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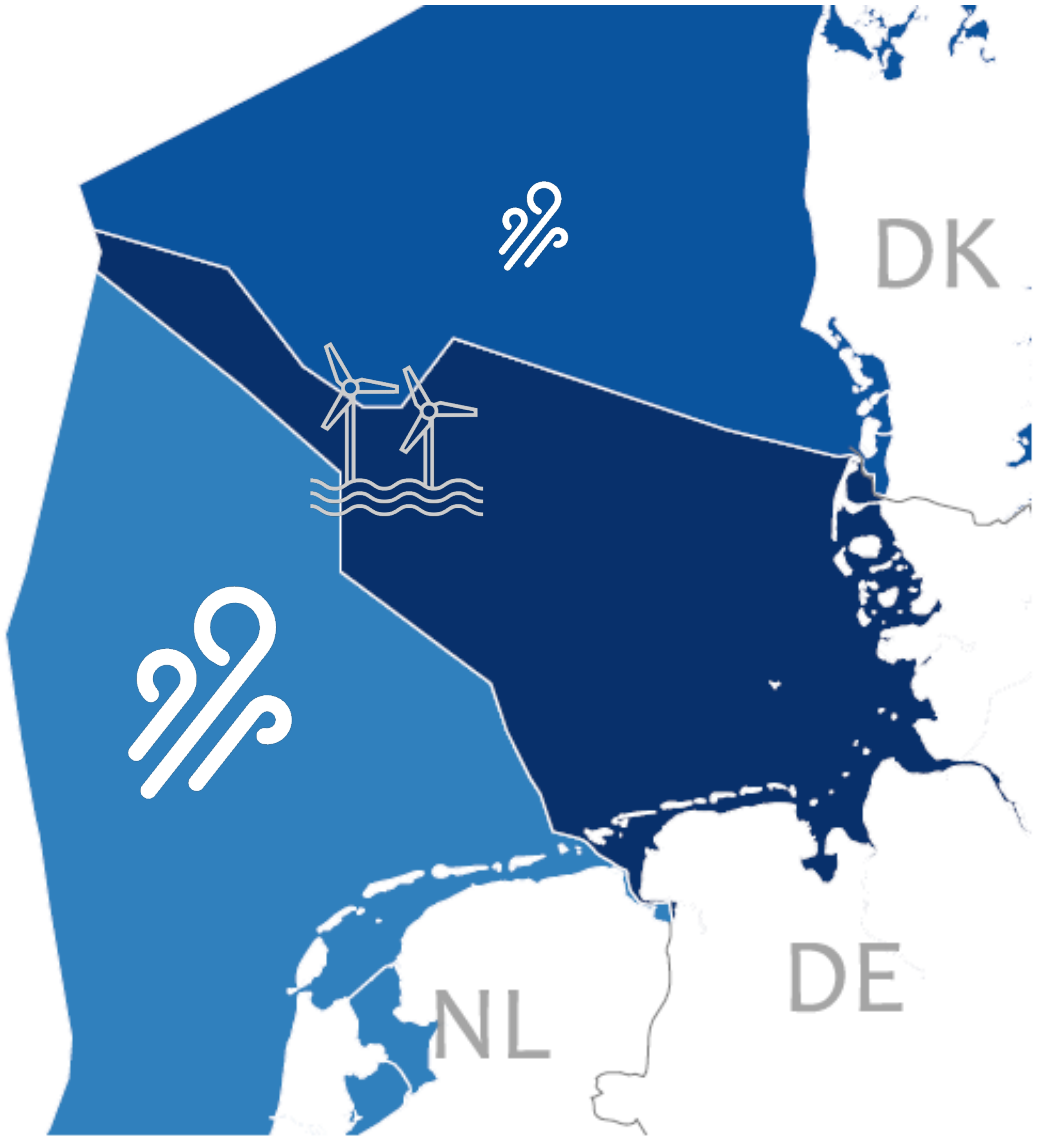
Gone with the wind?

Quantifying wake losses for offshore wind farms and a discussion of mitigation measures



Enerday, Dresden // 04.04.2025

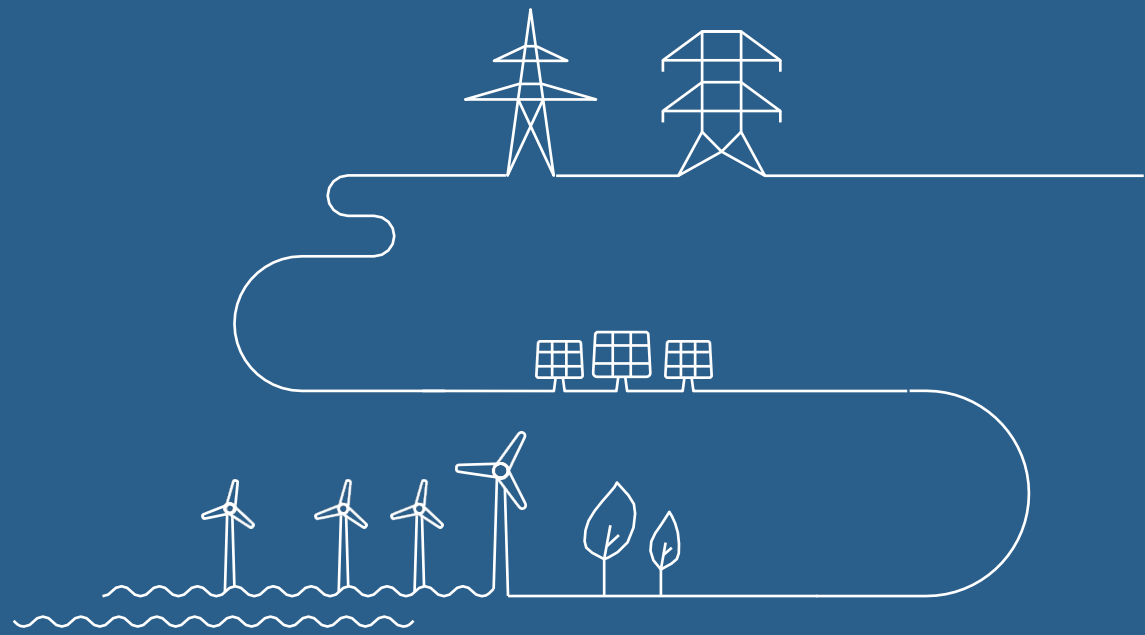
Content of this presentation is subject to the manuscript “Cross-border cooperation to mitigate wake losses in offshore wind energy - A 2050 case study for the North Sea” submitted to *International Journal of Energy Research.* It depicts the sole view of the author and does not allow any conclusion on the positioning of 50Hertz

