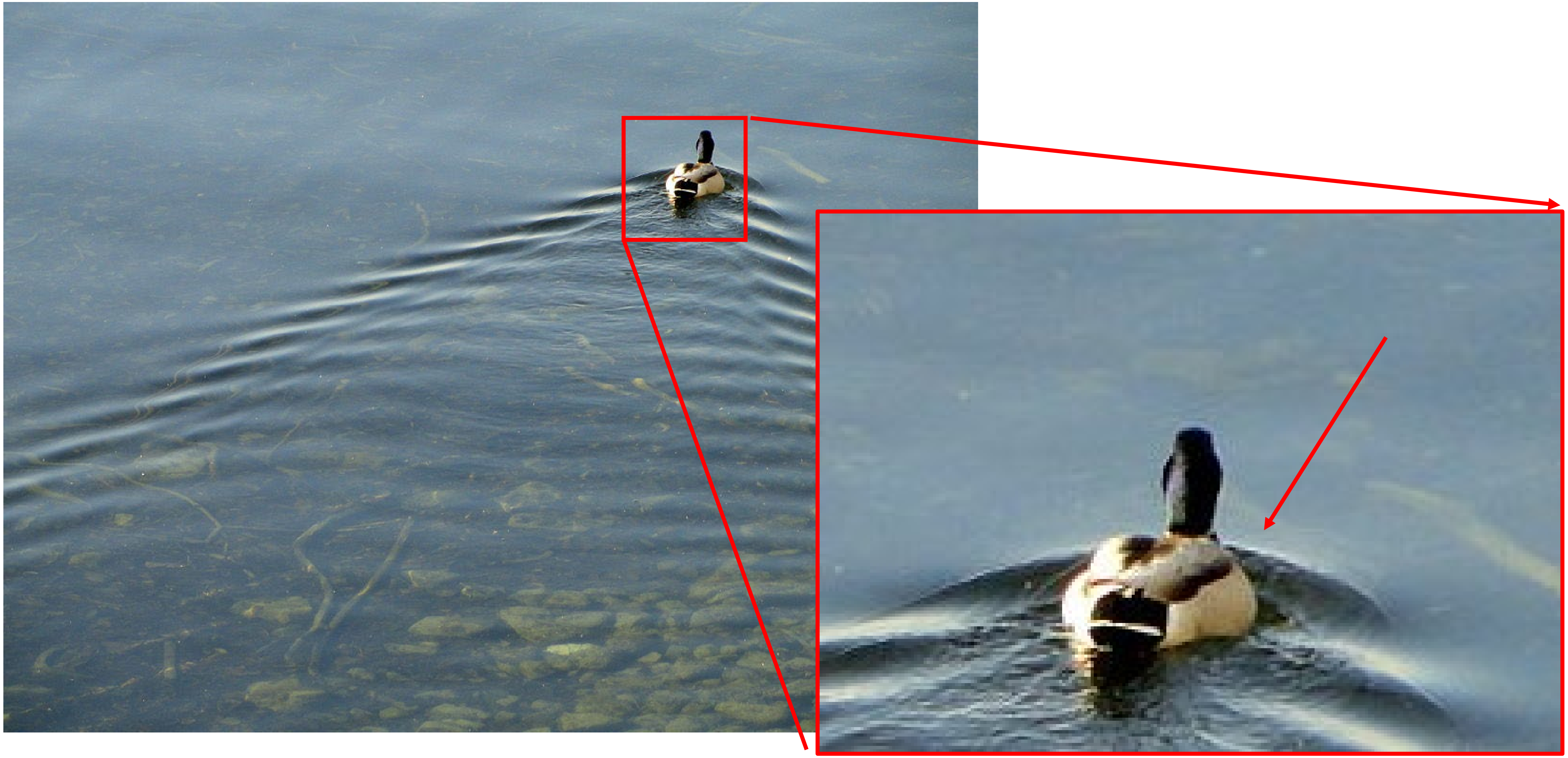
Capacity density [MW/km²]

2.8

6.4

11.3

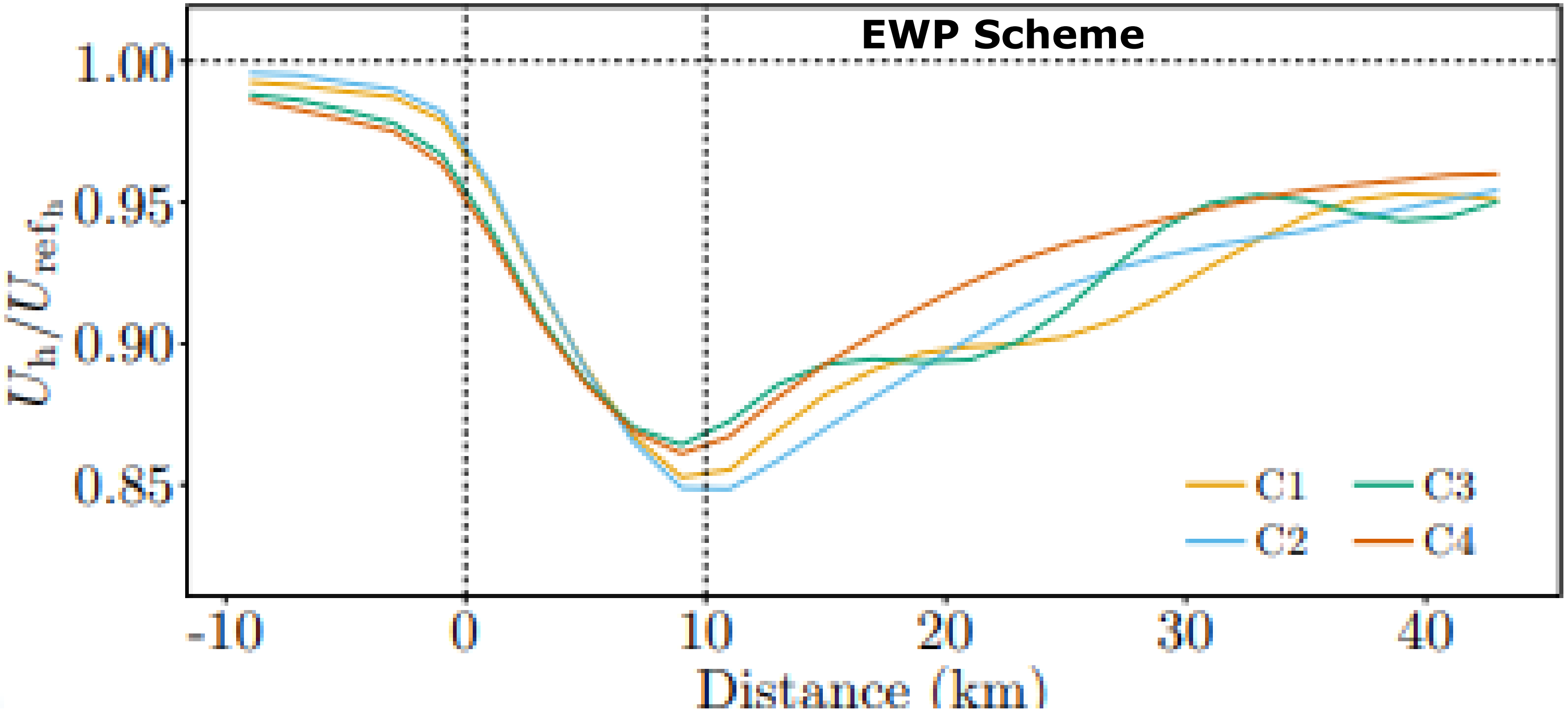
Volker, P, Hahmann, AN, Badger, J & Ejsing Jørgensen, H 2017, 'Prospects for generating electricity by large onshore and offshore wind farms: Letter', *Environmental Research Letters*, vol. 12, no. 3, 034022 . https://doi.org/10.1088/1748-9326/aa5d86



Picture: Daderot

Sensitivity to atmospheric state

Volker, P.J.H., 2014. Wake effects of large offshore wind farms-a study of the mesoscale atmosphere. *DTU Wind Energy, Ph. D. Thesis*, *132*.



Strong inversion

- greater blockage
- lesser deficit
- favourable pressure gradient in farm?

Barotropic atmosphere

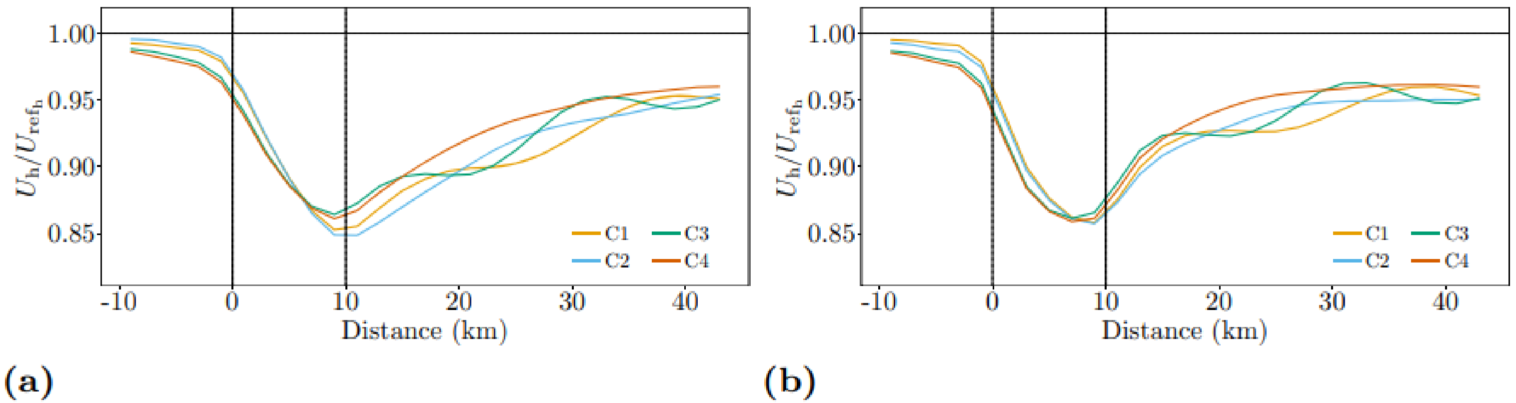
- wavy recovery
- modulated by inversion strength

Wind speed ahead, through, a behind Horns Rev 1 for different atmospheric conditions:

Weak inversion,	barotropic (C1 Yellow)	and baroclinic (C2 Blue)
Strong inversion,	barotropic (C3 Green)	and baroclinic (C4 Orange)

Review papers of interest (2)

- Fischereit, J., Brown, R., Larsén, X.G., Badger, J. and Hawkes, G., 2022. Review of mesoscale wind-farm parametrizations and their applications. *Boundary-Layer Meteorology*, *182*(2), pp.175-224.



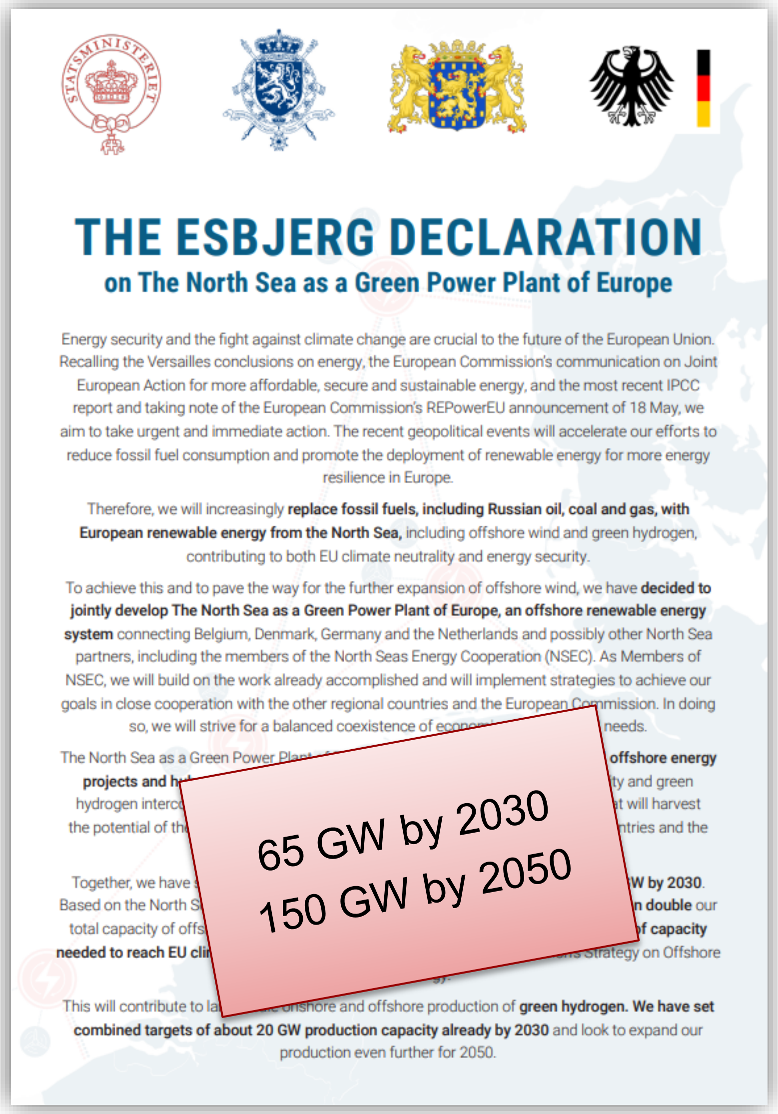
	Super-critical		Sub-critical	
	C1	C2	C3	C4
$\Delta\theta$ (K)	2	2	4.5	4.5
Fr	1.3	1.3	0.91	0.91
Geostrophic wind	Barotropic	Baroclinic	Barotropic	Baroclinic
$\Delta U/\Delta z$ (s^{-1})	-	-10^{-3}	-	-10^{-3}

