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International Optimization of Full Load Hours in the German Bight – Cross-Border Radials

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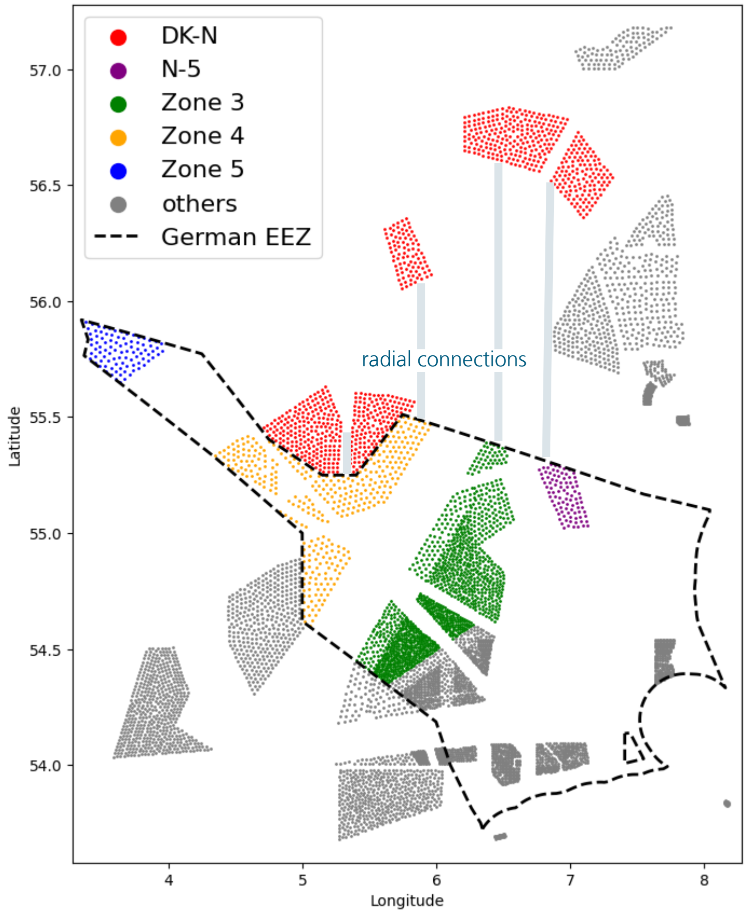
Executive Summary

International Optimization of Full Load Hours in the German Bight

Effects of the spatial reallocation to Danish and Swedish areas in the North Sea and Baltic Sea

- **Increase system-level efficiency of offshore wind** by reallocation of offshore wind farm capacity to Danish and Swedish areas in the North Sea and Baltic Sea
- **Reduced wake losses** through lower power density and improved spacing between offshore wind farms
- **Higher full load hours and energy yield** in German, Danish and Swedish areas
- **Moderate increases in installation and O&M costs** due to longer distances are **overcompensated by higher energy production**
- Additional areas achieve even higher full load hours and lower cost indices, **leading to a net improvement in system-level energy yield and cost efficiency** [€/MWh]