Content

1. Wake and offshore wind – Relevance and key challenges
2. Quantifying wake losses across borders – Kinetic Energy Budget of the Atmosphere
3. Mitigating wake losses – Discussion of measures and economic implications
4. Dissemination and conclusion

Wake and offshore wind

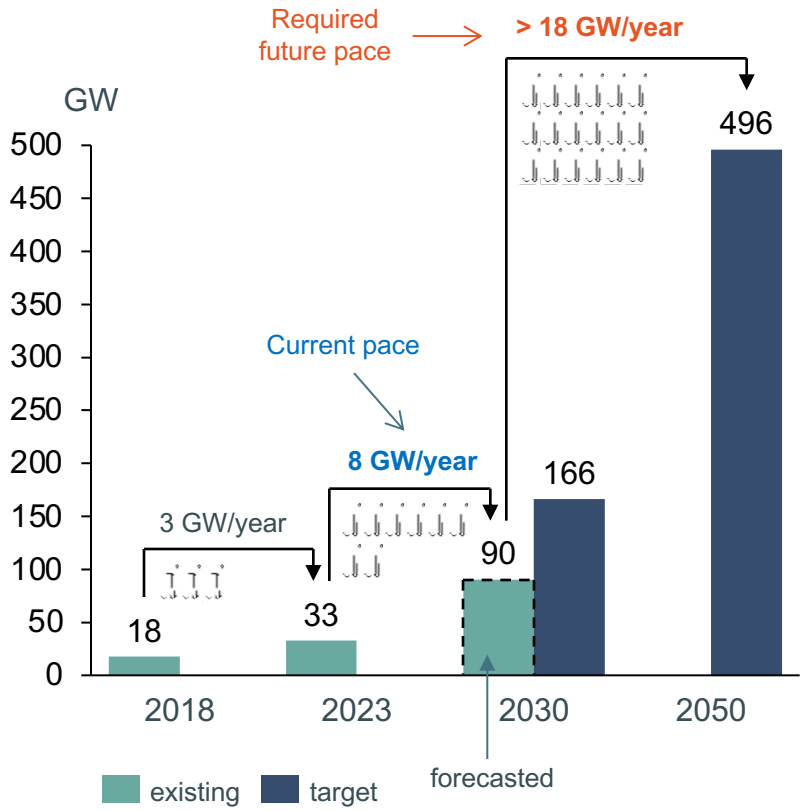
Relevance and key challenges



Offshore wind is bound to become a key element of Europe's future energy mix

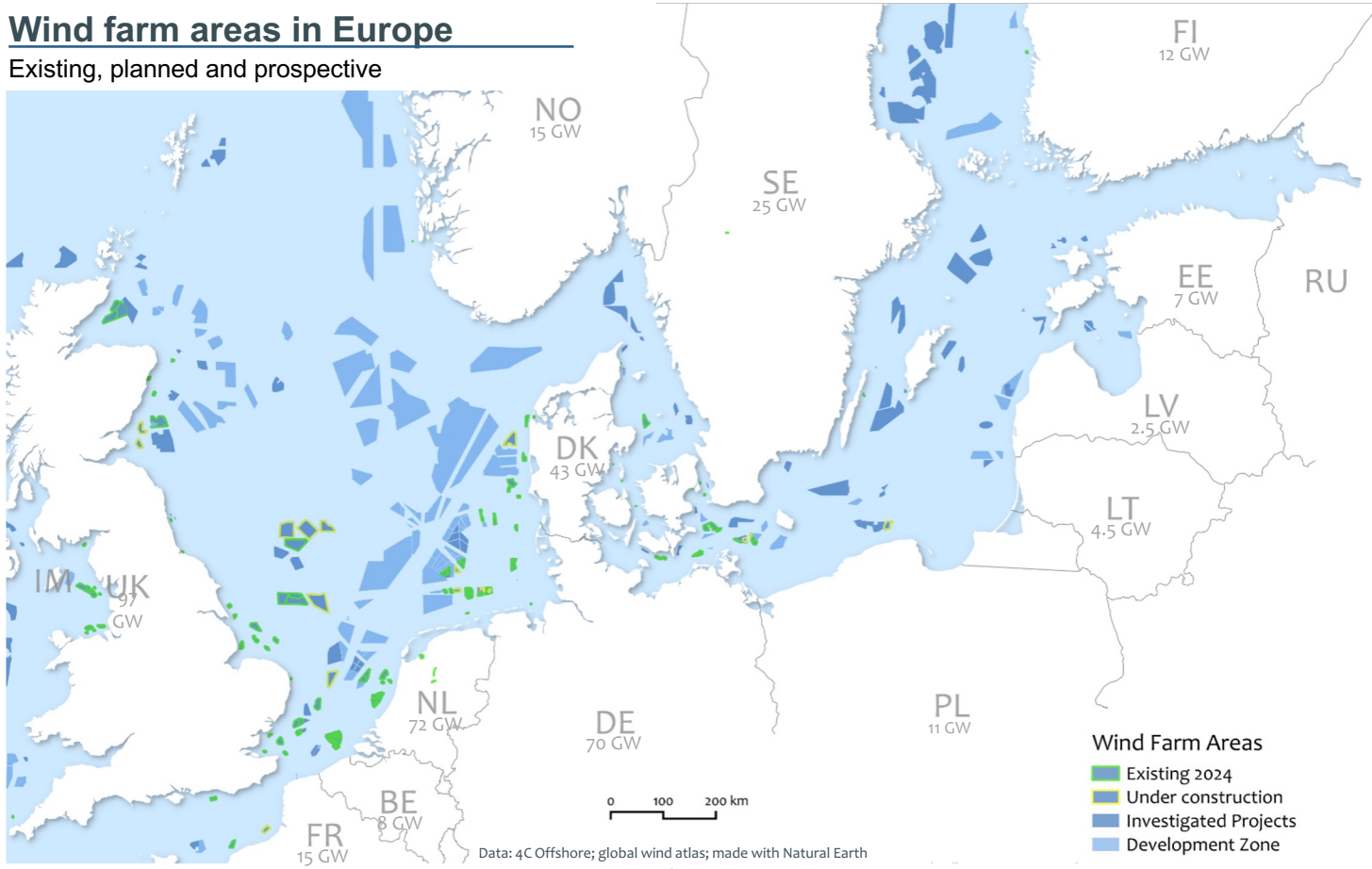
Offshore wind targets

European Union + United Kingdom + Norway