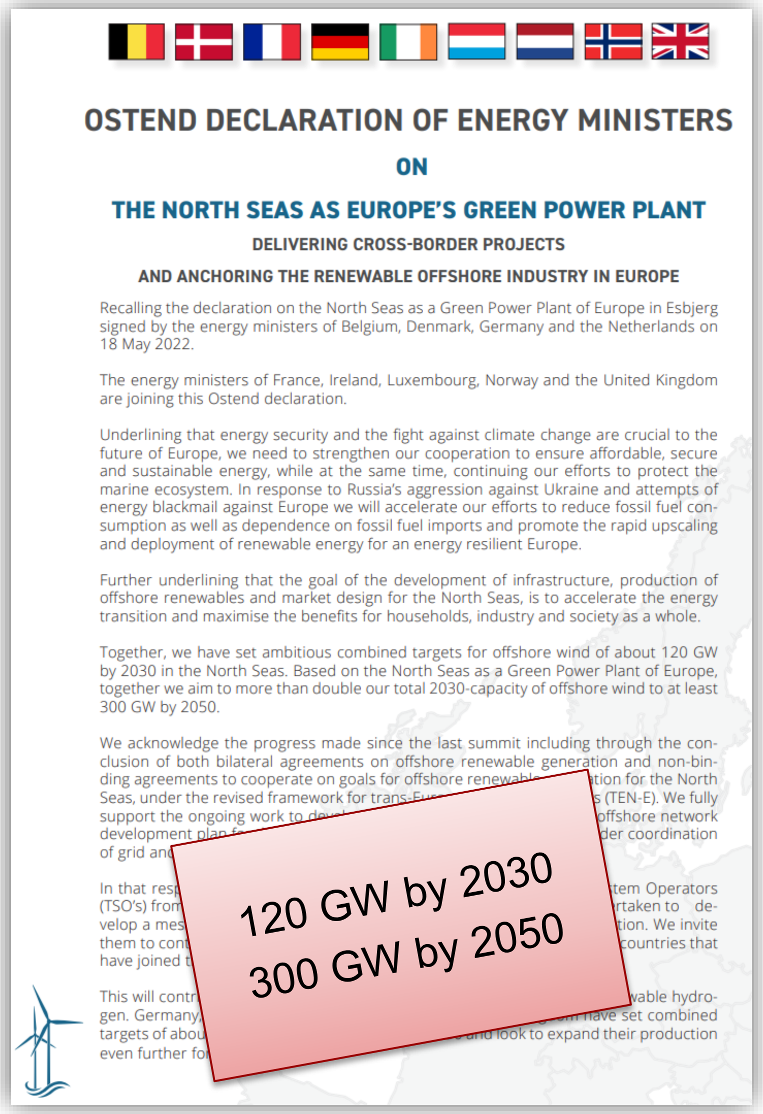
Fig. 12 Normalized wind speed at hub height for different scenarios (C1–C4) using the EWP WFP (**a**) and the Fitch WFP (**b**). The wind-farm extension is marked by the vertical dotted lines. The scenarios are given in the table, where θ refers to the potential temperature and Fr to the Froude number. Reprinted with permission from Volker (2014)

Volker, P 2014, *Wake Effects of Large Offshore Wind Farms - a study of the Mesoscale Atmosphere*. DTU Wind Energy PhD, no. 0035(EN), DTU Wind Energy.

DTU’s activities on large wind farm clusters

Declarations setting ambitious political ambitions





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)

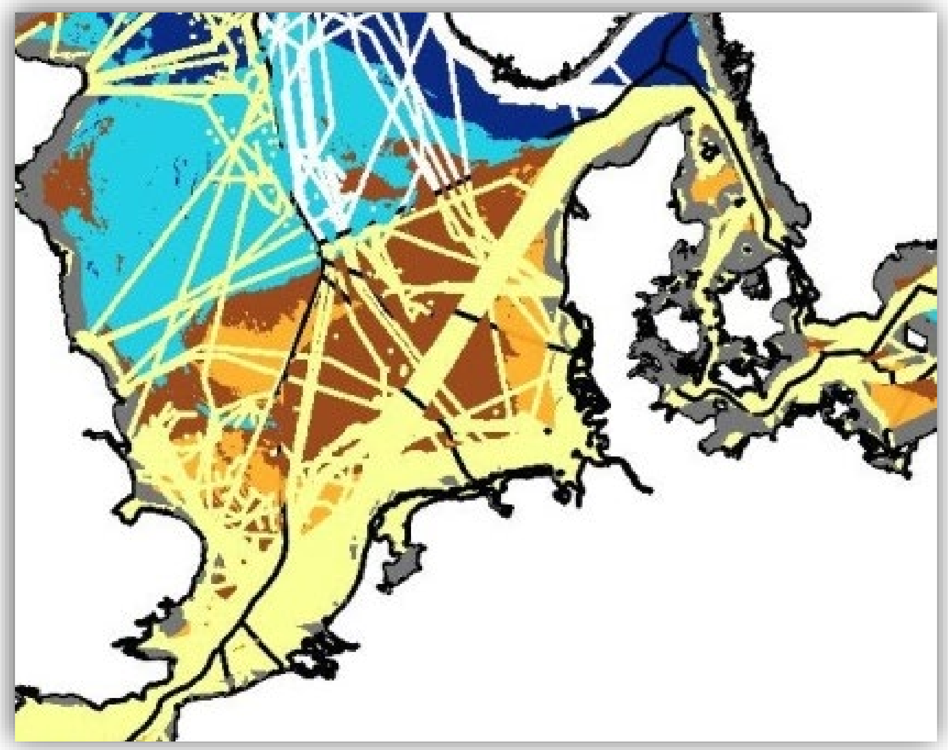
For the case of the Esbjerg Declaration countries,

...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

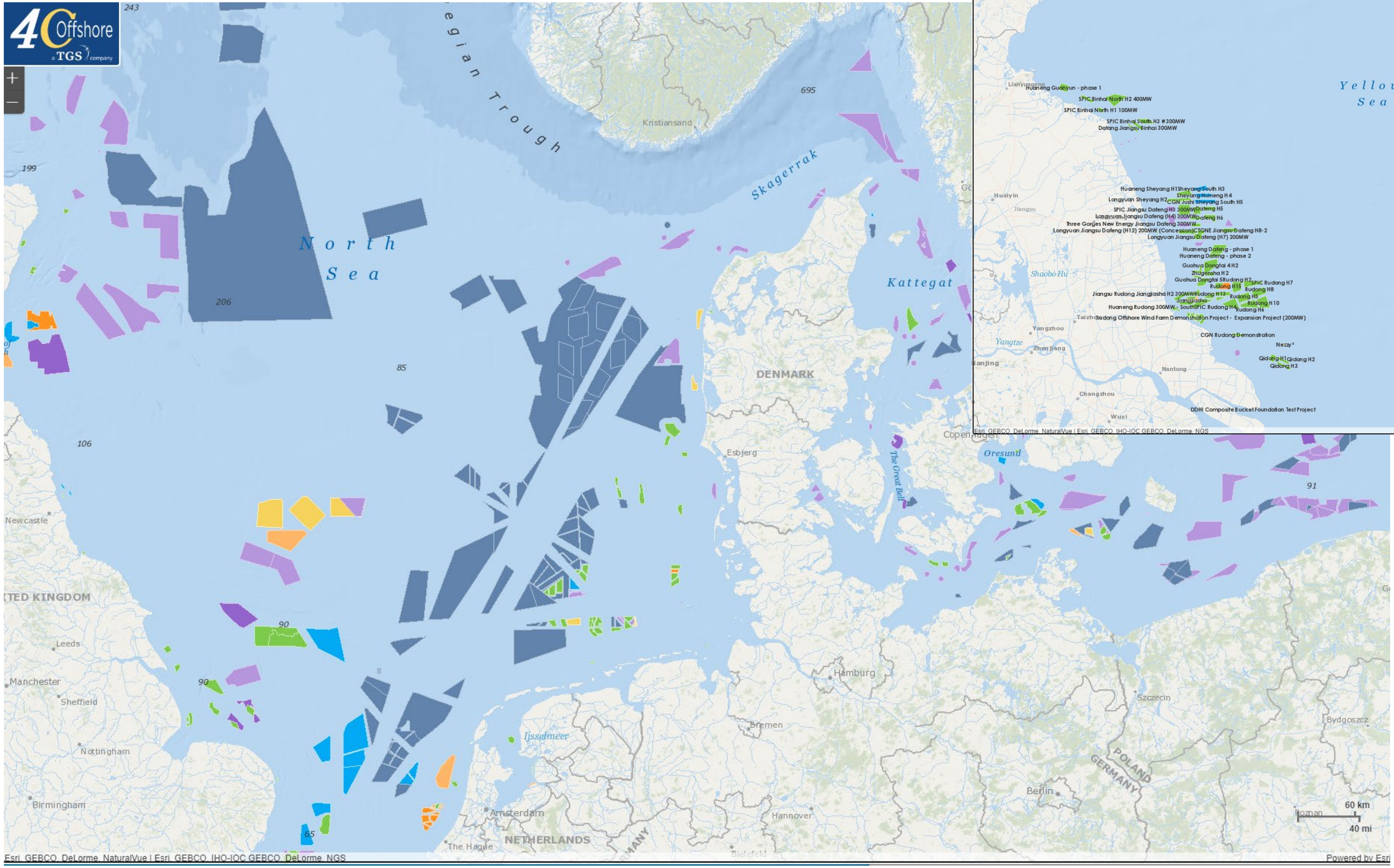
  - **Total 105-431GW**

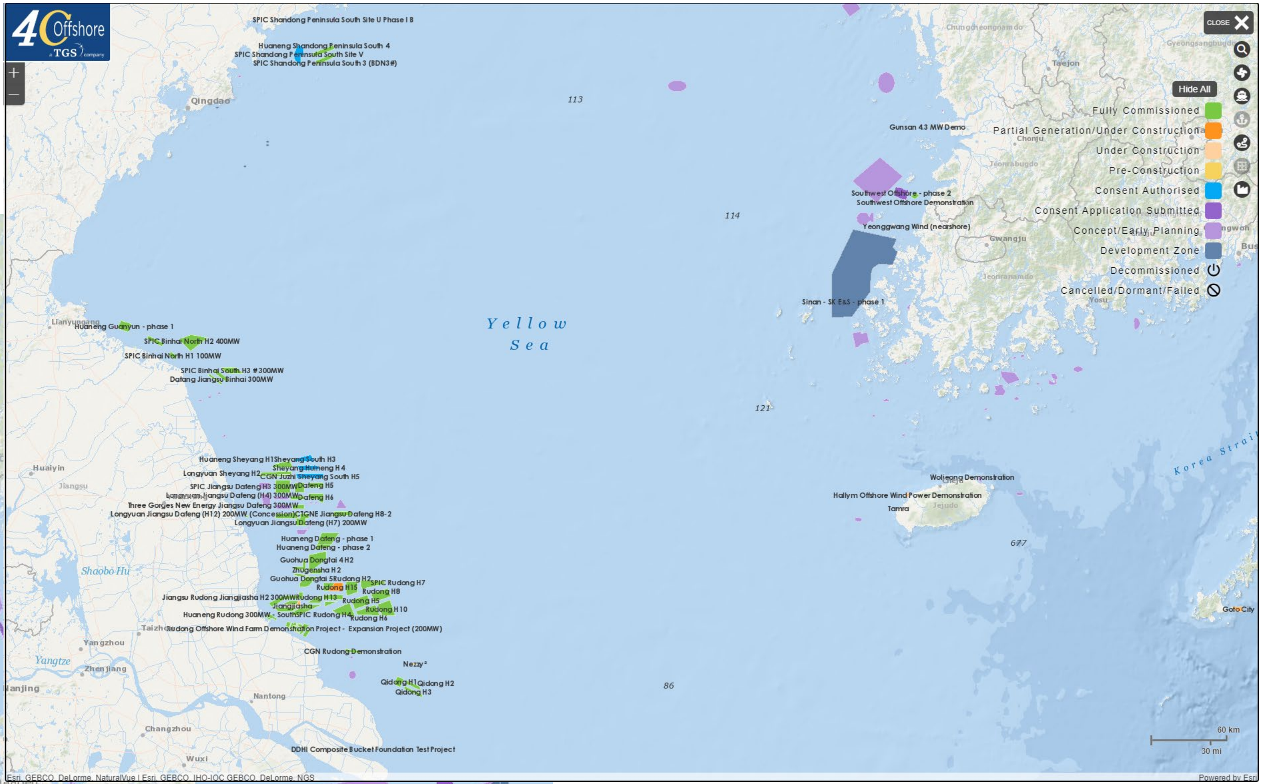
Esbjerg Declaration:
65 GW by 2030
150 GW by 2050



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?



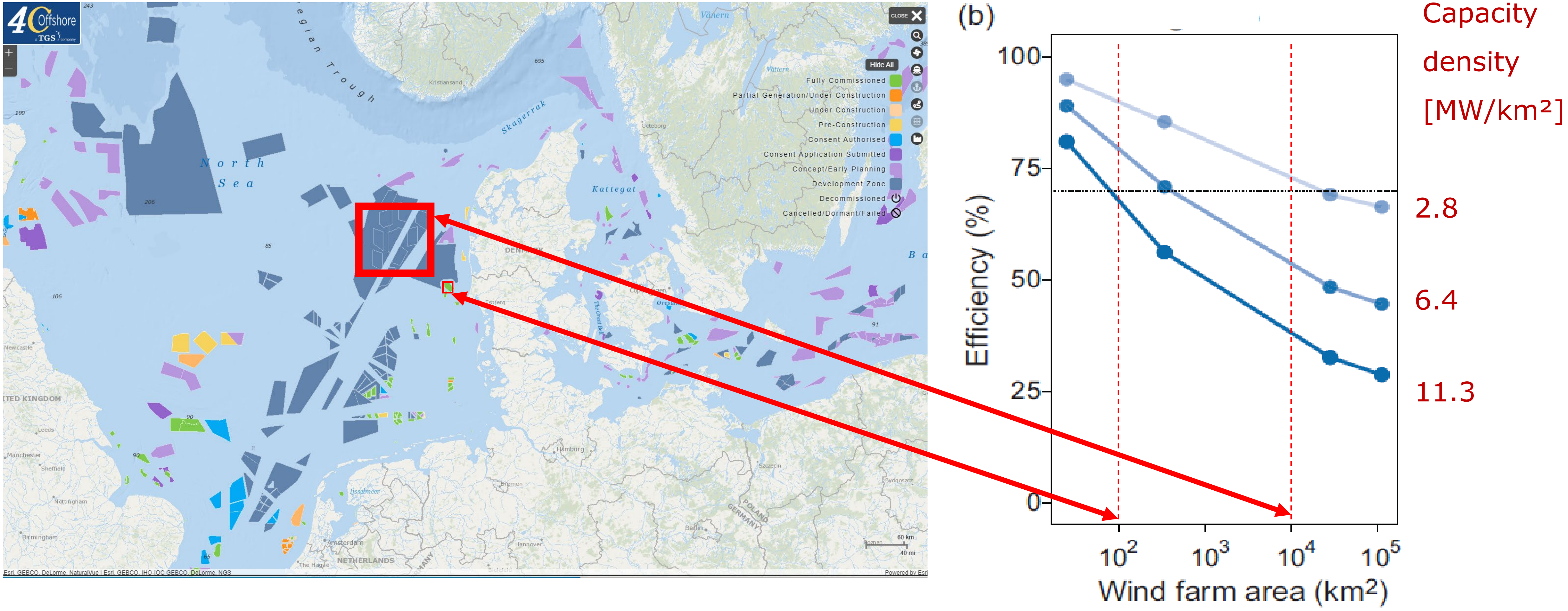


This scale of wind energy deployment is completely new.