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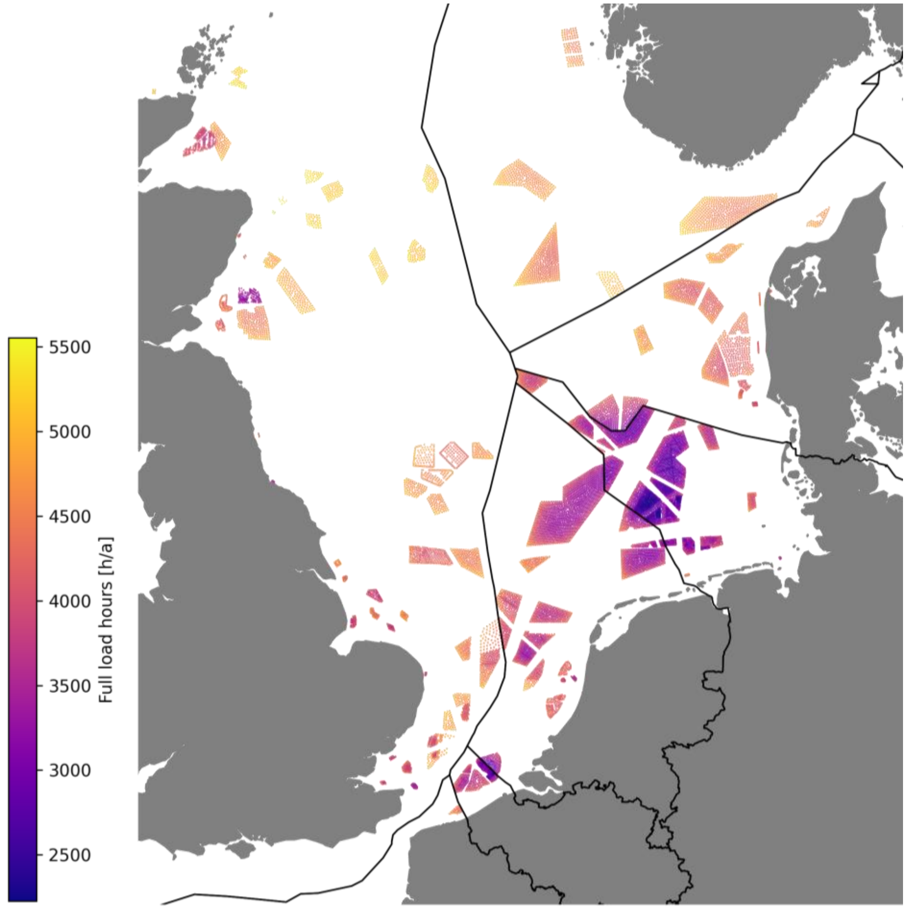
Objective

- **Increase system-level efficiency of offshore wind in the German Bight** through spatial optimization of offshore wind deployment
- Total installed capacity and grid connection to the German electricity grid remain unchanged
- The base scenario follows the continuation of the Site Development Plan (FEP 2025)