Wind farm areas in Europe

Existing, planned and prospective

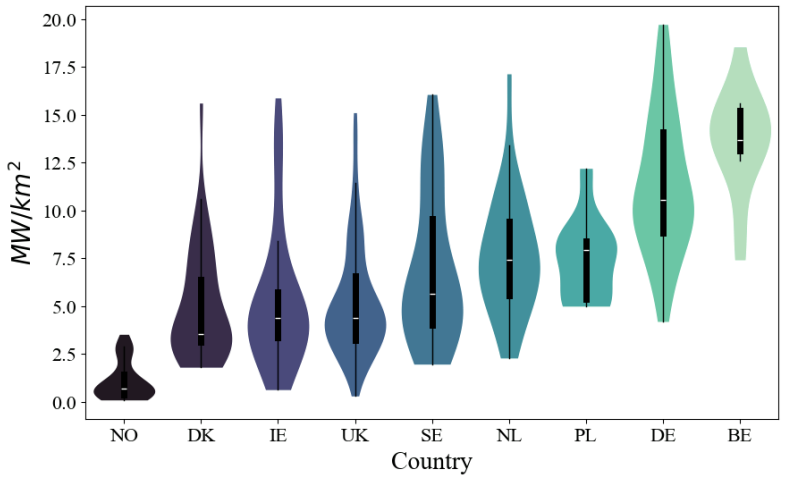


Data: WindEurope annual statistics, BNEF Wind Market Outlook 1H 2024, ONDP 2024, Global wind atlas
Net capacity additions, retrofit or decommissioning not considered.

Dominant wind direction and power density impact wake losses the most

Power densities per EEZ

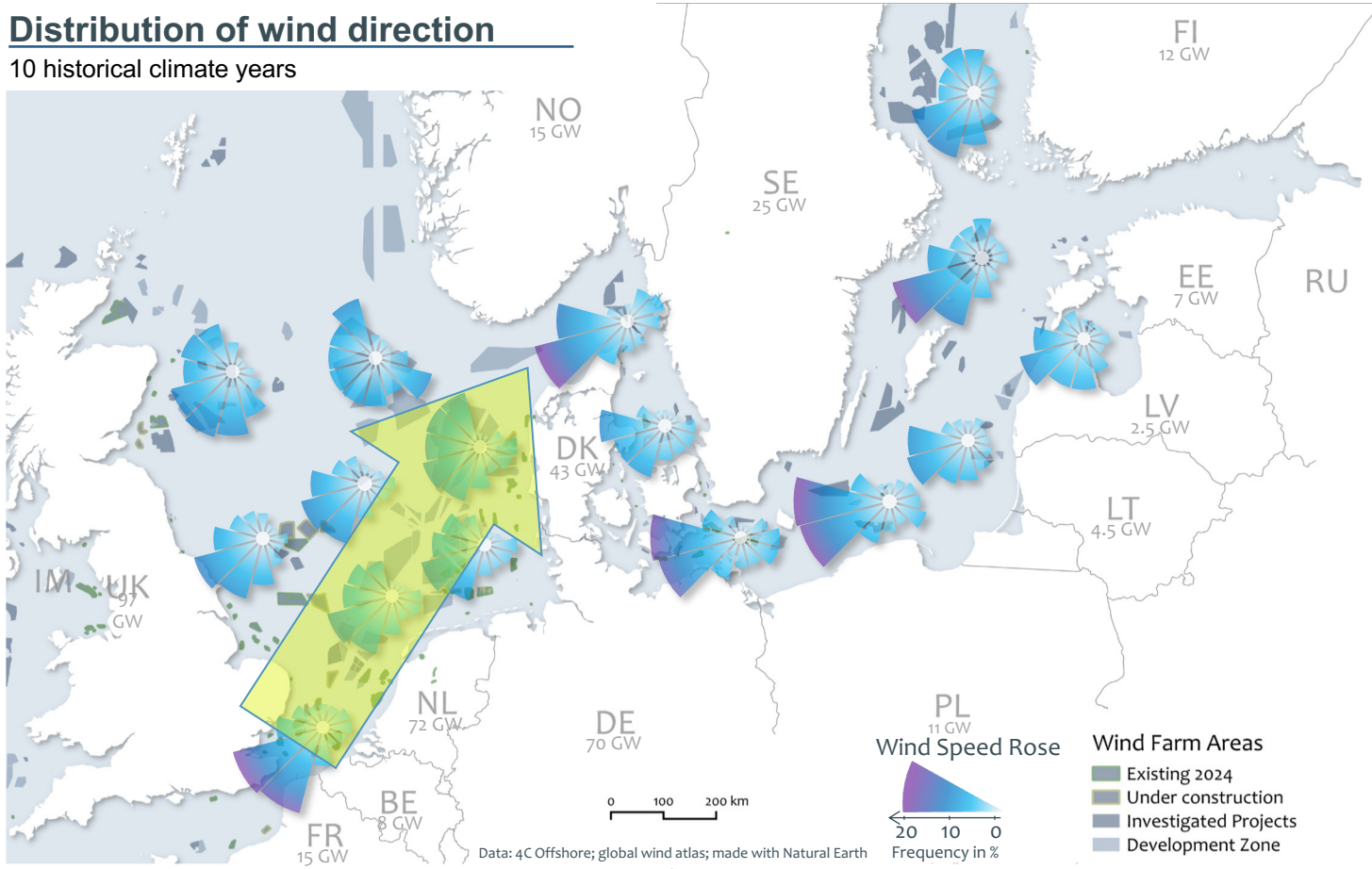
Existing and future wind farms



30% of the future offshore wind capacity in the North Sea will be located in the same wind corridor.

