Making the most of offshore wind

Re-Evaluating the Potential of Offshore Wind in the German North Sea

Matthias Deutsch, Jake Badger, Axel Kleidon

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## Outline

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Project overview: Making the Most of Offshore Wind

Commissioned by: Agora Energiewende and Agora Verkehrswende

Partners: Max-Planck-Institute for Biogeochemistry (MPI-BGC)  
Technical University of Denmark, Department of Wind Energy (DTU)

Question: How many full-load hours can offshore wind reach assuming a huge expansion in the German North Sea until 2050?

Background: Climate target scenarios for Germany typically assume around 4000 full load hours

Methodology:

→ Simulations of installed offshore wind capacity with two different physics-based approaches that include how the atmosphere reacts

→ MPI: Box model implemented in a spreadsheet (“KEBA”)

→ DTU: Numerical Weather Research and Forecast model (WRF-EWP), running on a computer cluster

Download:
• Publication
• Feed-in time series
• KEBA model
## Key conclusions

1. Offshore wind energy, which has an installed capacity potential of up to 1,000 GW, is a key pillar of the European energy transition.

2. Scenarios projecting near climate neutrality by 2050 assume an installed capacity of 50 to 70 GW of offshore wind in Germany, generating some 200 to 280 TWh of electricity per year.

3. Offshore wind power needs sufficient space, as the full load operating time may otherwise shrink from currently around 4,000 hours per year to between 3,000 and 3,300 hours.

4. Countries on the North and Baltic Seas should cooperate with a view to maximizing the wind yield and full-load hours of their offshore wind farms.
Analysis
by DTU and MPI
Climate model simulations show that many turbines reduce wind speeds, turbine efficiencies, and wind energy resource potentials.

Motivation

Miller und Kleidon (2016) PNAS

Volker et al. (2017) ERL
More than wakes…

Present scales of wind farm development
Well observed
Simulated by engineering models

Future scales of wind farm development
Not yet observed
Simulated by physics-based models

Large horizontal kinetic energy flux density
Typical value: \(550 \text{ W m}^{-2}\) per cross-sectional area

Wake effects
Small vertical renewal rate from above
Typical value: \(\approx 2 \text{ W m}^{-2}\) per surface area

Reduced wind speeds

Individually

Wind farm

Regionally
Scenarios for 2050

→ Scenarios for 2050 expect 45 – 70 GW of offshore installed capacity, yielding 200 – 280 TWh/a.

→ To which extent are yields likely to be reduced due to reduced wind speeds?

Formulation of the Scenarios

- Focus on EEZ of the German Bight
- Consideration of possible areas, separated into Area 1 and Area 2
- Evaluation of different installed capacity densities (5, 7.5, 10, 12.5, 20 MW/km²)
- Hypothetical 12 MW turbines
- Use of “Area 1”, “Area 2”, and both areas (“Area 3”)
- Yields scenarios of 13.8 – 144.8 GW
- Current expansion plans focus on “Area 1” only
Estimation of Expected Yields

**KEBA**
Kinetic Energy Balance of the Atmosphere (MPI)

- **Downward transport of kinetic energy**: $\rho C_v \nu^2$
- **Horizontal import of kinetic energy**: $\rho/2 \nu^2$
- **Effective velocity** $v$
- **Turbulent dissipation**: $\rho C_v \nu^2$
- **Energy extraction by wind turbines**: (electricity + wake)

**WRF**
Weather Research and Forecasting model (DTU)

- **Surface elevation (m)**
- **Numerical simulation model, highly detailed**, uses ECMWF weather forcing fields for year 2006

Spreadsheets, highly aggregated, uses FINO-1 wind observations for 2004-2015

Both models are based on physical constraints, specifically the budgeting of kinetic energy (in contrast to engineering models)
Both methods estimate similar reduction in average capacity factors

Both methods estimate substantial reductions in yields (up to 50% for the largest scenario)
Reduction in Winds

**KEBA:** simulated shift in frequency distribution of wind speeds

**WRF:** simulated spatial patterns of reduced wind speeds (average)
Interpretation of Results

Reduced yields and wind speeds come from limited influxes of kinetic energy into the region.
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)
Summary of findings

Estimation of yields for 13.8 to 144.8 GW of installed capacity in the German Bight

Two methods (KEBA, WRF) yield similar estimates

Both methods estimate efficiencies of from 82-85% (13.8 GW) to 42-48% (144.8 GW).

Yield reductions are to be expected in currently considered expansion scenarios for offshore wind energy.

Illustrative example:
- Density: 10 MW/km²
- Capacity: 28 to 72 GW
- Full-load hours: ~3400 to ~3000
- Capacity factor: 39% to 34%

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<th>Formulation of scenarios</th>
<th>Results With wakes caused by kinetic energy removal</th>
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<td>Yield (GW)</td>
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<td>Density (W/m² or MW/km²)</td>
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<tr>
<td>Area 1</td>
<td>Area 2</td>
</tr>
<tr>
<td>10</td>
<td>x</td>
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<td>10</td>
<td>x</td>
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* Other losses not included.
Conclusions drawn by Agora Energiewende and Agora Verkehrswende
Offshore wind energy, which has an installed capacity potential of up to 1,000 GW, is a key pillar of the European energy transition.