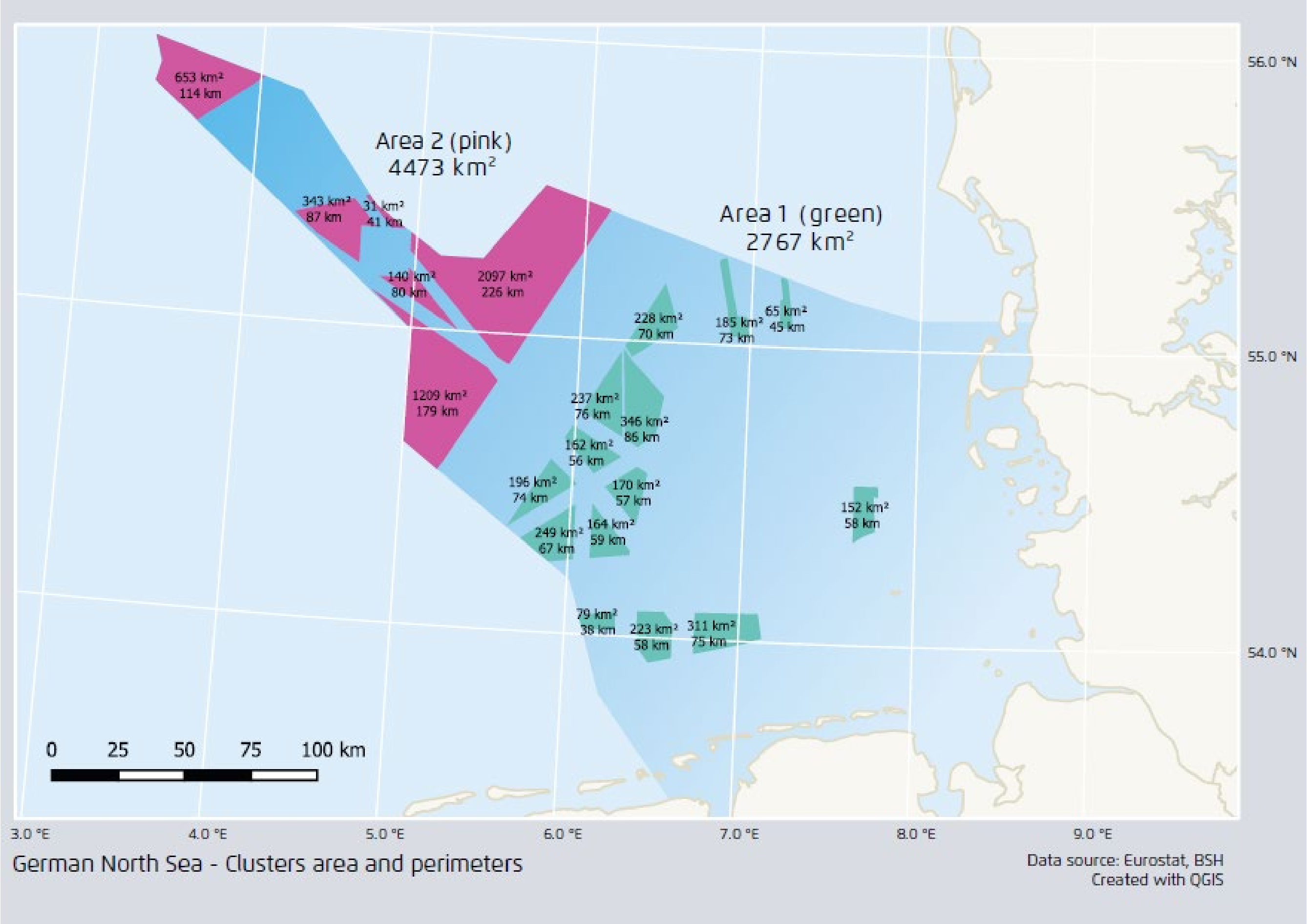
No or limited experience of such development in the real world.

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):

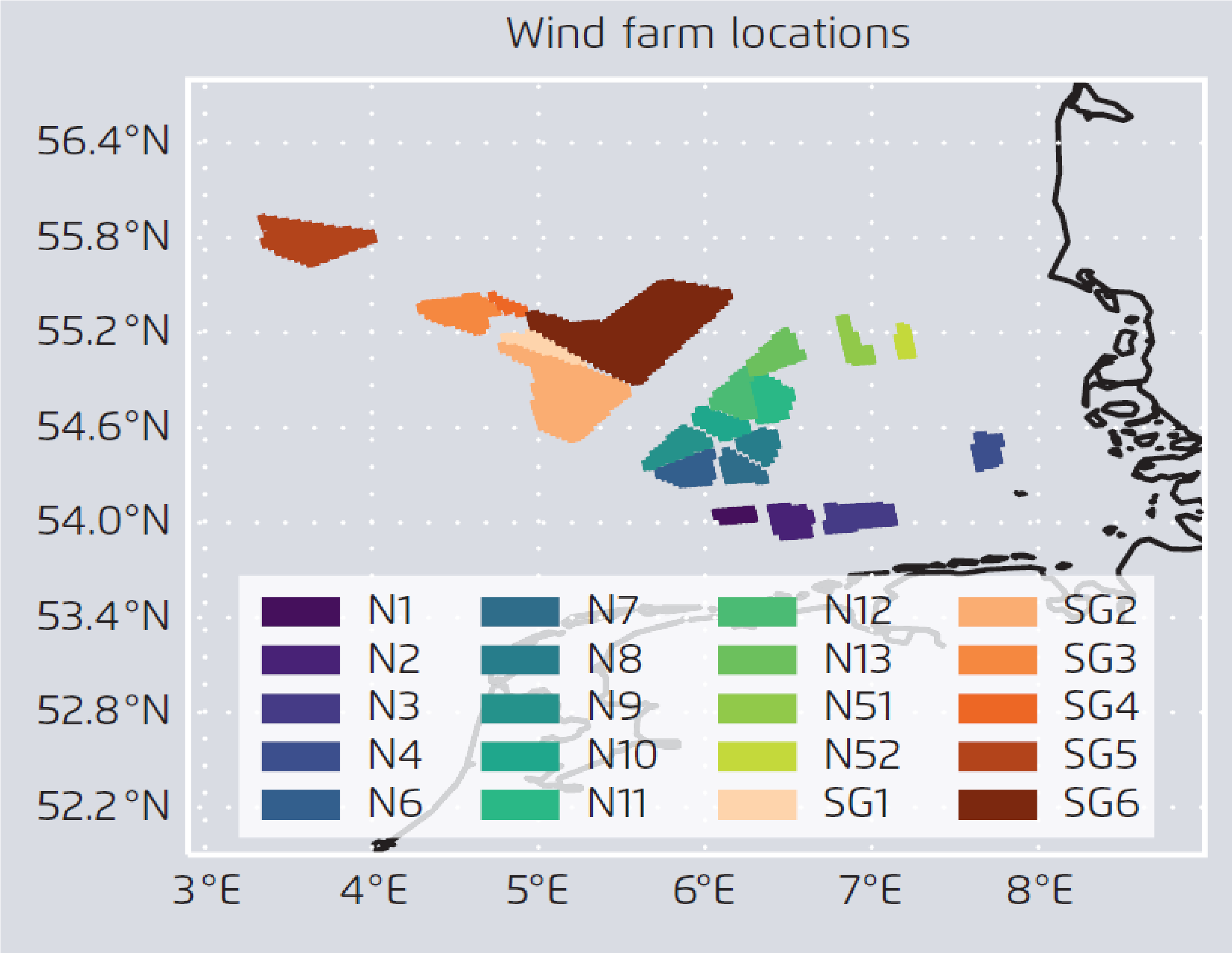
Technical University of Denmark and Max-Planck Institute (2020): Making the Most of Offshore Wind: Re-Evaluating the Potential of Offshore Wind in the German North Sea. Study commissioned by Agora Energiewende and Agora Verkehrswende.

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



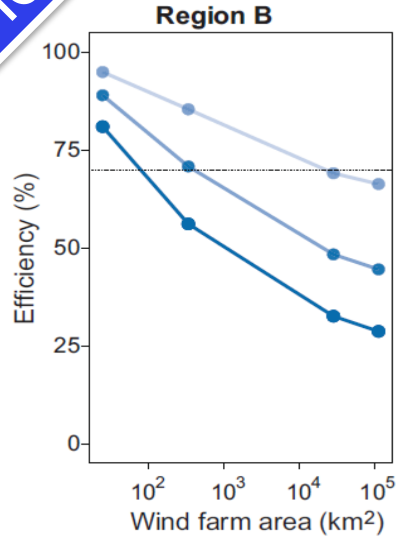
https://www.agora-energiewende.de/en/publications/making-the-most-of-offshore-wind/

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.