Distribution of wind direction

10 historical climate years



Data: 4C Offshore, Global wind atlas

Accurate assumptions on (wind) time series data are vital for robust analysis results

Relevance of (wind) time series data

In energy system modelling…

Input data
Capacities, weather,…

Optimisation
Socio economic welfare

Result
capacity expansion, dispatch, cost sharing

…and cost-benefit calculation

Input data
Yield, market prices,…

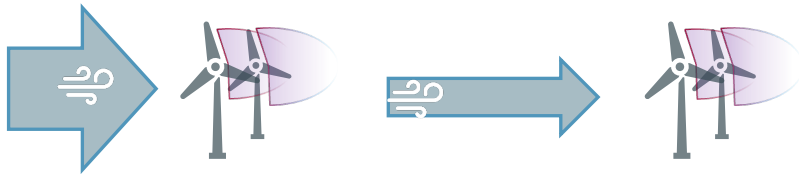
CBA
Levelized cost of electricity

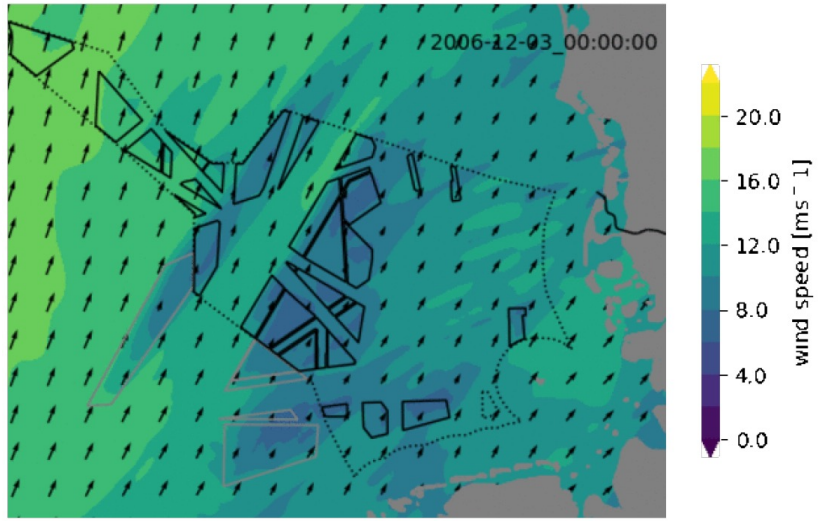
Result
Investment decision

Offshore wake losses are often underestimated in system studies

Impact of wake losses on yield expectations

Measured in reductions of capacity factors and wind speeds





Wake losses…

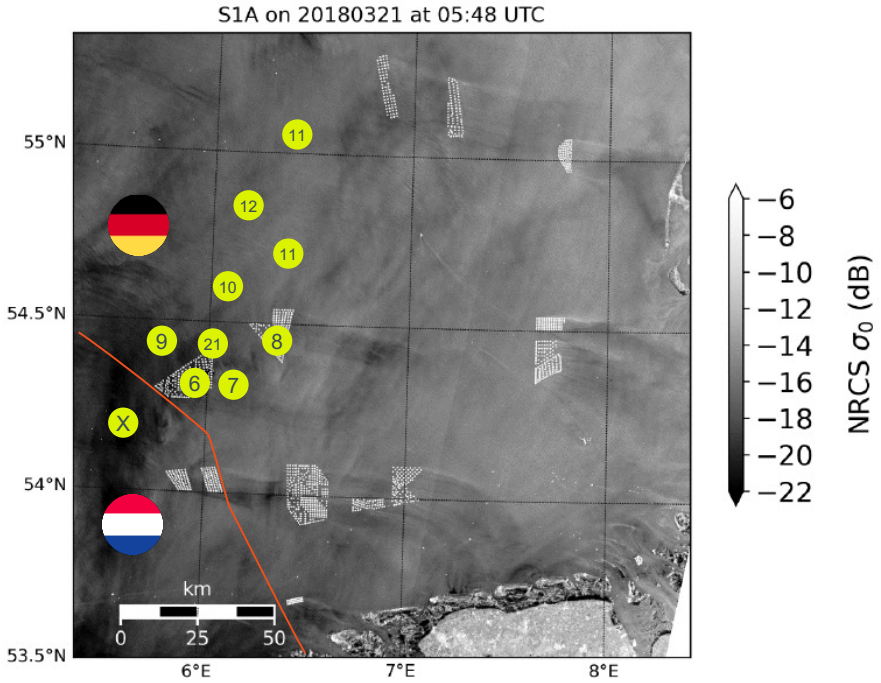
- grow with larger wind farms
- are sensitive to local conditions
- can impact distant areas still

Koivisto, et al. (2022): “Offshore energy hubs: Cost-effectiveness in the Baltic Sea energy system towards 2050”
Fraunhofer IWES (2023): “Estimation of long-term offshore wind energy yield in the German EEZ”

Wake losses concern both, future and existing wind farms

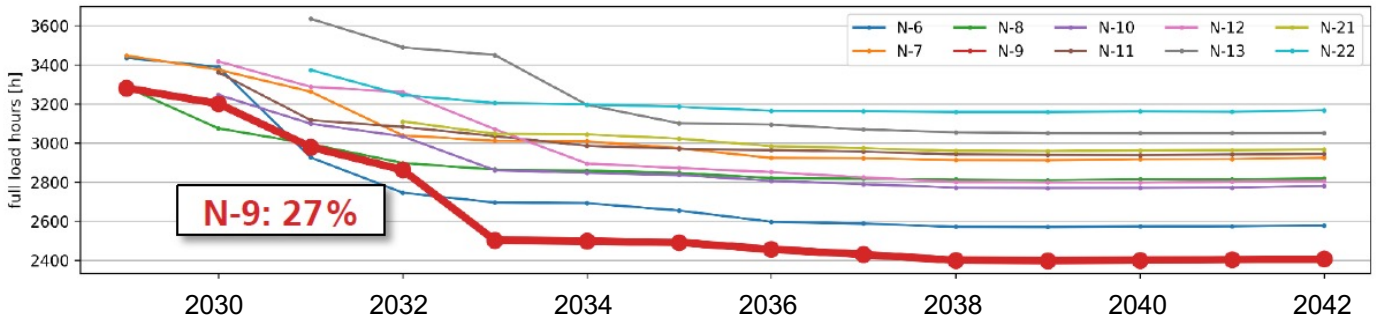
Empirical evidence for wake shadows

German Bight of the North Sea in 2018



Future projections for existing wind farms

German Bight of the North Sea in 2018



Interdependence of cross-border wind farm development will increase significantly past 2030

Fraunhofer IWES (2023): “Estimation of long-term offshore wind energy yield in the German EEZ”