- Two additional scenarios evaluate **cross-border spatial reallocation** to Denmark and Sweden, while keeping total capacity in line with the BSH base case scenario



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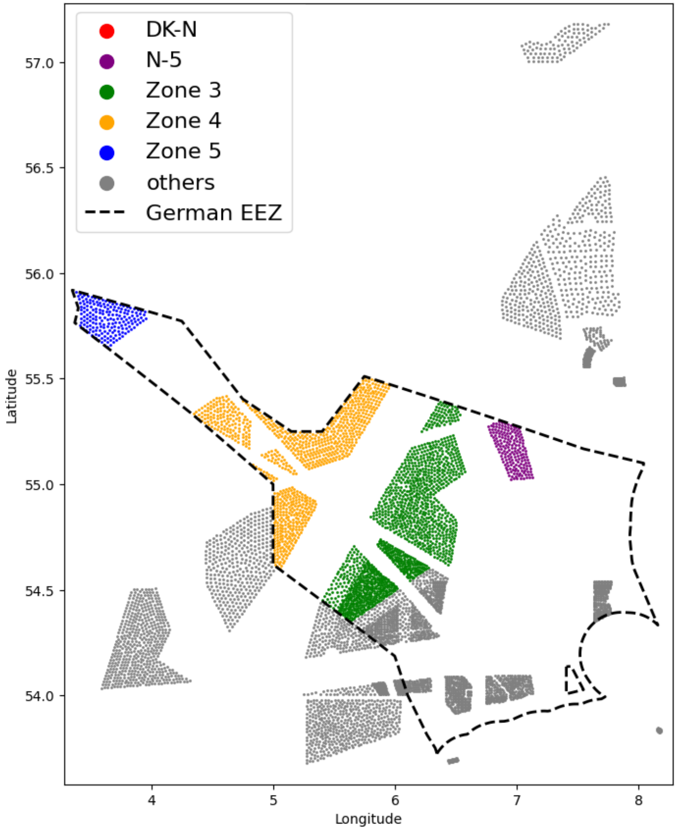
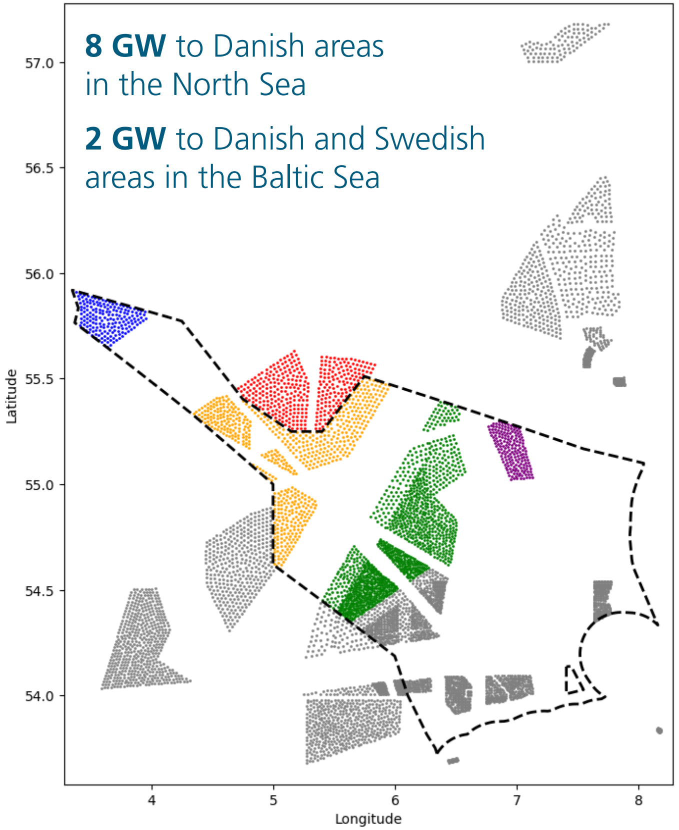
Scenario definition: increasing scale of cross-border spatial reallocation