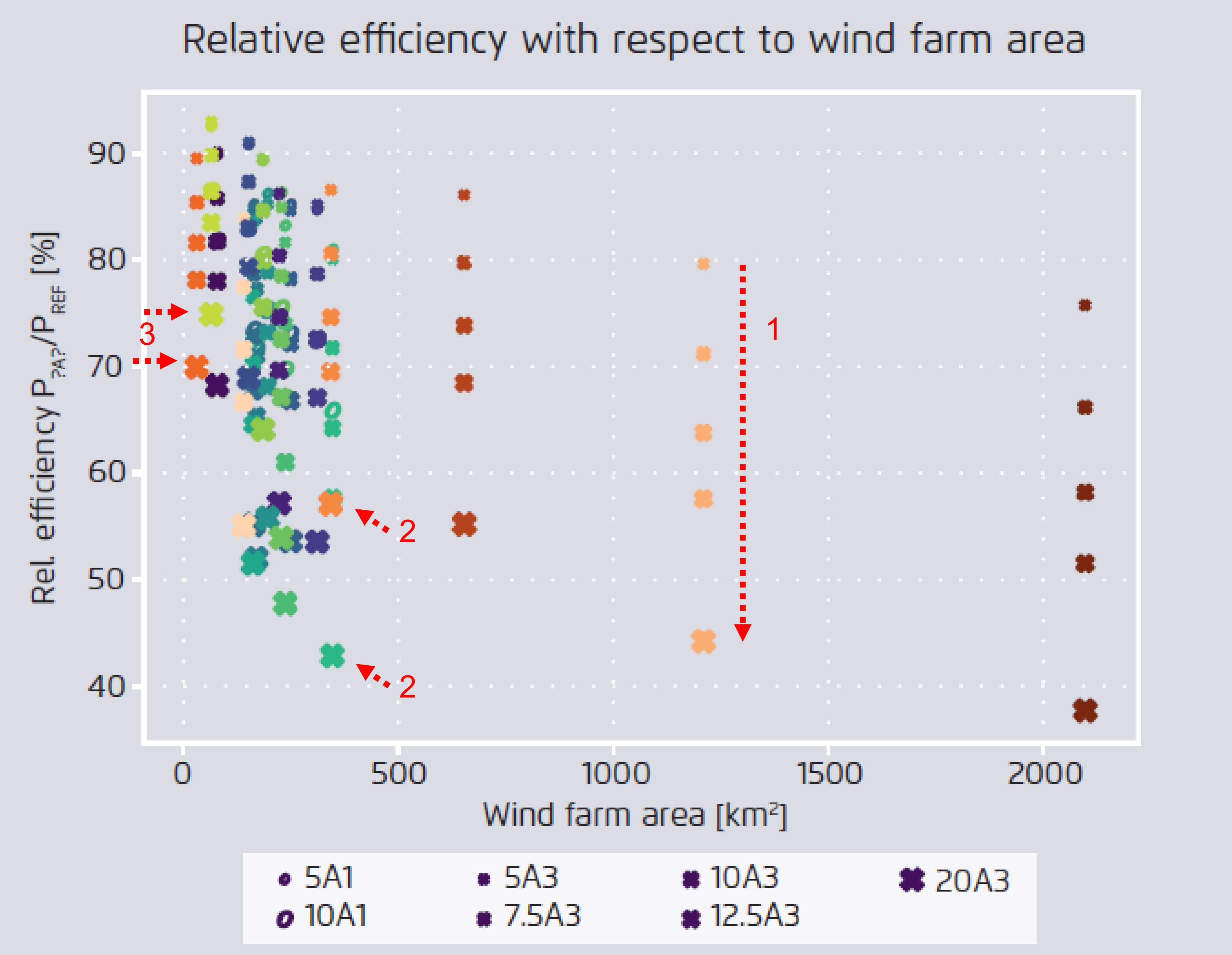
WRF results

Reminder



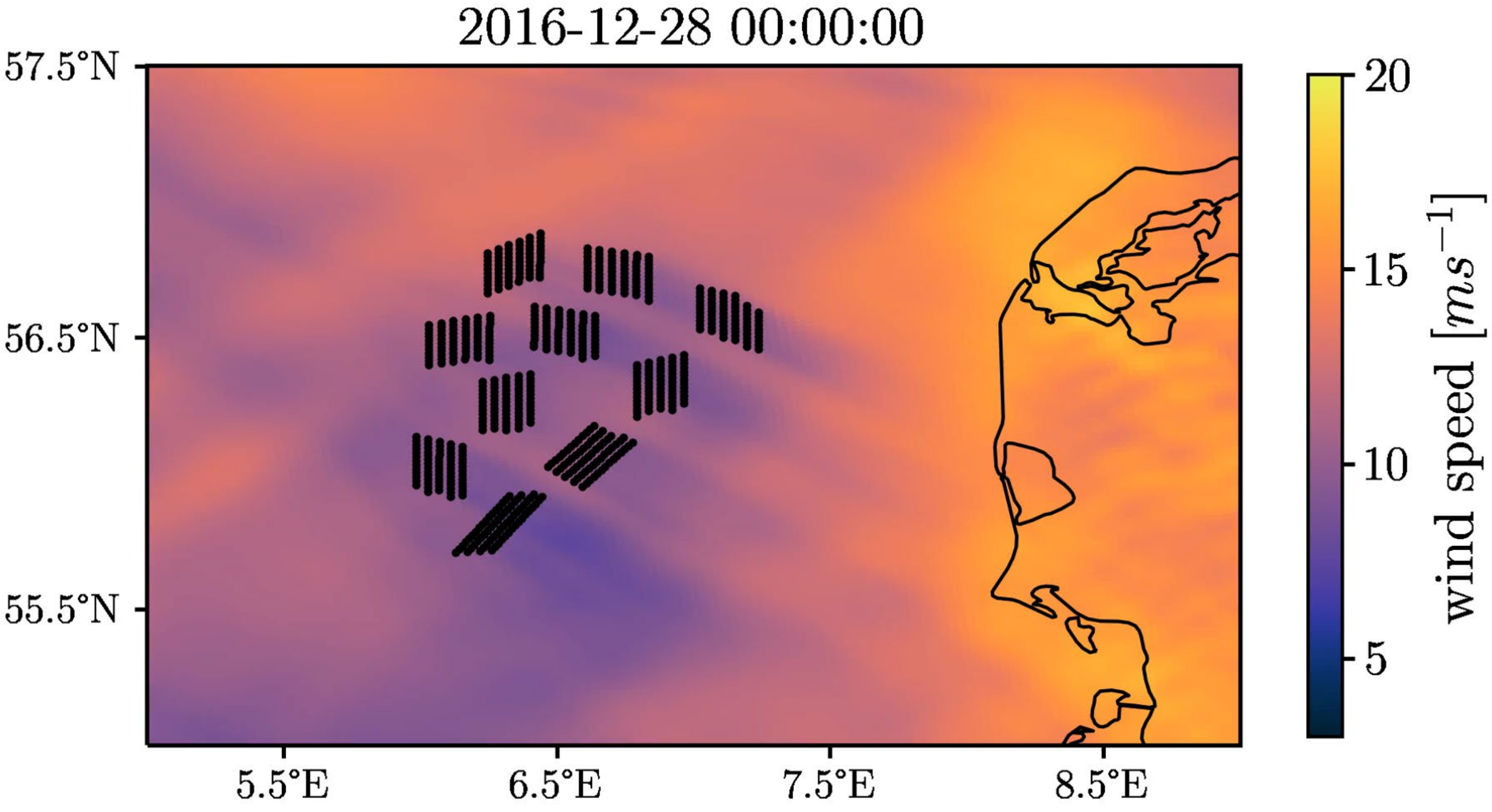
- Efficiency drops for higher installed capacity densities (1)
- Efficiency also depends on wind farm location and climate. (2)
- Efficiency depends on farm size and proximity of large expanse of neighbouring wind farms (3)

Agora (2020)



DTU Wind Energy

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

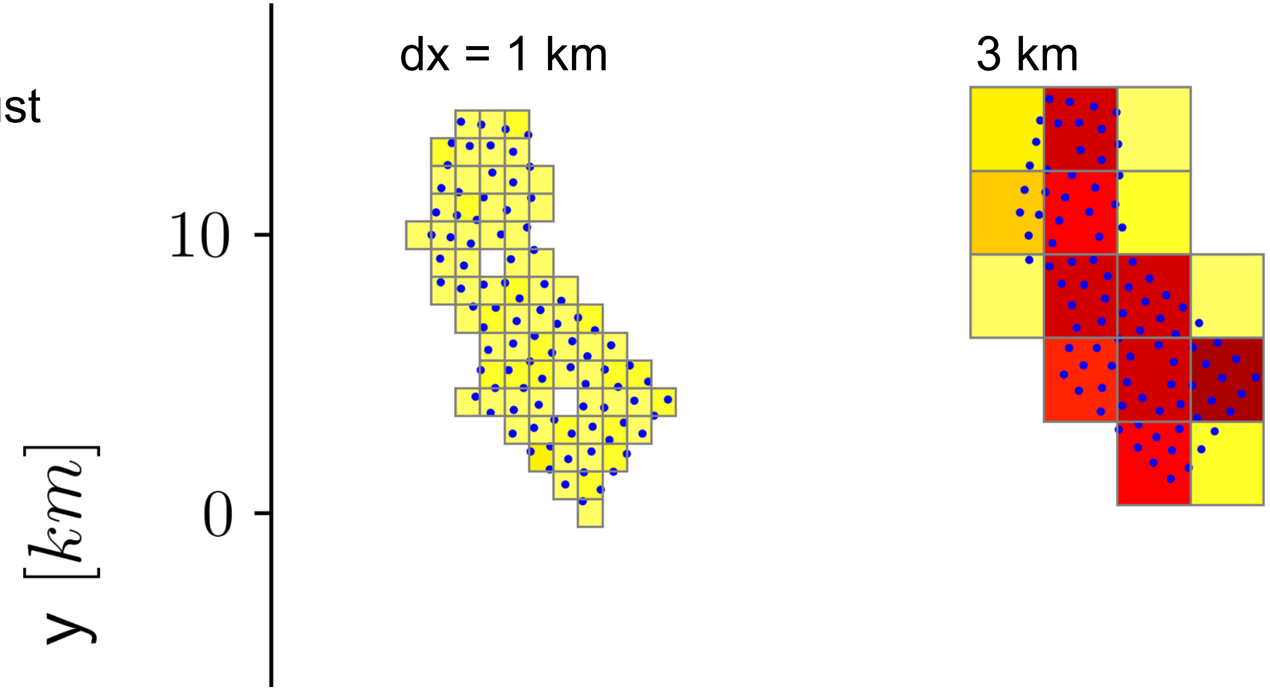
Race Bank (UK)

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

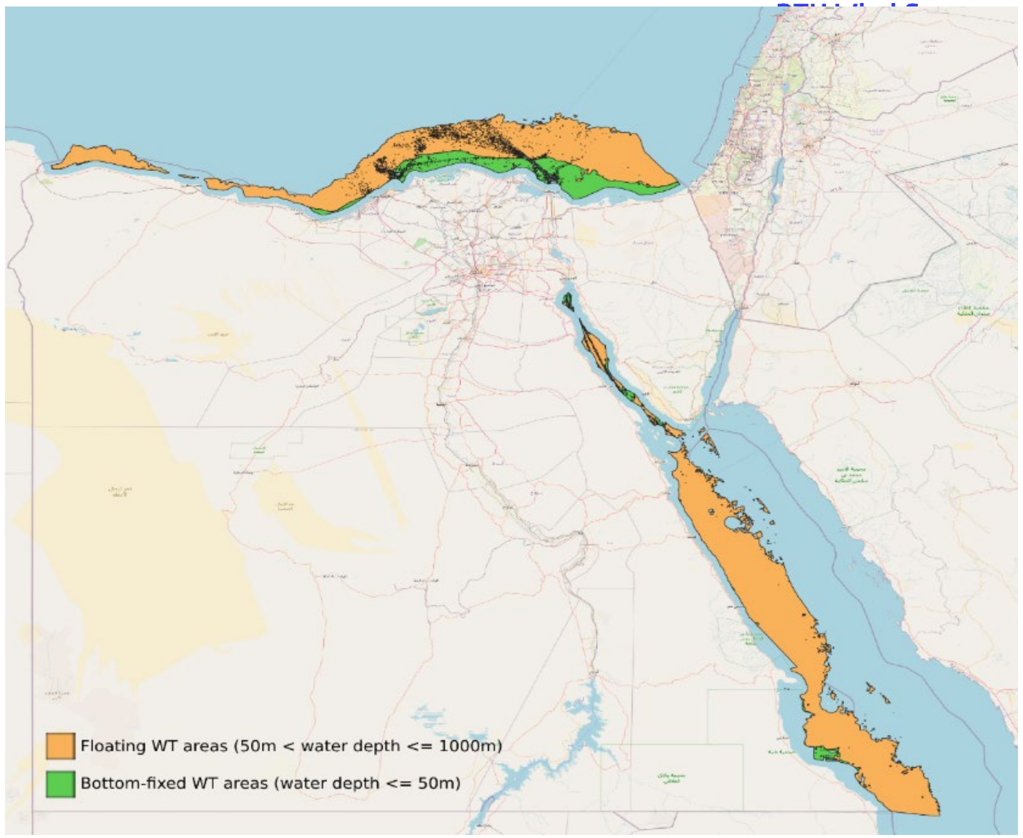
Use Volker et al (2017) to guide capacity density as function of area available.

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.

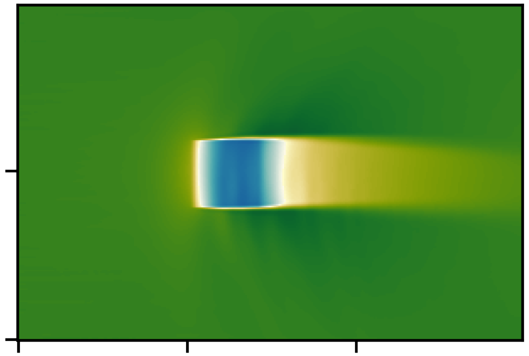
https://orbit.dtu.dk/en/publications/case-study-based-prefeasibility-assessment-of-offshore-wind-resou

Calculated wind farm power curves including farm efficiency

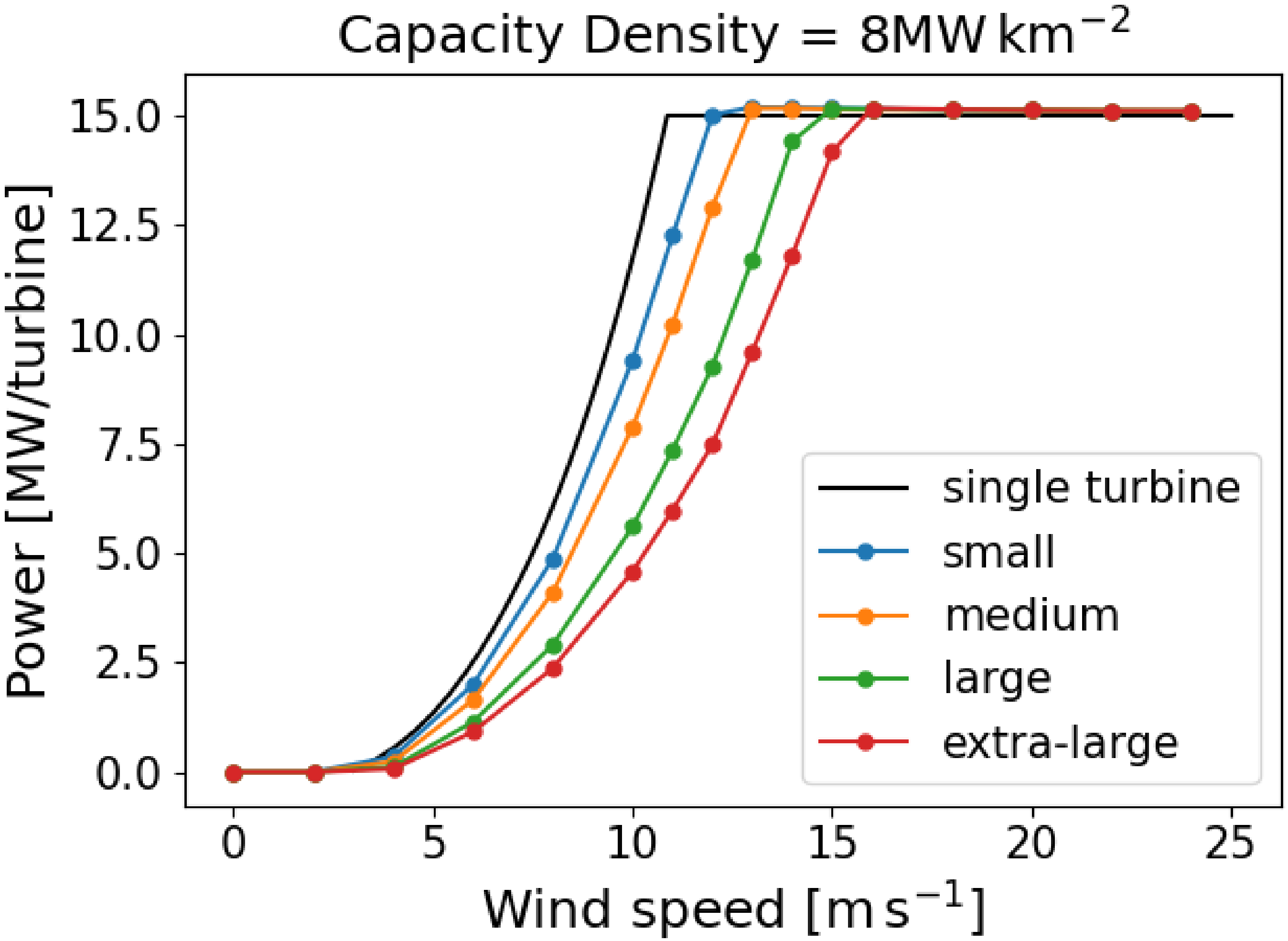
Useful for power time series studies…

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)

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

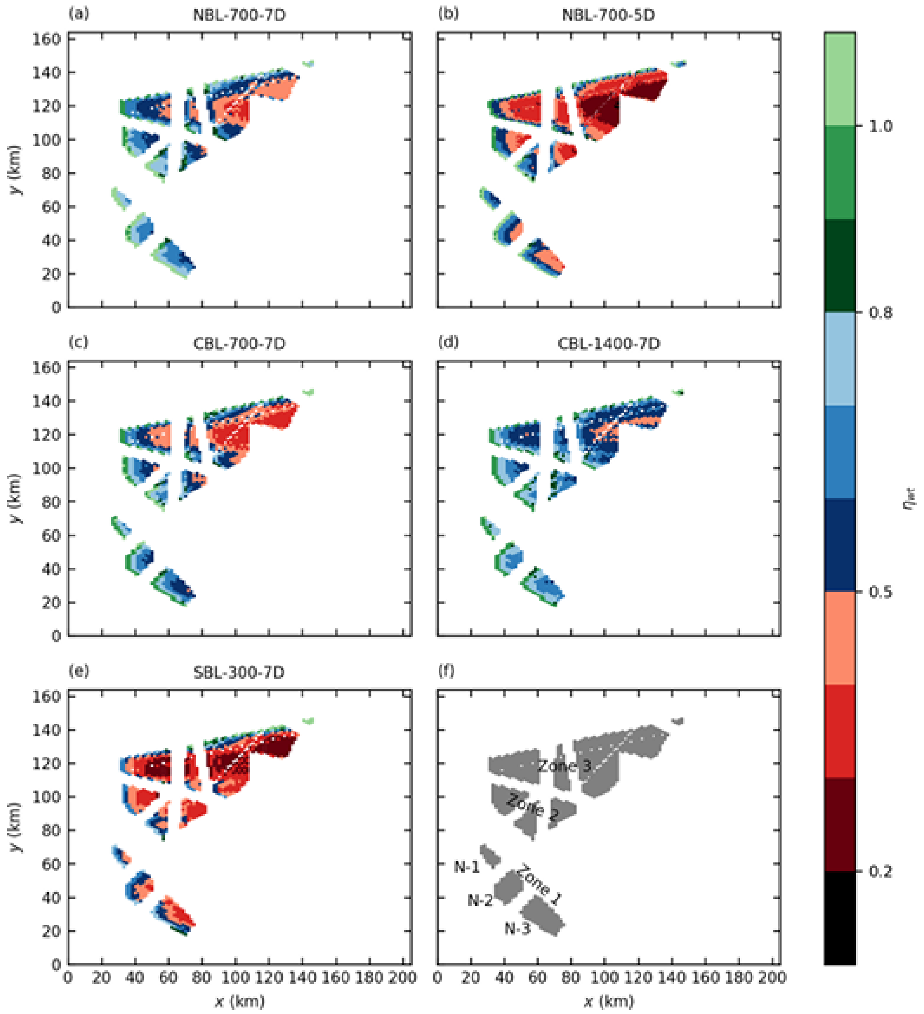


Figure 10. Wind turbine efficiencies η_{wt} for all five cases (**a–e**) and overview of wind farm names (**f**).