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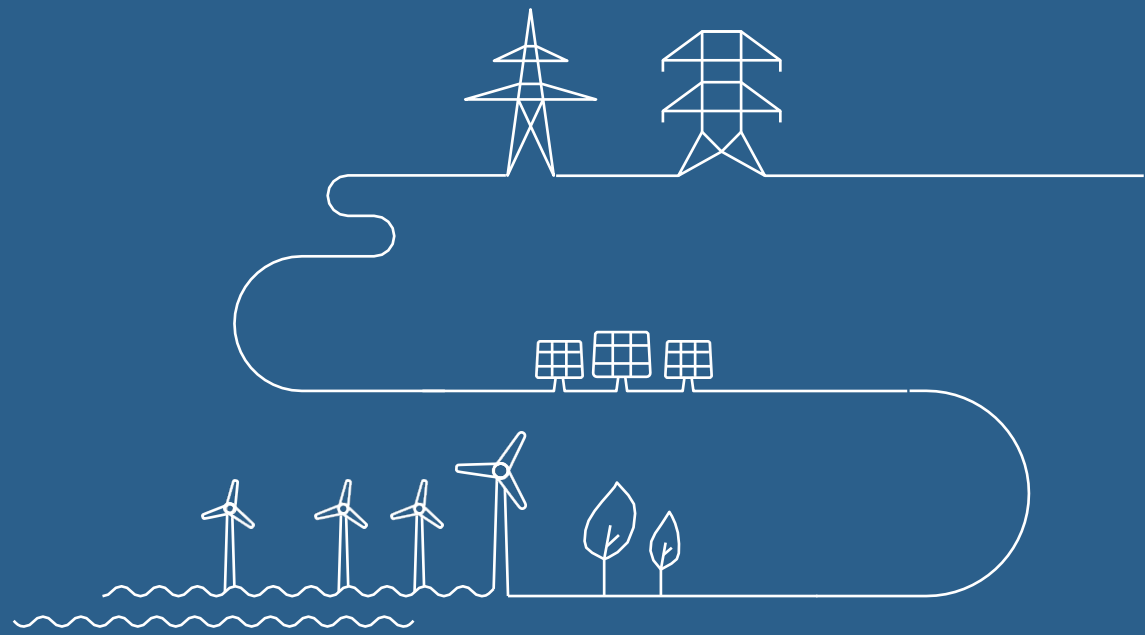
Quantifying wake losses

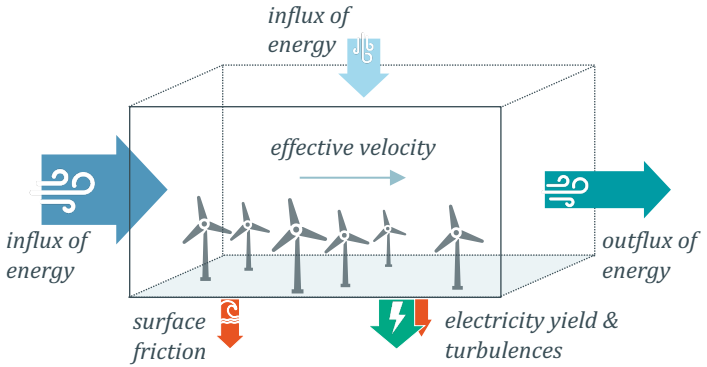
Kinetic Energy Budget of the Atmosphere



Simulation of the kinetic energy budget of the atmosphere (KEBA) to quantify wake losses and mitigation options

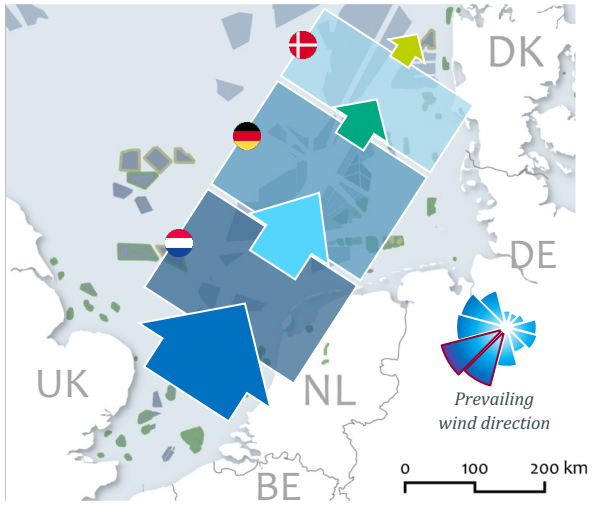
Input/Output simulation model

Kinetic energy budget of the atmosphere



Three coupled boxes in a row

The Netherlands, Germany, Denmark



Three scenarios

1
- ▶ 35 GW
- ▶ 66 GW
- ▶ 72 GW

Base case
Planned wind farm capacities and densities

2
- ▶ 35 GW
- ▶ 66 GW
- ▶ 72 GW

More Space
Same capacity, but lower power densities

3
- ▶ 50 GW
- ▶ 51 GW
- ▶ 72 GW

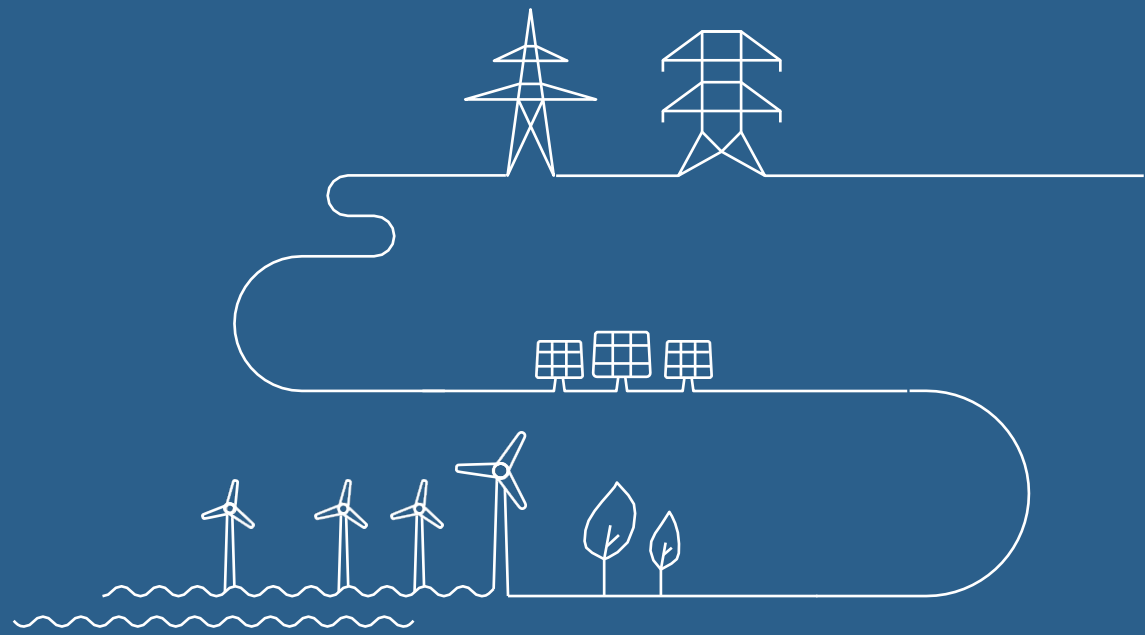
Redistribution
Same capacity, but some capacity shifted to DK