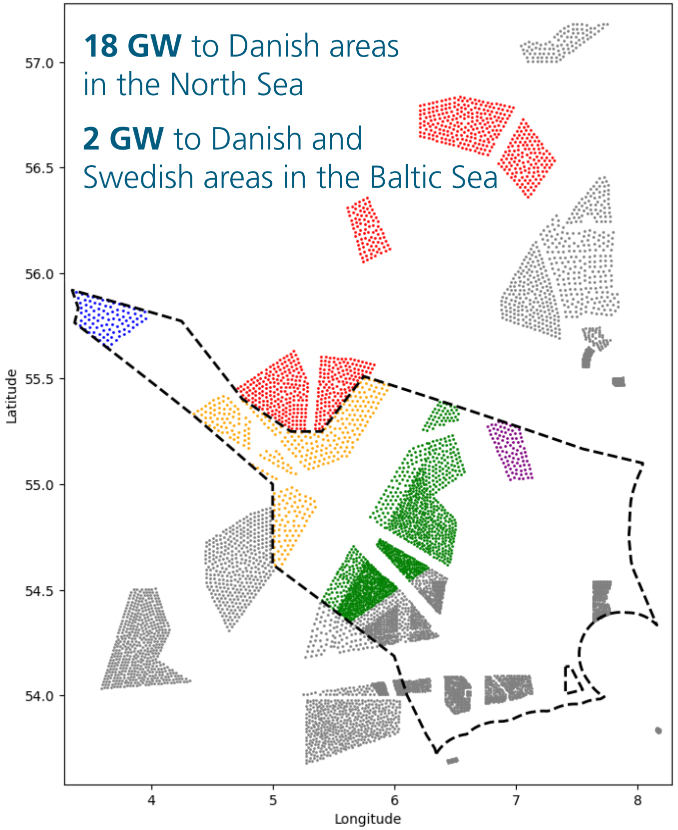
Base Scenario



Scenario 1



Scenario 2



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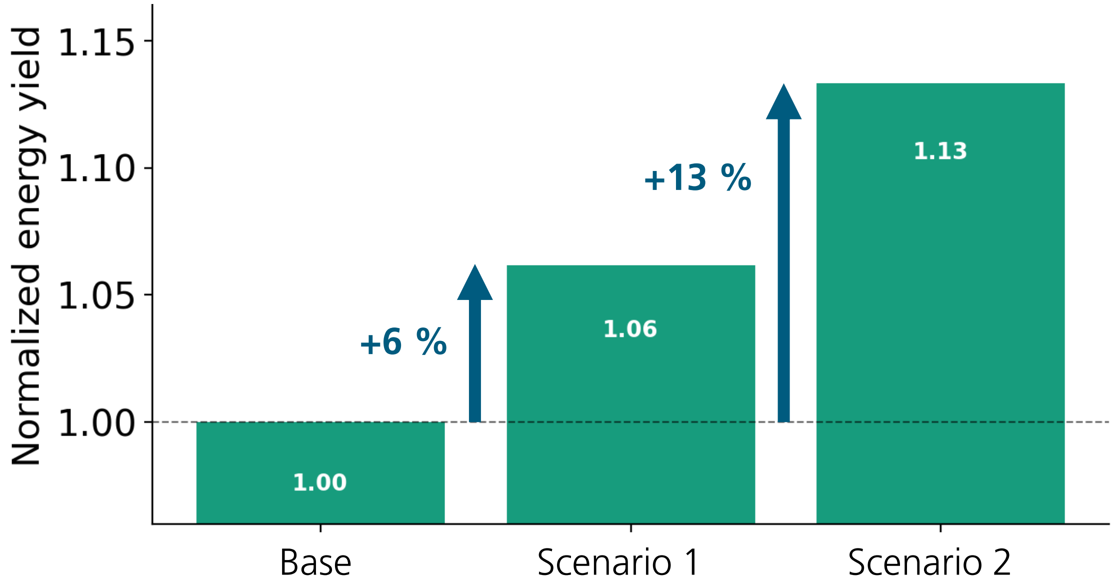
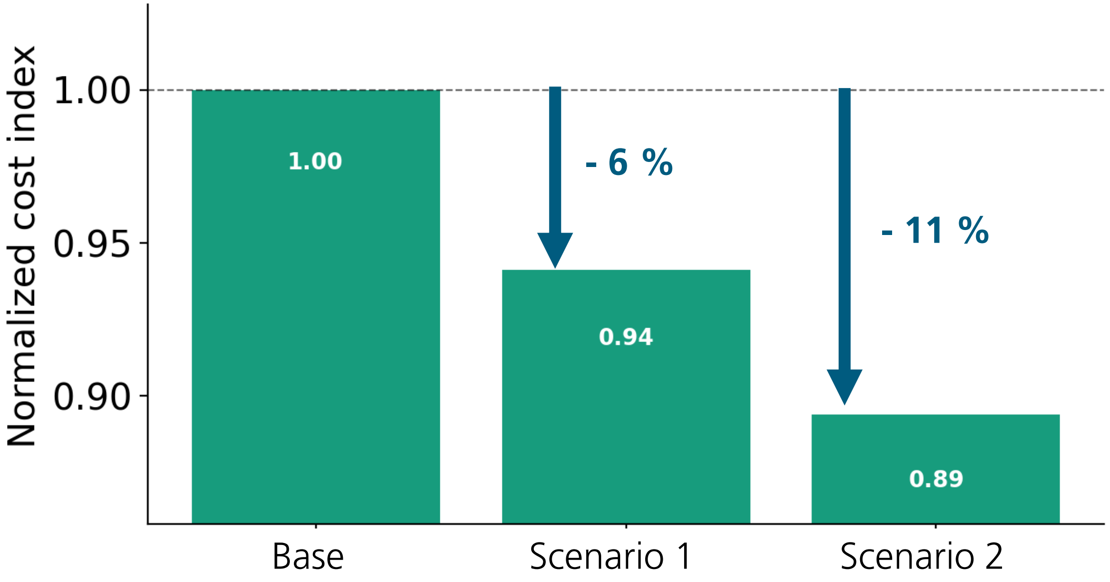
More energy at lower system cost through spatial optimization





- **Scenario 1 and Scenario 2 increase total energy yield**
- Higher energy yield outweighs higher installation and O&M costs, resulting in a lower cost index [€/MWh] in both scenarios
- Total installed capacity remains unchanged across all scenarios
- Including zones 3, 4, and 5, area N-5 and the capacities moved to the Danish and Swedish areas, as indicated on the previous page

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Approach / Methodology

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Scenario definition: power density as key control variable

In alignment with the FEP 2025 BSH scenario

Two scenarios evaluate **cross-border spatial allocation** to Denmark and Sweden, **maintaining the total installed capacity**

Base Scenario

- Capacities according to the FEP 2025 draft
- Average power density of **10.2 MW/km²** for all newly built offshore wind farms