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

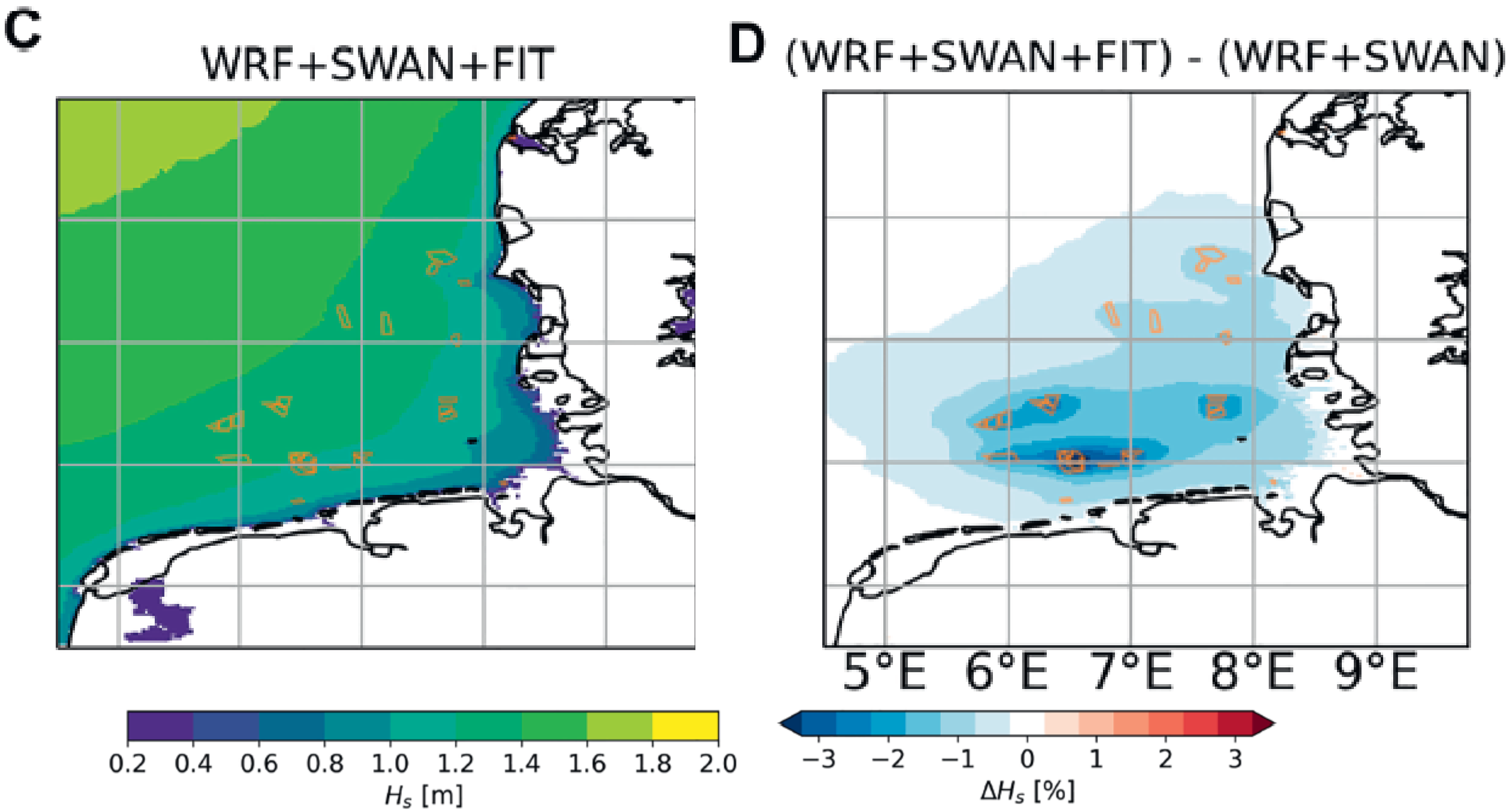


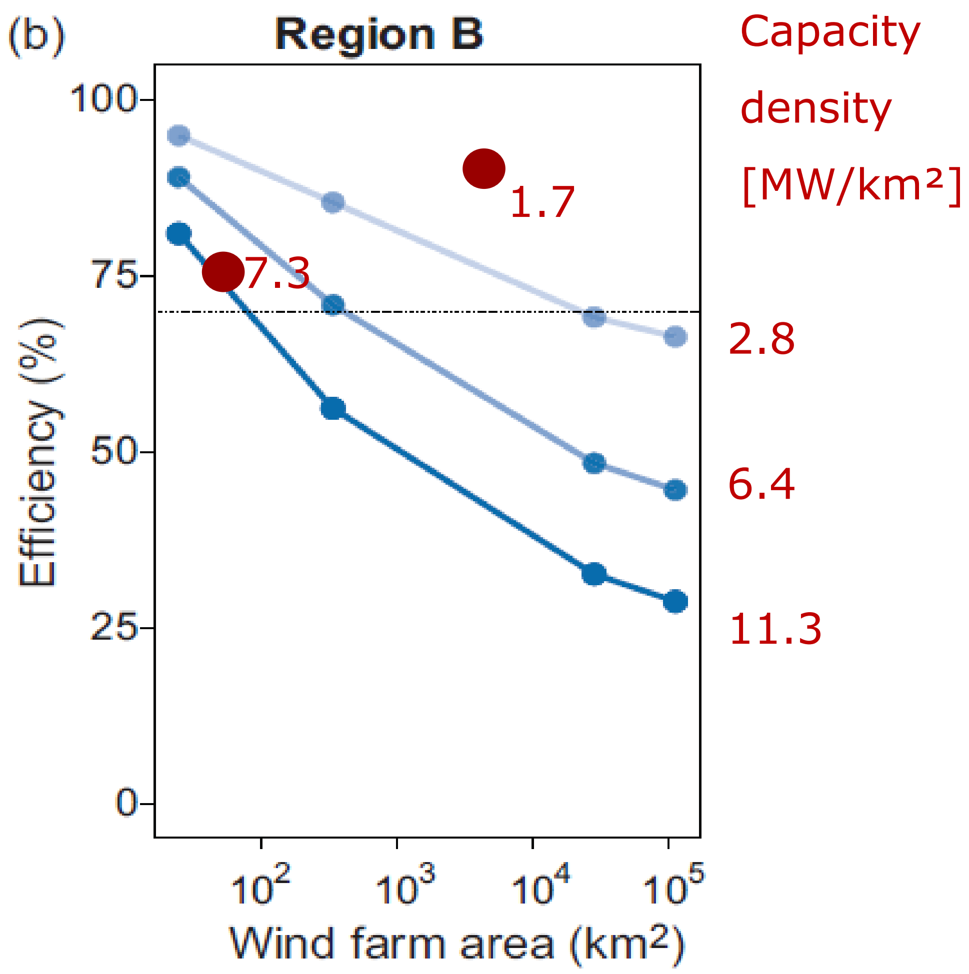
FIGURE 13 | (A) Long-term significant wave height (H_s) from ERA5 and simulated by **(B)** WRF + SWAN and **(C)** WRF + SWAN + FIT. **(D)** Relative reduction on significant wave height from (WRF + SWAN + FIT)-(WRF + SWAN) normalized by (WRF + SWAN).

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.

Production Estimate

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



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

DTU

Next-generation wind farm parameterizations

Research ongoing in the topic

Oscar Garcia

More accurate wind farm parameterizations

Given the importance of their **applications**, the wind farm parameterizations are required to be as **accurate** as possible.

What can be improved?

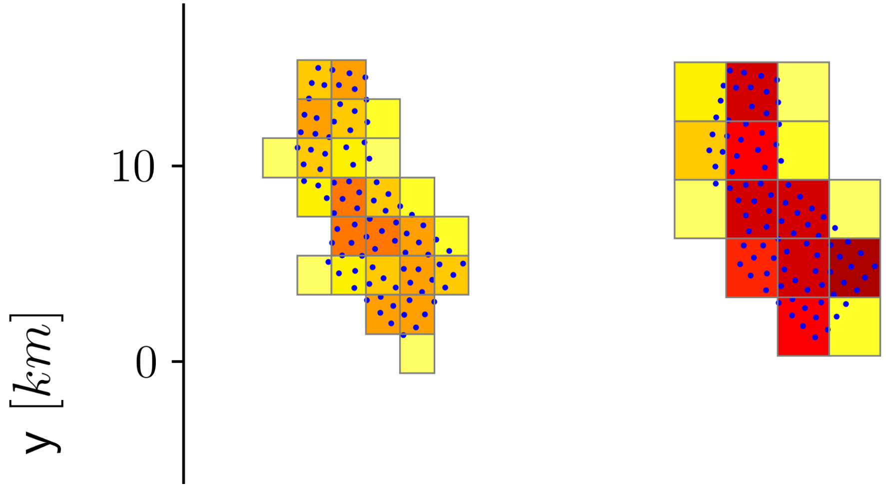
Better power modelling

Wind farm effects on the atmosphere

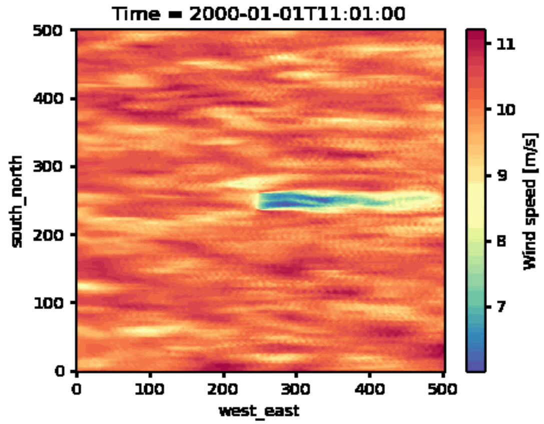
Accounting subgrid-scale wakes

Better representation of turbulence

Same wind farm, different power



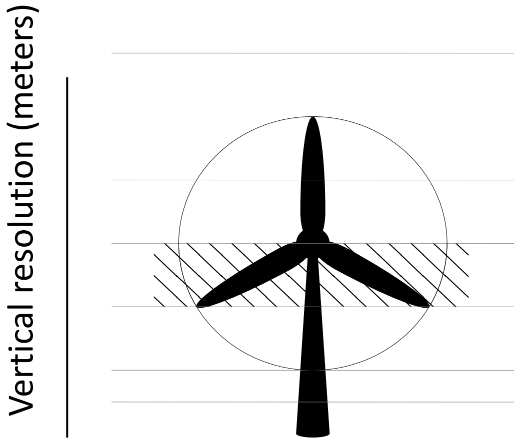
Capturing turbulent features



Representation of turbines in WRF's grid-cells

The resolved wake from the parameterizations depends highly in the resolution of the model.

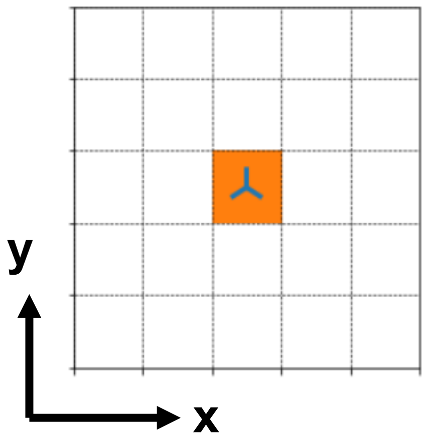
In the vertical



From Fischereit et al. (2020)

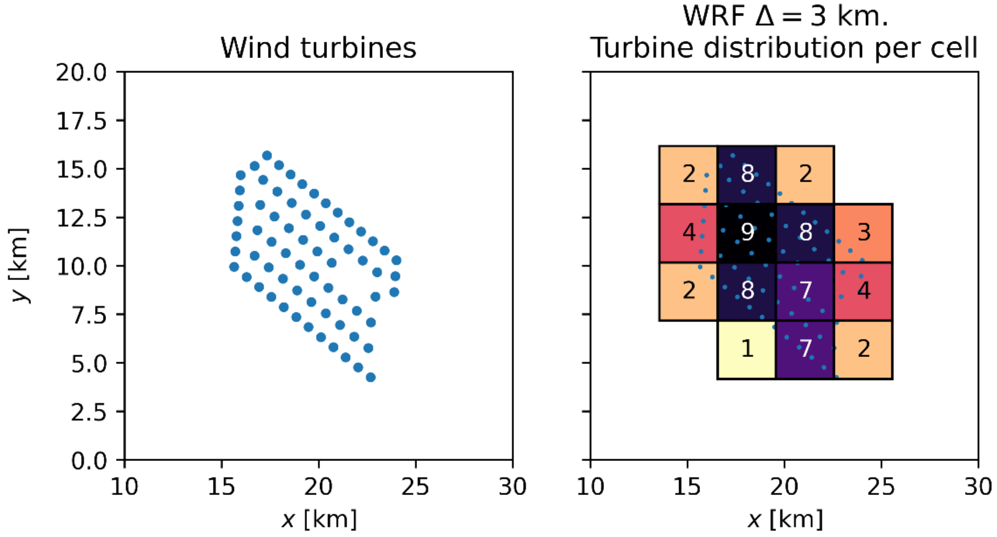
Close to the ground, the vertical resolution covers several heights of the rotor. Partially resolved

In the horizontal …



Horizontal resolution is coarse to resolve details. Grid-cell average taken.