With key assumptions

- ▶ Single main wind direction from South-West *representing 25-30% of all hours*
- ▶ Three coupled bounding boxes for covering the EEZ of NL, DE and DK respectively
- ▶ Simulation of 10 historical climate years in hourly resolution

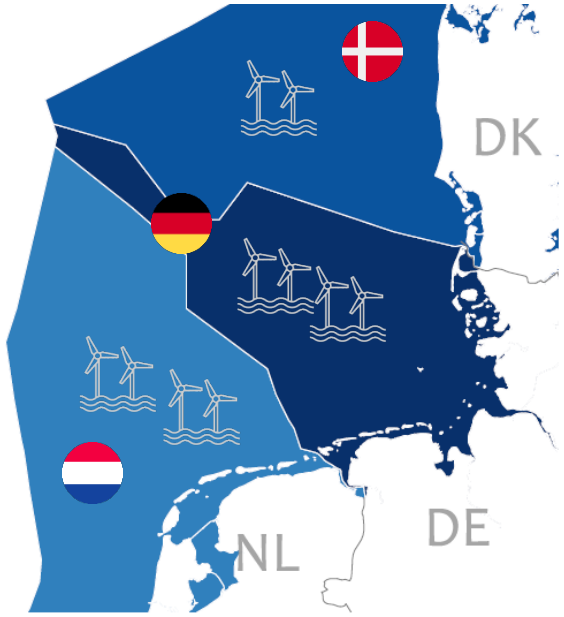
Kleidon, Miller (2020): The Kinetic Energy Budget of the Atmosphere KEBA model 1.0

Results

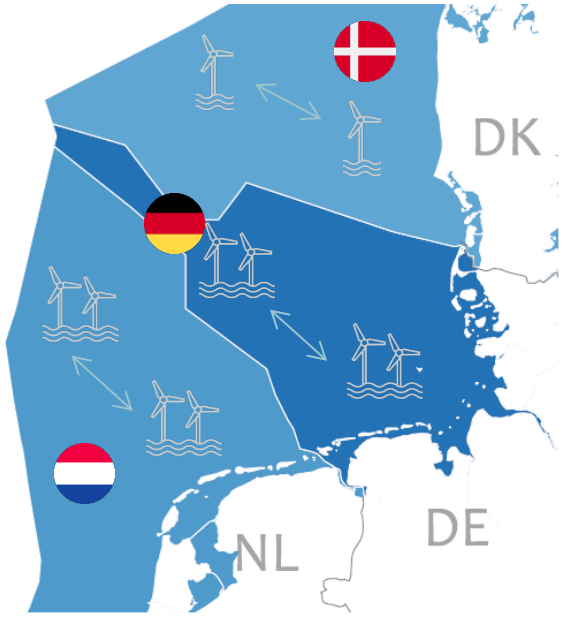


Reducing power densities and shifting capacity further north can reduce but not eliminate wake losses

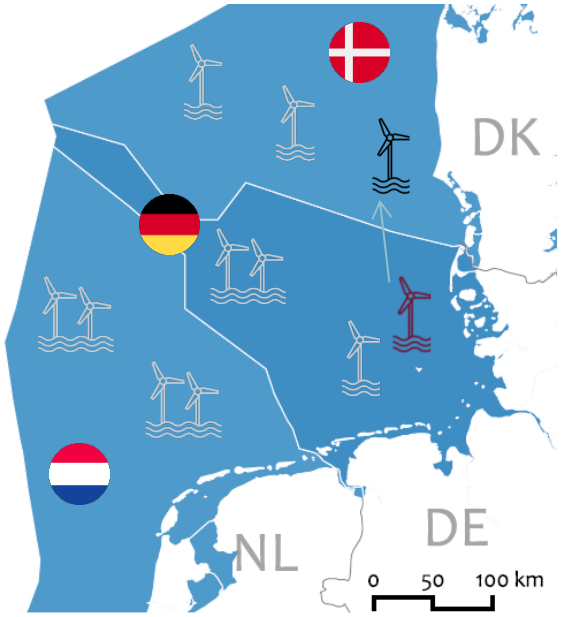
Base case
Current planning



More space for wind farms
Reduced power densities



Redistribution
Cross border shift of some capacity

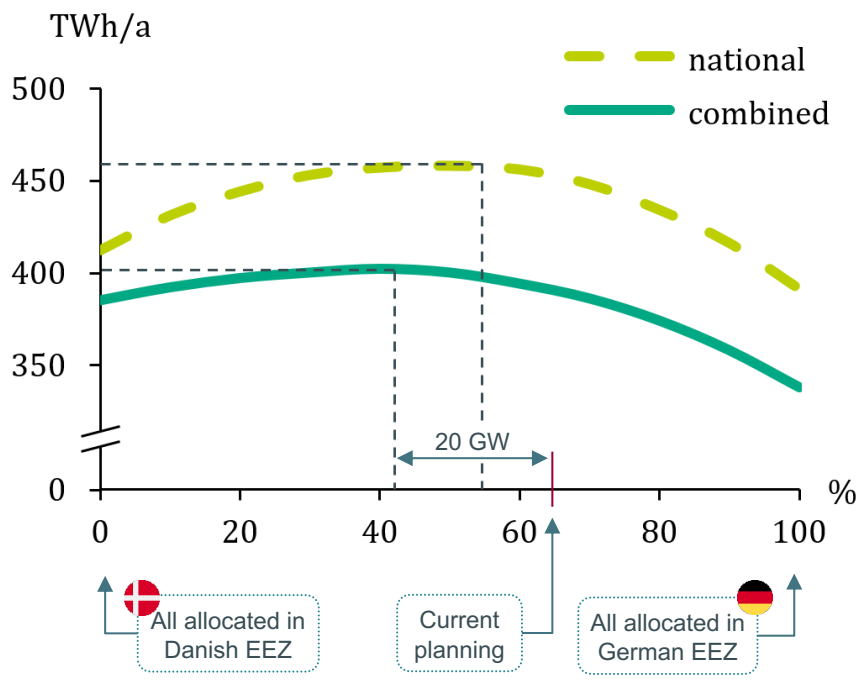


Reduction in full-load hours compared to idle conditions with no wake

Neglecting a cross-border (combined) view on the generation potential of offshore wind can lead to suboptimal planning.