The net-zero decarbonization scenarios contained in the European Commission’s Long-Term Strategy assume some 400 to 450 GW of offshore wind capacity by 2050.

Additional demand of up to 500 GW may be created by dedicating offshore farms to electrolysis for renewable hydrogen production.

In modelling for the European Commission, offshore wind is assumed to reach 4,000 to 5,000 full-load hours at very good sites.
Scenarios projecting near climate neutrality by 2050 assume an installed capacity of 50 to 70 GW of offshore wind in Germany.

- Generating some **200 to 280 TWh** of electricity per year.
- Given the 8 GW of installed capacity today and current plans for 20 GW by 2030, the **pace of spatial planning** for offshore wind deployment needs to pick up significantly.
- Reaching 20 GW by 2030 implies an increase of the installation rate to **around 1.1 GW per year**.
- After 2030, achieving the higher scenario end of 70 GW would involve more than a doubling of annual deployment to **2.5 GW per year** from 2030 to 2050.
Offshore wind power needs sufficient space, as the full load operating time may otherwise shrink from currently around 4,000 hours per year to between 3,000 and 3,300 hours.

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<th>Full-load hours achievable depending on area for offshore wind deployment in the North Sea (and expected yield in TWh)</th>
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<tr>
<td>Area used in km²</td>
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<tr>
<td>0</td>
</tr>
<tr>
<td>2000</td>
</tr>
<tr>
<td>4000</td>
</tr>
<tr>
<td>6000</td>
</tr>
<tr>
<td>8000</td>
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- 7.5 MW/km² (KEBA)
- 10 MW/km² (KEBA)
- 12.5 MW/km² (KEBA)
- 10 MW/km² (WRF)

Agora Energiewende & Agora Verkehrswende (2020)
The more turbines are installed in a region, the less efficient offshore wind production becomes due to a lack of wind recovery.

The yields of many wind turbines decline by different factors

- The more the surrounding horizontal air flow is affected, the greater the reduction in downstream wind speeds, because additional kinetic energy can effectively only come from higher atmospheric layers, and the vertical renewal rate from above is limited.

- If Germany were to install 50 to 70 GW solely in the German Bight, the number of full-load hours achieved by offshore wind farms would decrease considerably.

Source: Agora Energiewende & Agora Verkehrswende (2020)
Countries on the North and Baltic Seas should cooperate with a view to maximizing the wind yield and full-load hours of their offshore wind farms.

→ In order to maximize the efficiency and potential of offshore wind, the planning and development of wind farms – as well as broader maritime spatial planning – should be intelligently coordinated across national borders.

→ This finding is relevant to both the North and Baltic Seas.

→ In addition, floating offshore wind farms could enable the creative integration of deep waters into wind farm planning.

Agora Energiewende & Agora Verkehrswende (2020), adapted
### Key conclusions

1. **Offshore wind energy, which has an installed capacity potential of up to 1,000 GW, is a key pillar of the European energy transition.** The net-zero decarbonization scenarios contained in the European Commission’s Long-Term Strategy assume some 400 to 450 GW of offshore wind capacity by 2050. Additional demand of up to 500 GW may be created by dedicating offshore farms to electrolysis for renewable hydrogen production.

2. **Scenarios projecting near climate neutrality by 2050 assume an installed capacity of 50 to 70 GW of offshore wind in Germany, generating some 200 to 280 TWh of electricity per year.** Given the 8 GW of installed capacity today and current plans for 20 GW by 2030, the pace of spatial planning for offshore wind deployment needs to pick up significantly. The slowing of onshore wind development could further enhance the importance of offshore wind in achieving net zero.

3. **Offshore wind power needs sufficient space, as the full load operating time may otherwise shrink from currently around 4,000 hours per year to between 3,000 and 3,300 hours.** The more turbines are installed in a region, the less efficient offshore wind production becomes due to a lack of wind recovery. If Germany were to install 50 to 70 GW solely in the German Bight, the number of full-load hours achieved by offshore wind farms would decrease considerably.

4. **Countries on the North and Baltic Seas should cooperate with a view to maximizing the wind yield and full-load hours of their offshore wind farms.** In order to maximize the efficiency and potential of offshore wind, the planning and development of wind farms – as well as broader maritime spatial planning – should be intelligently coordinated across national borders. This finding is relevant to both the North and Baltic Seas. In addition, floating offshore wind farms could enable the creative integration of deep waters into wind farm planning.
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Agora Energiewende is a joint initiative of the Mercator Foundation and the European Climate Foundation.
Further publications by Agora Energiewende

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<th>Building sector Efficiency: A crucial Component of the Energy Transition</th>
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<th>The Future Cost of Electricity-Based Synthetic Fuels</th>
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