In a wind farm



Turbines allocated to the nearest grid cell. Wakes inside the grid cell are not taken into account.

Improvement: accounting for subgrid-scale wakes

There are two ways to account for the subgrid-scale wakes

Current:

Modify the single parameter to obtain the global thrust equal to a reference.

New method: Meso + micro

Thrust and power information from:

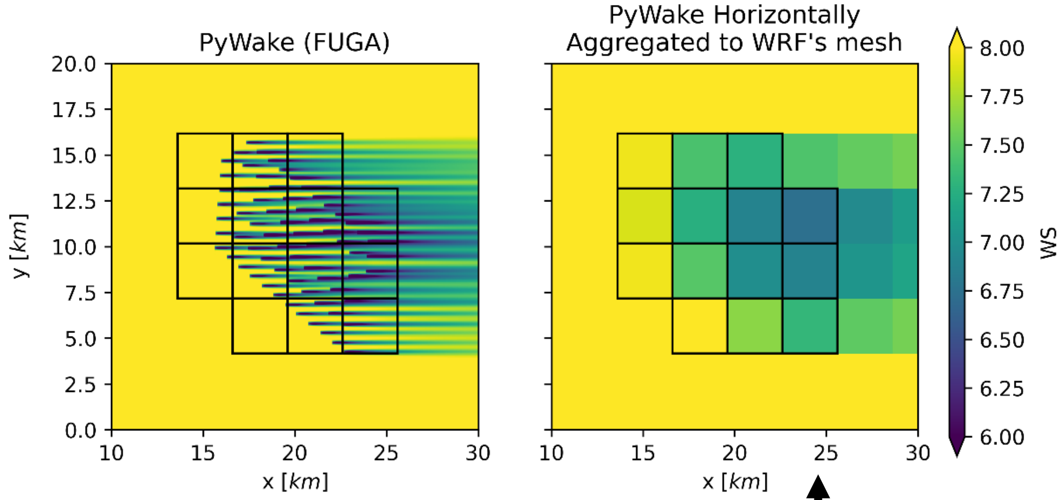
Engineering models

RANS CFD

PyWake

Input to WRF

Example:



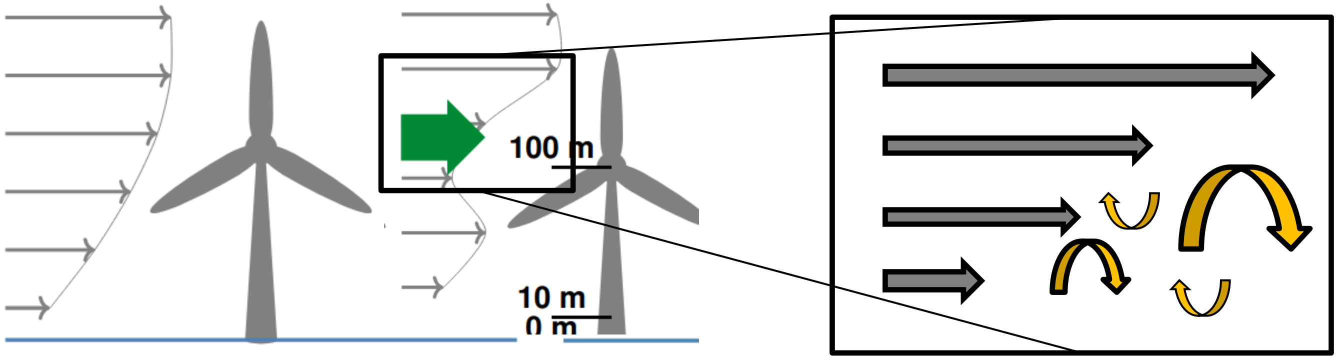
Suitable for WRF

Turbulence representation

In addition to the reduction of wind speed, turbulence is generated in the wake of the wind turbines

Photo Bel Air Aviation, Denmark

Wind speed gradient (shear)



Vortices generated

Why important to model it?

Turbulence in the downstream of the wakes, contributes to wake recovery

Turbulence modeling

How turbulence from wind turbines is represented across different modelling types

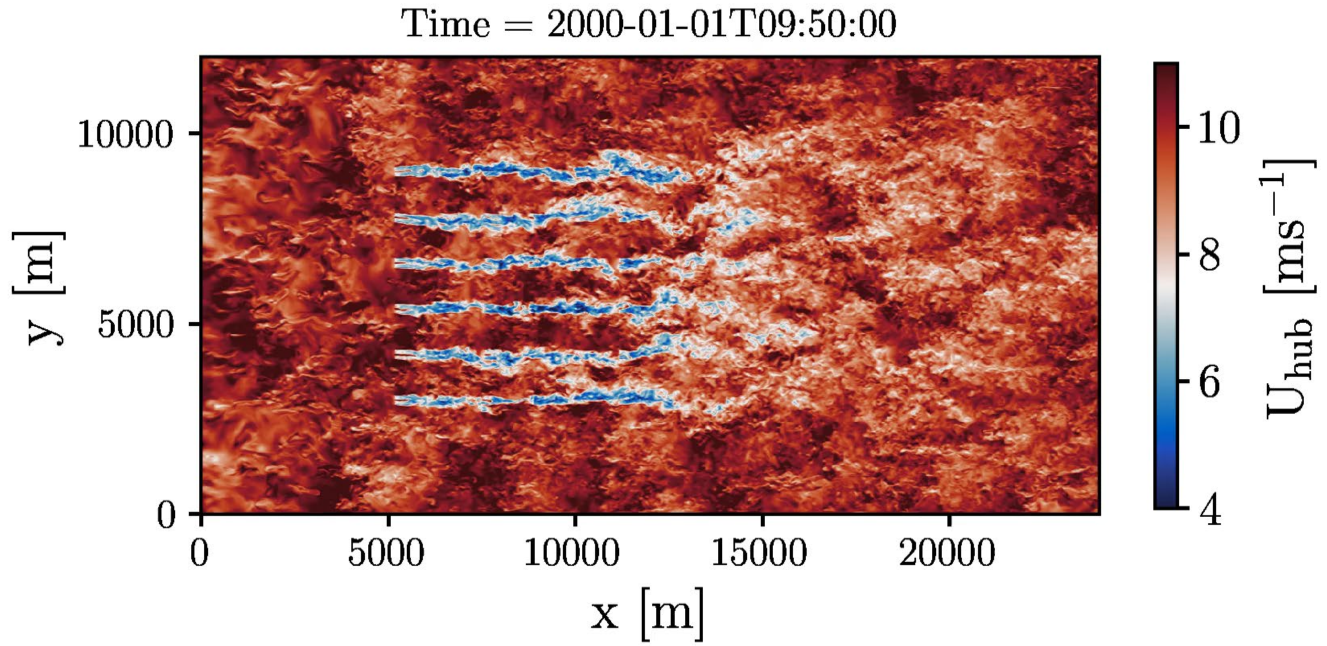
Engineering models

Parameterization of turbulence intensity

Wind farm parameterizations

Either an explicit source of **Turbulent Kinetic Energy (TKE)** or an implicit source from WRF.

Large-Eddy simulations

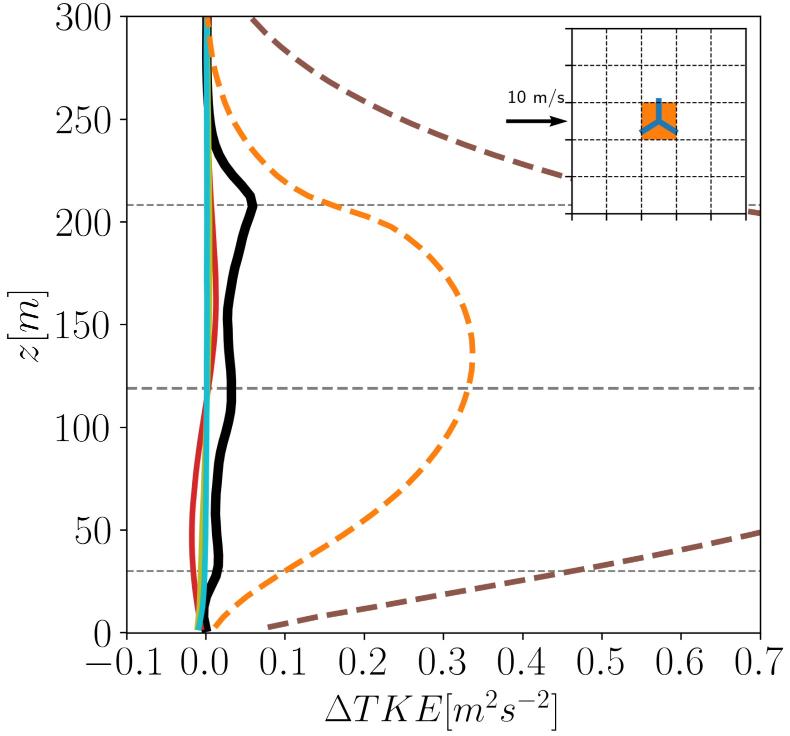


Expensive to perform, but we can use it to refine parameterizations

Turbulence handling in wind farm parameterizations

The parametrized turbulence production needs to be placed in the proper location and right magnitude

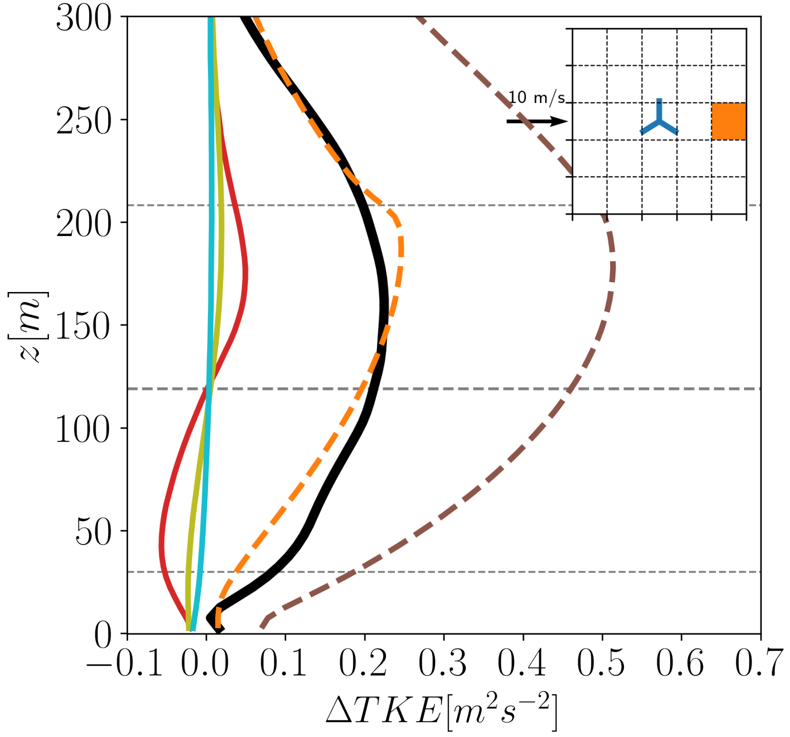
For this example, LES results are averaged to the 1 km mesoscale simulations



The **black** line is the LES

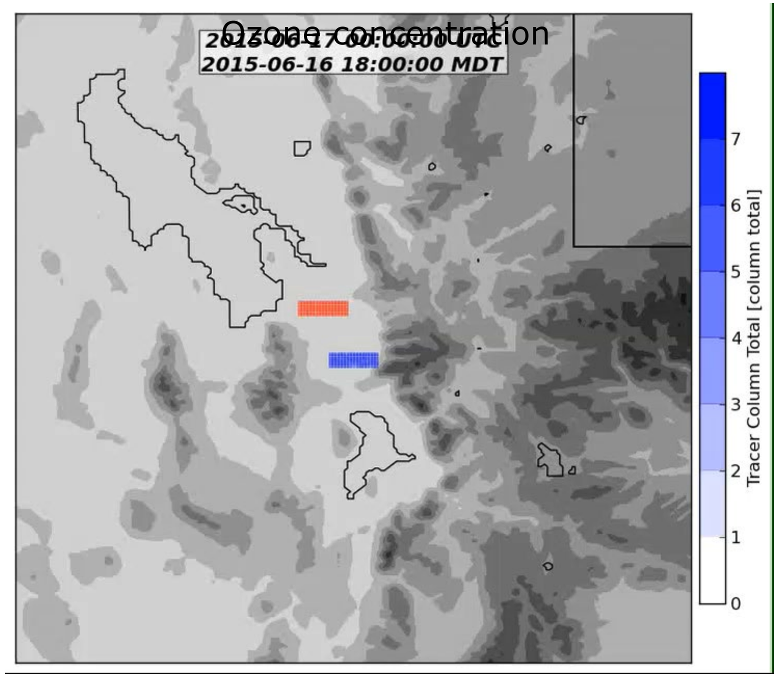
Colored lines are the wind farm parametrizations

Moving to the downstream cell



Improvement: a new turbulence model

Inspiration from plume dispersion simulations with WRF



pyPlots_v2/WRF-Tracers at master · blaylockbk/pyPlots_v2 · GitHub

We use the **tracer** capabilities of the WRF model to develop a new turbulence model:

The **Latent Kinetic Energy (LKE)** model

The model is implemented in the Explicit Wake Parametrization (**EWP**; Volker et al., 2015)

Aspects improved:

- Measured TKE structure
- Works with any PBL

Evaluation of the new parameterization with LES

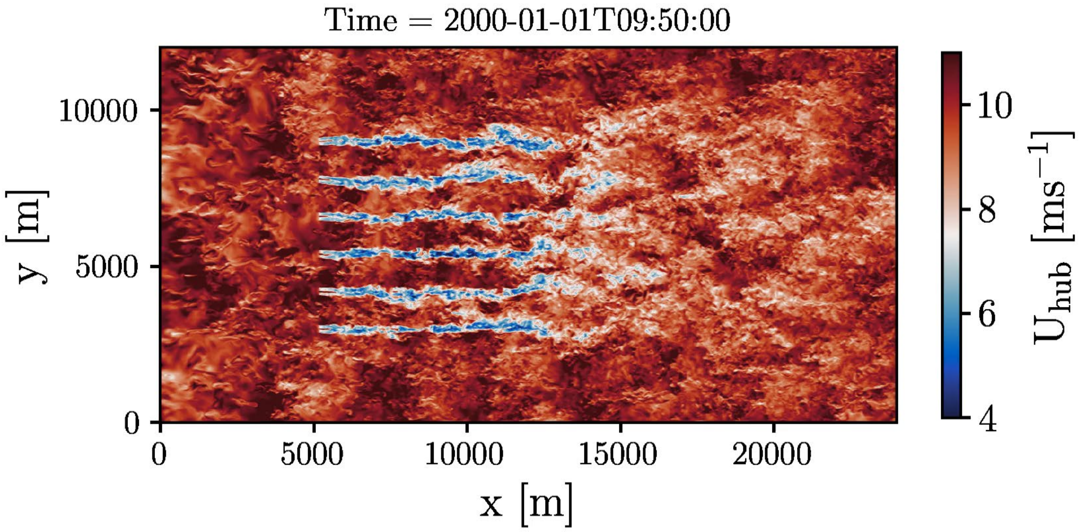
Modeling a **6x6** wind farm.