Sum of annual yield in DE and DK for different capacity allocations

As a function of share (%) of total capacity being in German EEZ



National optimisation
only accounting for domestic wake losses, not for cross-border effects

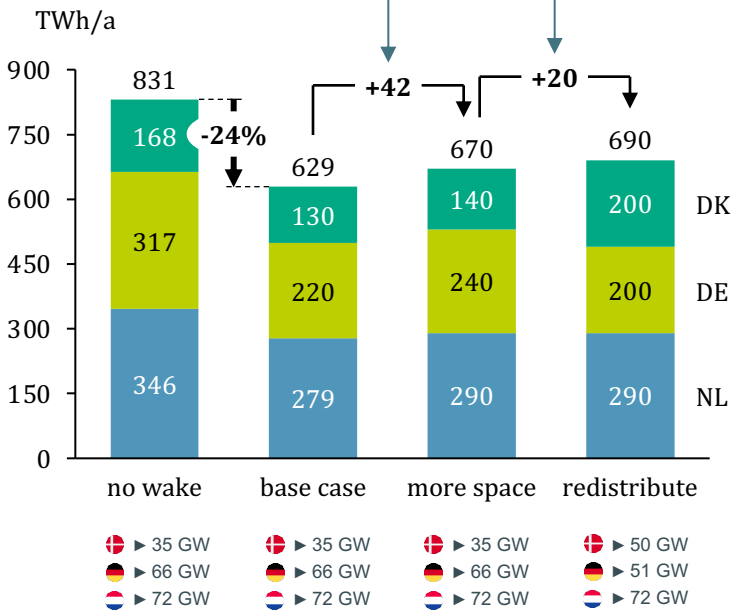
Combined optimisation
Including both, national and cross-border wake effects

Optimal development of offshore wind is achieved when focussing on energy targets as opposed to capacity targets.

Spatial distribution of wind farms has strong impact on resulting yield

Impact on yield across all scenarios

Measured annually in TWh/a



Lower power densities can theoretically yield +40 TWh (11 GW) at same installed capacity

Cross border cooperation between DK and DE can yield additional +20 TWh (5 GW) at same installed capacity

It assumed that only 20% of this effect can be leveraged due to spatial planning constraints

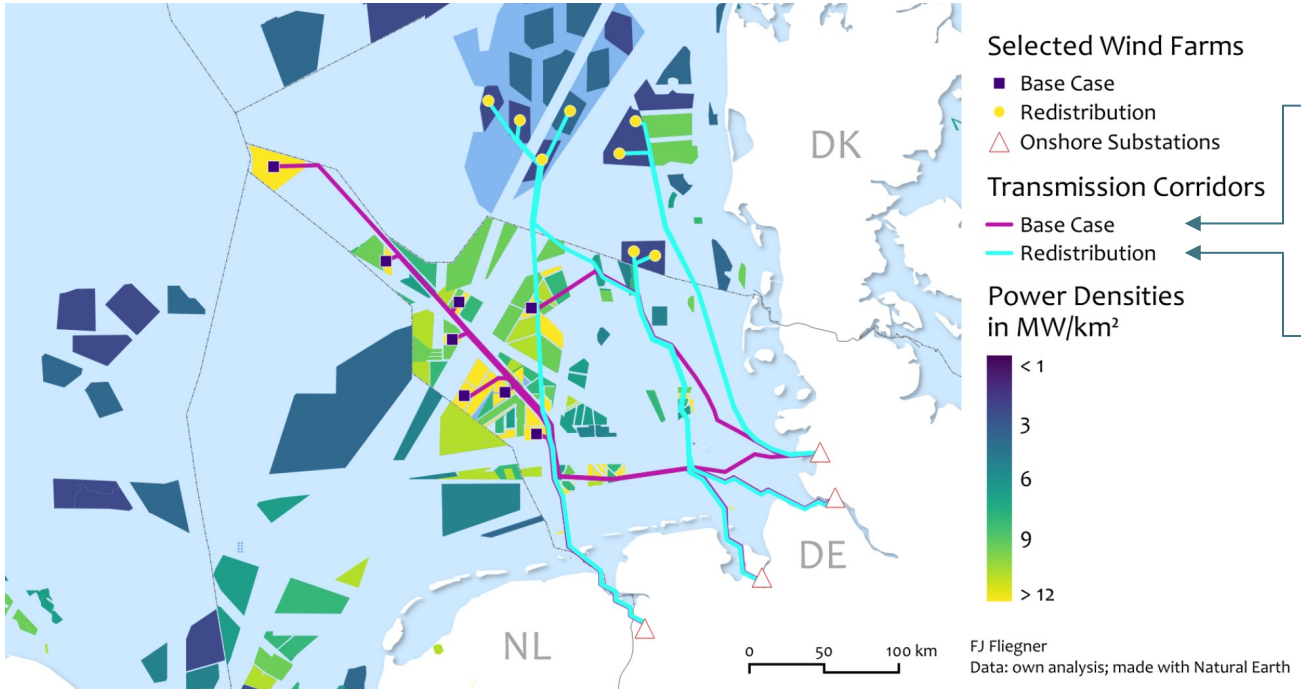
Approx. 8 GW generation capacity can be saved from wake losses.

Cross-border accumulation is a significant driver of wake losses.

Cross-border shift of capacity can be spatially and economically viable (conditions apply)

Possible routes for connecting redistributed wind farms

As a function of power density



Base case

shortest national connection: 2,320 km

FLH 3,400

LCOE 108 €/MWh

Redistribution of wind farms from DE to DK

shortest national connection: 2,450 km +5%

FLH 4,050 +19%

LCOE 95 €/MWh -12%

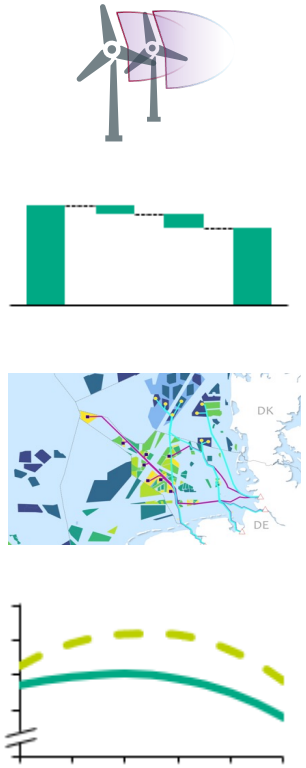
With key assumptions

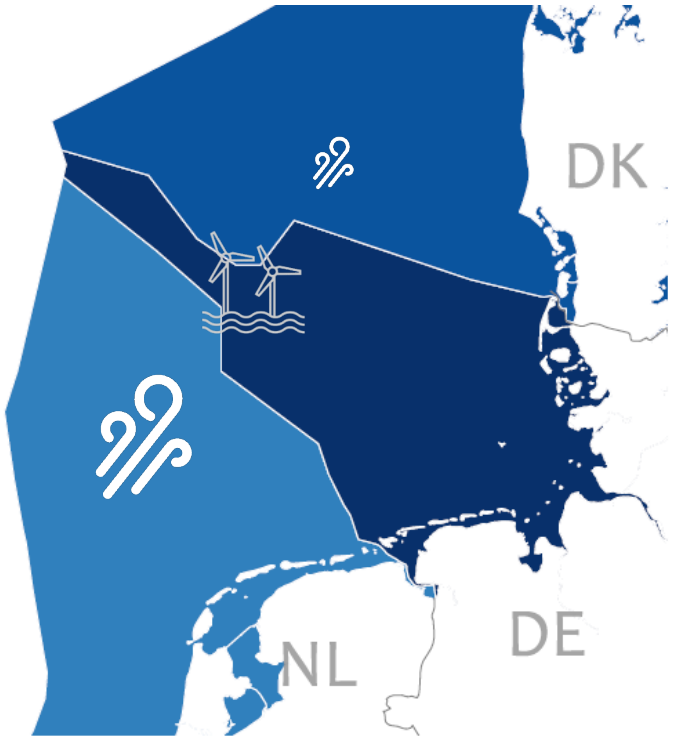
- Connection only to DE
- No alternative onshore grid DK-DE considered
- Invest in wind farms is the same in DK and DE
- No compensation for DK

Fliegner (2025): The power of coordinated planning – A spatial planning perspective on mitigating offshore wake losses in the North Sea 2050 (preprint)

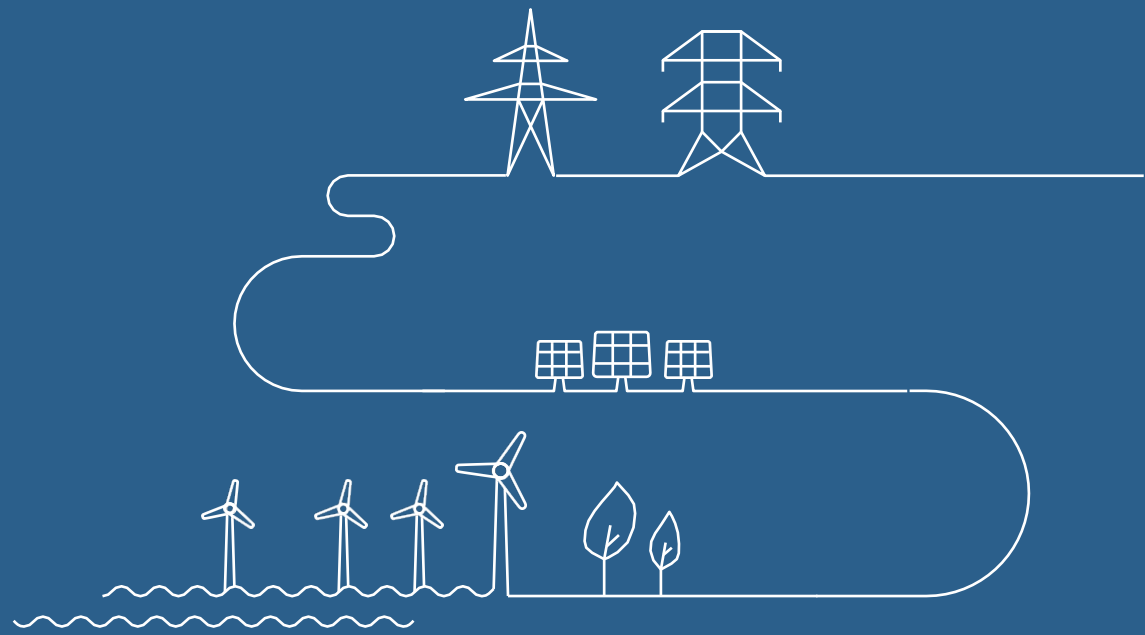
“Less is more” – Acknowledgement of wake losses can help mitigating it and improve overall generation efficiency

- Wake is inextricably linked to the large-scale deployment of offshore wind power
- Neglecting it during system planning or project development can overestimate yields by 20-30%
- A large-scale, long-term and cross-border planning perspective can reduce the losses effectively
- Optimising for an energy target instead of capacity target can incentivise a more efficient development





Backup



Input data

Offshore wind capacities

Per scenario

Scenario	Offshore wind capacity in [GW]		
	NL	DE	DK
1 base case	72	66	35
2 more space	72	66	35
3 redistribute	72	0..101	0..101

Box dimensions and power densities

For the boundary box for the KEBA analysis

	density in [km²]	width in [km]	length in [km]	f
Boxes for scenario 1				
NL	6.8	170	62	0.54
DE	11.7	170	33	0.54
DK	7.6	170	27	0.69
Boxes for scenarios 2 & 3				
NL	3.2	170	314	0.27
DE	2.3	170	168	0.24
DK	1.0	170	292	0.26

Wind speeds

Duration curves for 10 historical climate years