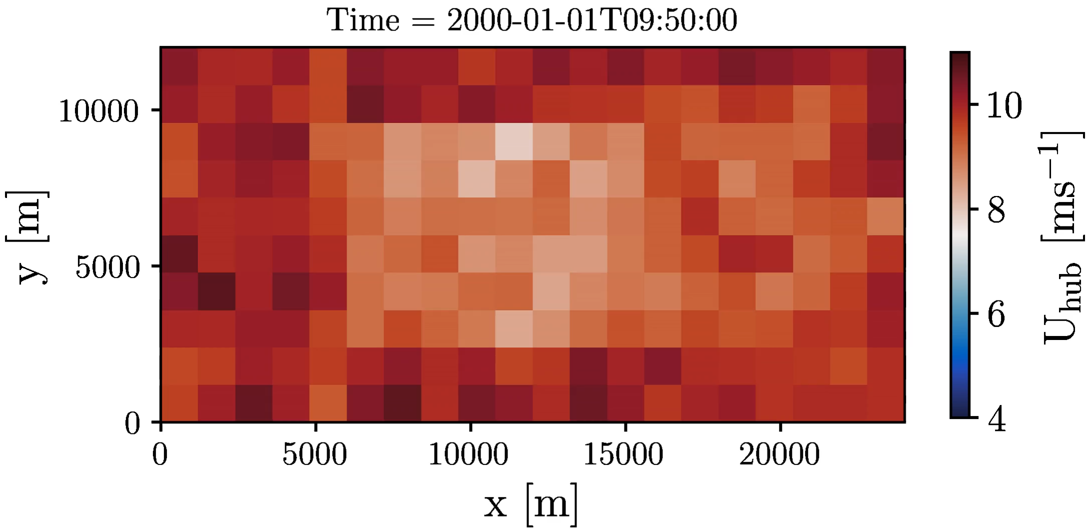
15 MW turbines

5 rotor diameters spacing = 1200m

Comparable with mesoscale results

Spatial aggregation

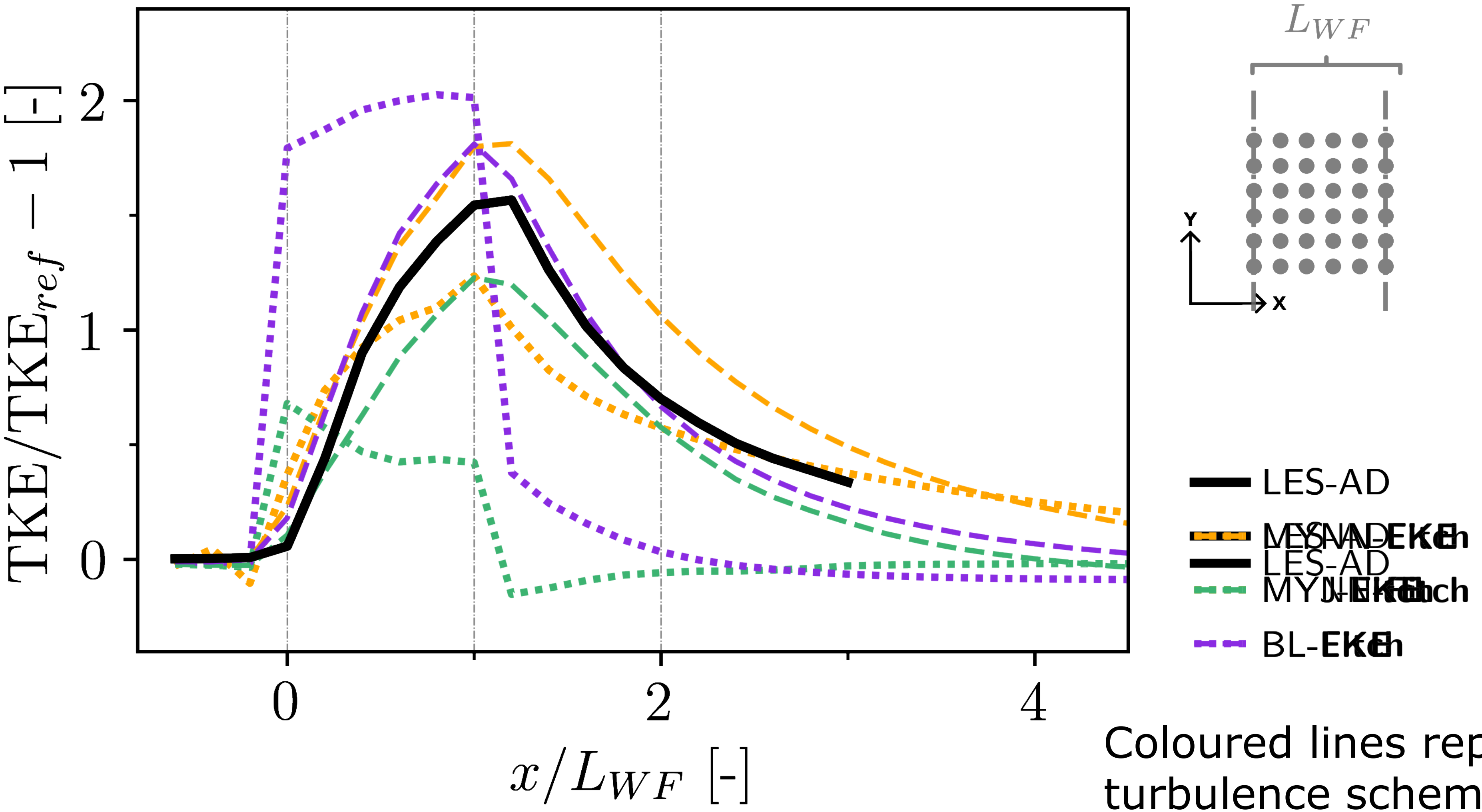




DX = 20 m

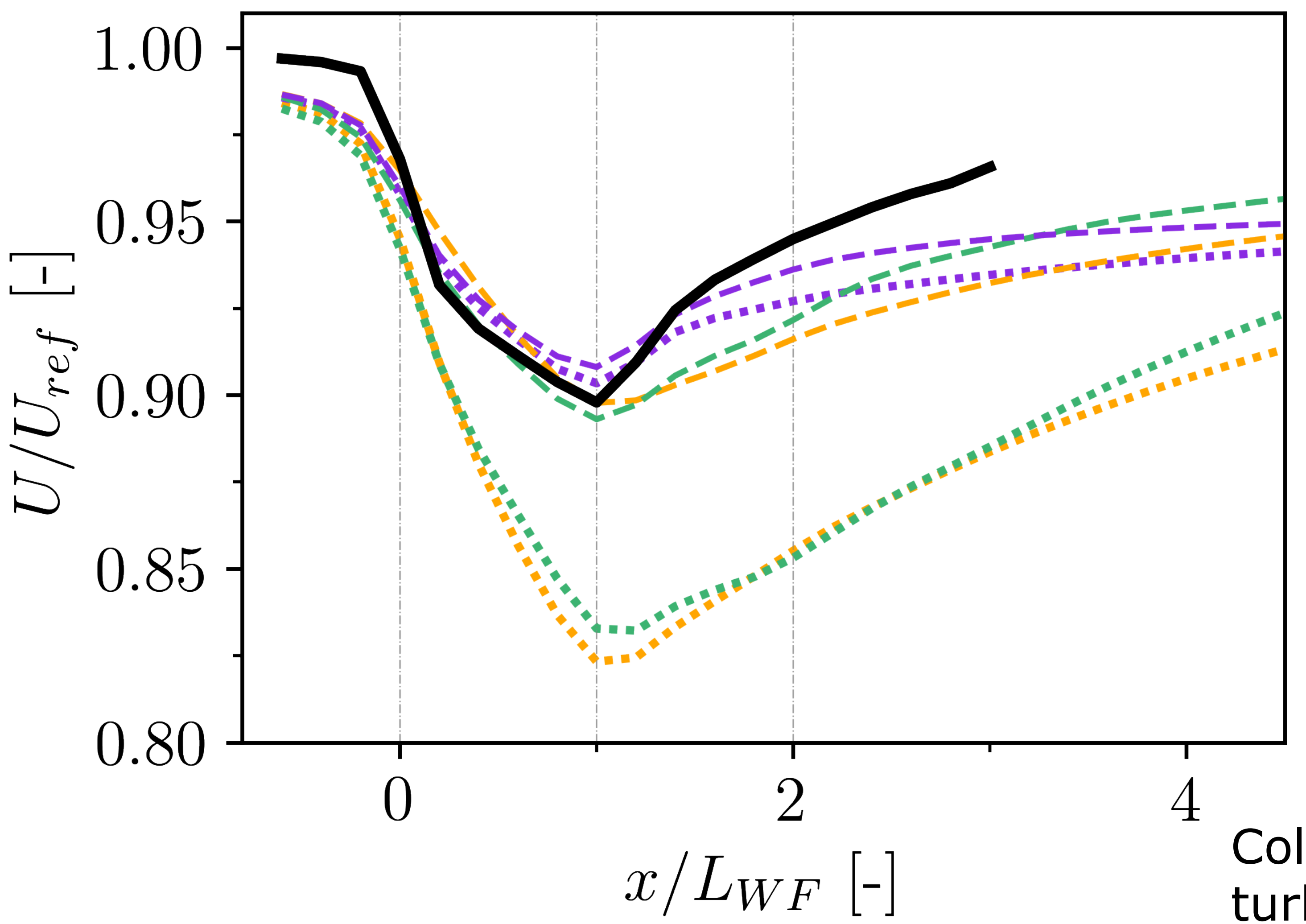
DX = 1200 m

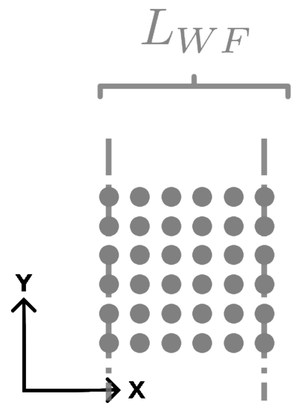
Streamwise added TKE



Coloured lines represent the turbulence schemes in WRF

Wind speed reduction through the wind farm



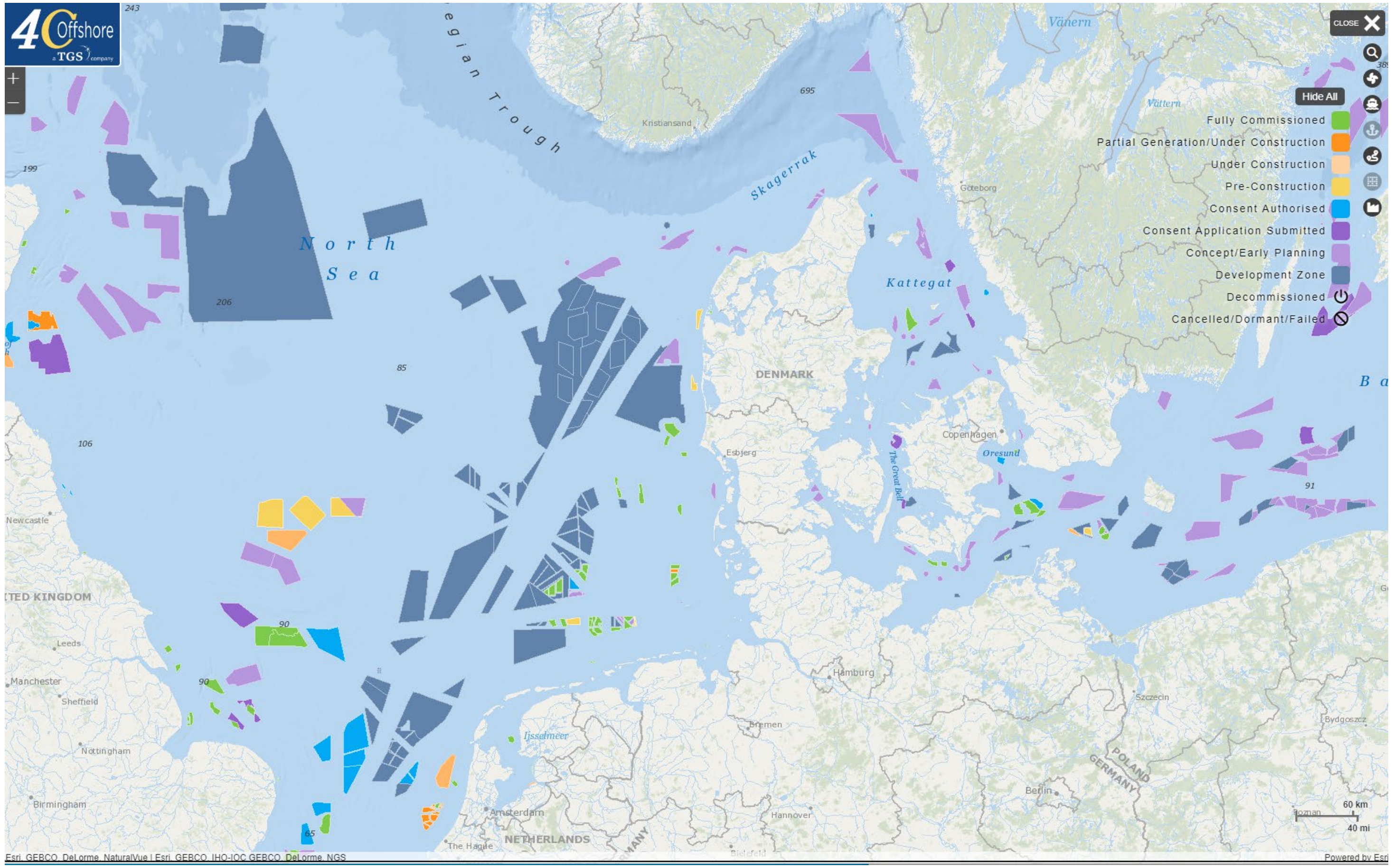


Coloured lines represent the turbulence schemes in WRF

Future research and application in this topic area

Oscar Garcia

Revisiting the farm efficiency

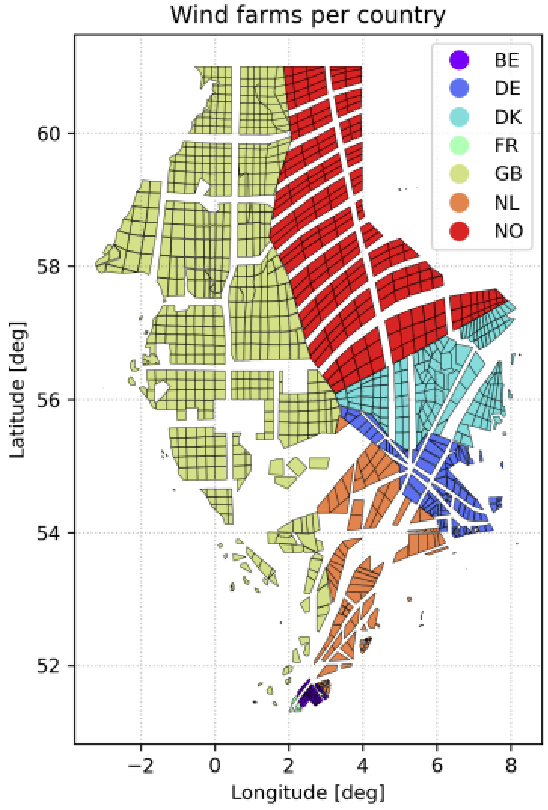


Modelling the whole North and Baltic Sea with the **new** parameterization

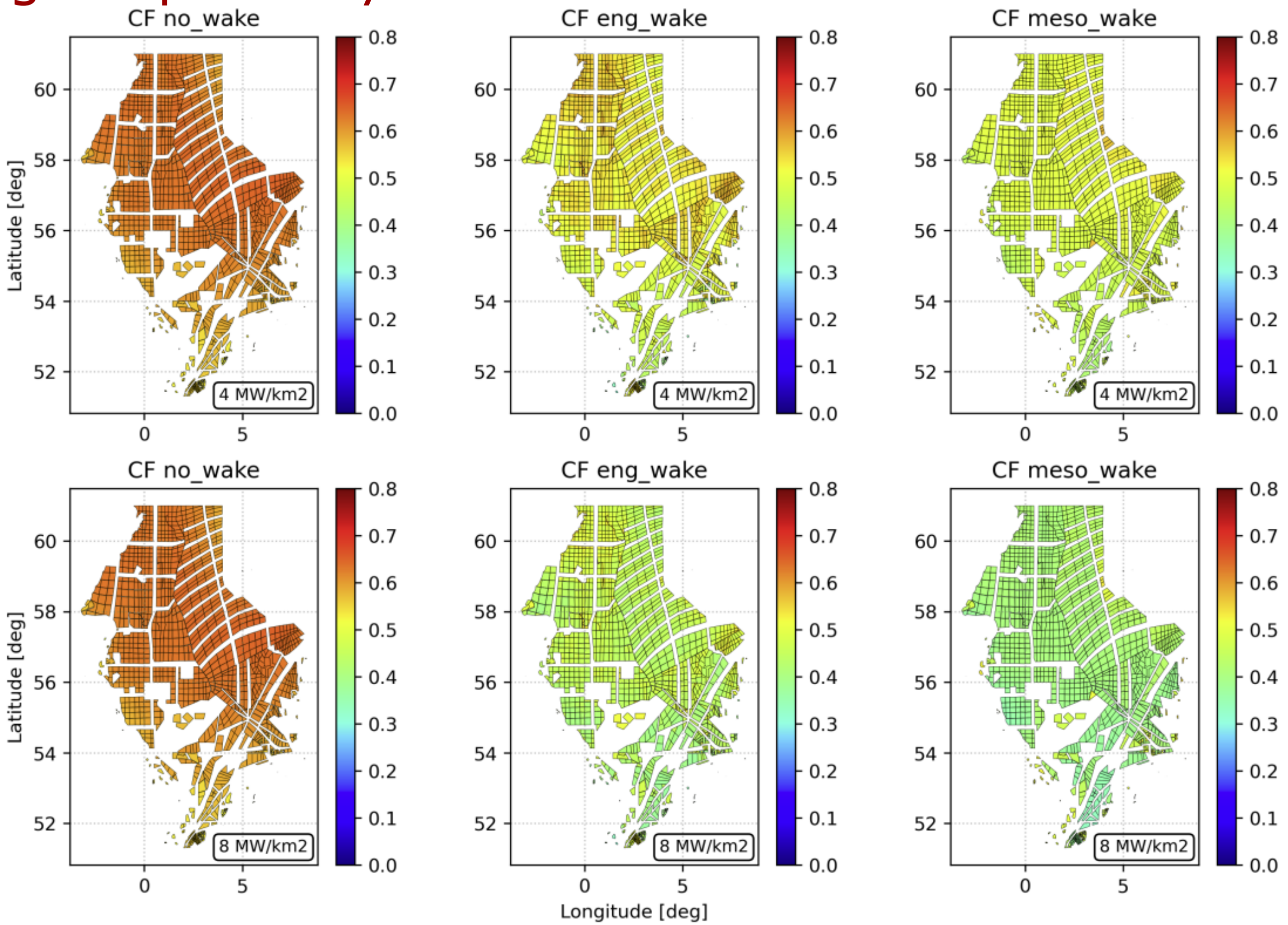
- With the current wind farms
- With future wind farms
- Or wind future climate

Towards optimization of wind farm cluster layouts

Ideal scenario of the North Sea full of wind farms



Using a square layout for each cluster and different spacings



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.

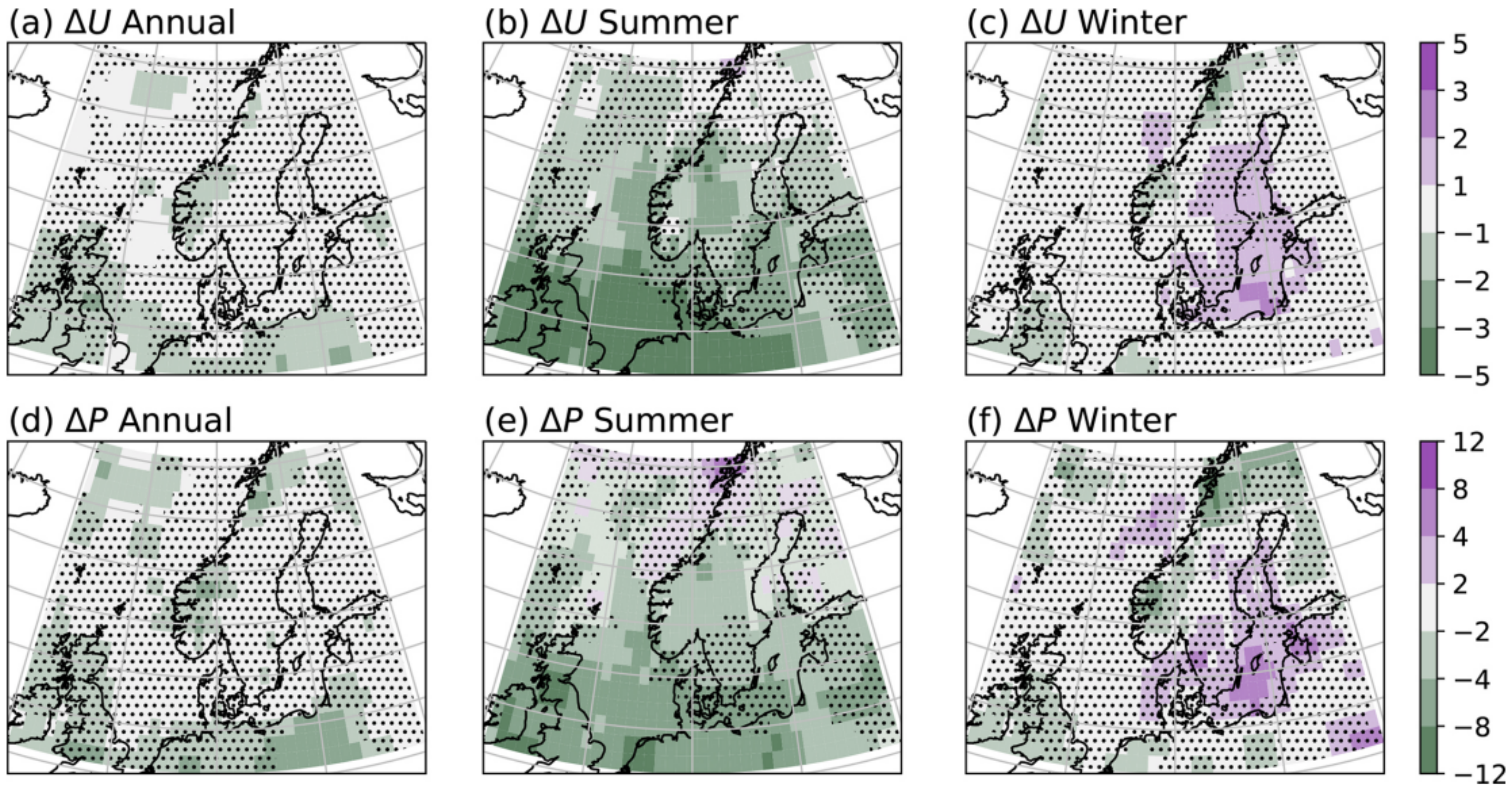
https://backend.orbit.dtu.dk/ws/portalfiles/portal/322712205/TennetProjectReport2023_final.pdf

Consideration of climate change

How might climate change affect the performance of these wind farm clusters?

Wind speed

Power

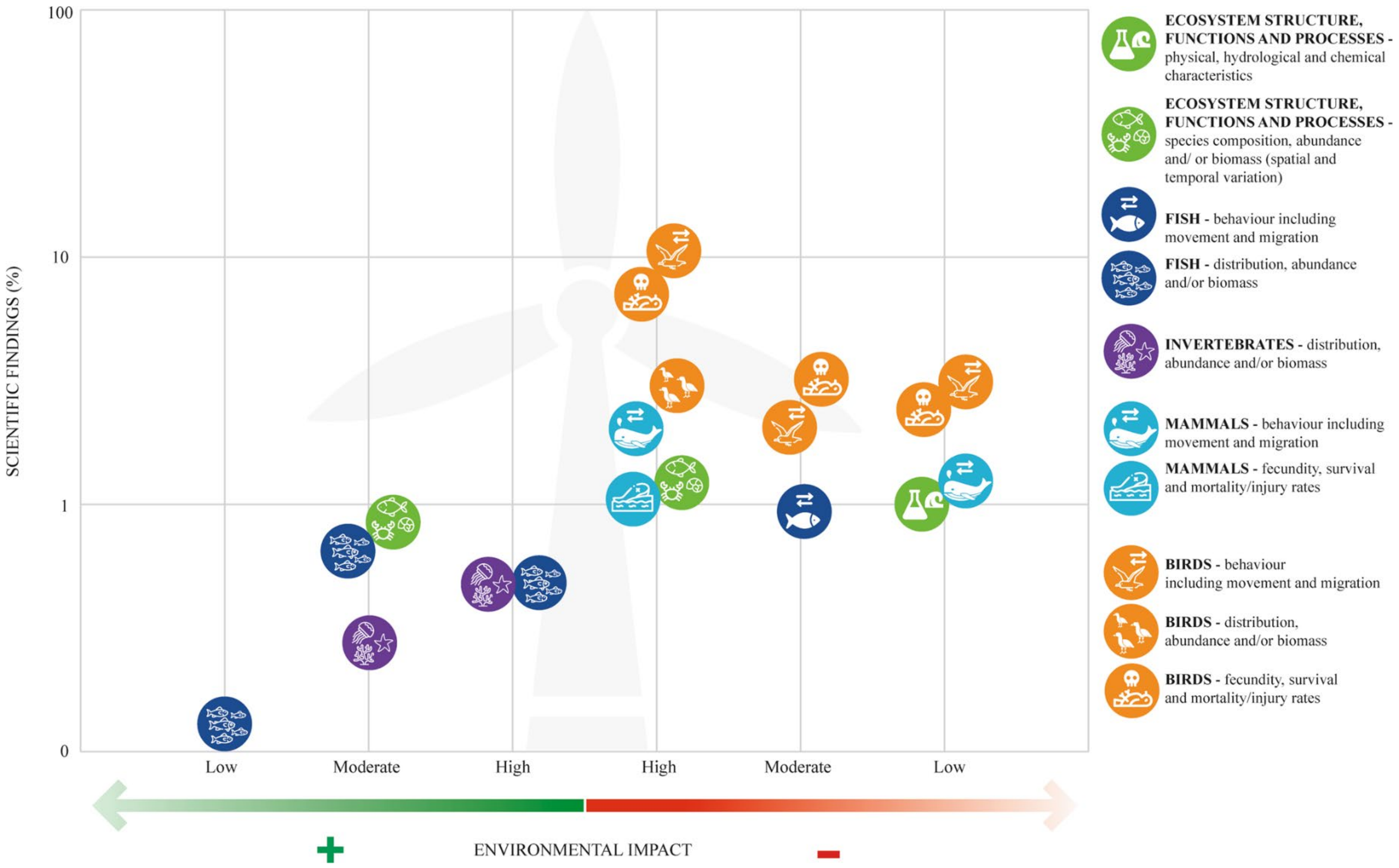


Changes in percentages

Ensemble of 16 models of the recent CMIP6

Hahmann, A. N., García-Santiago, O., & Peña, A. (2022). Current and future wind energy resources in the North Sea according to CMIP6. Wind Energy Science, 2022, 1-32.
https://doi.org/10.5194/wes-7-2373-2022

Considering environmental impact



Including in the layout optimization, information from environmental sources

Galparsoro, I., Menchaca, I., Garmendia, J. M., Borja, Á., Maldonado, A. D., Iglesias, G., & Bald, J. (2022). Reviewing the ecological impacts of offshore wind farms. npj Ocean Sustainability, 1(1), 1-8.

https://doi.org/10.1038/s44183-022-00003-5

And lastly … more WAKES

The AWAKEN benchmarks

AWAKEN
U.S. DEPARTMENT OF ENERGY

Validating our models with measurement and comparing the results from other institutes.

[The AWAKEN benchmarks — AWAKEN Benchmarks 0.1 documentation (awaken-benchmark.readthedocs.io)]