Scenario 1 – Moderate Density Reduction

- Average power density reduced to **8.4 MW/km²** for newly built offshore wind farms
- Partial reduction of capacity at Doordewind I & II (4 GW → 2 GW)

Scenario 2 – Strong Density Reduction

- Average power density reduced to **6.6 MW/km²** for newly built offshore wind farms
- Further spatial reallocation of capacity

		Base Scenario		Scenario 1		Scenario 2	
Area	Zone	Capacity [GW]	Power Density [MW/km²]	Capacity [GW]	Power Density [MW/km²]	Capacity [GW]	Power Density [MW/km²]
N-5	2	4.0	10.1	4.0	10.1	2.0	5.1
N-9	3	7.7	10.3	7.7	10.3	7.7	10.3
N-10	3	2.5	13.7	2.5	13.7	2.5	13.7
N-11	3	3.5	9.3	3.5	9.3	3.5	9.3
N-12.1-3	3	5.0	10.1	5.0	10.1	5.0	10.1
N-12.4-6	3	4.0	9.3	2.0	4.6	2.0	4.6
N-13	3	5.5	9.9	3.5	6.3	3.5	6.3
N-14	4	6.0	10.4	4.0	6.9	2.0	3.5
N-16	4	10.0	9.1	6.0	5.5	4.0	3.6
N-17 + N-20	4	4.0	8.6	4.0	8.6	2.0	4.3
N-19	5	4.0	7.1	4.0	7.1	2.0	3.6
Total		56.2	**10.2**	46.2	**8.4**	36.2	**6.6**
Other German OWFs		18.9		18.9		18.9	
Total DE		75.1		65.1		55.1	
DK North Sea		0.0		8.0	5.2	18.0	5.2
DK + SE Baltic Sea		0.0		**2.0**	8.5	**2.0**	8.5
Total		75.1		75.1		75.1	
Doordewind I and II		4.0	7.3	2.0	3.6	2.0	3.6

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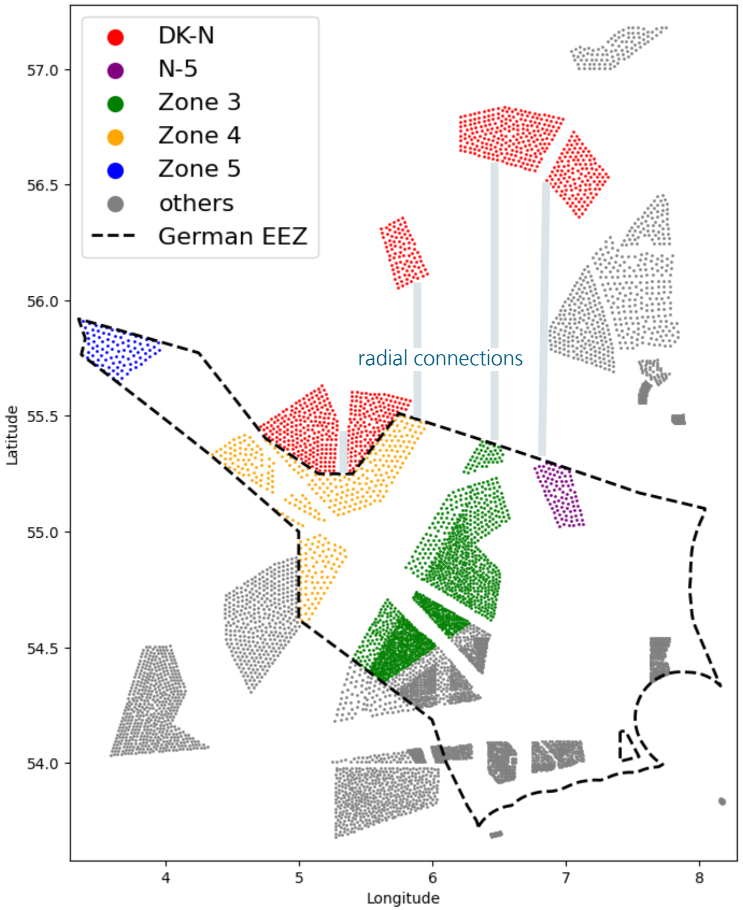
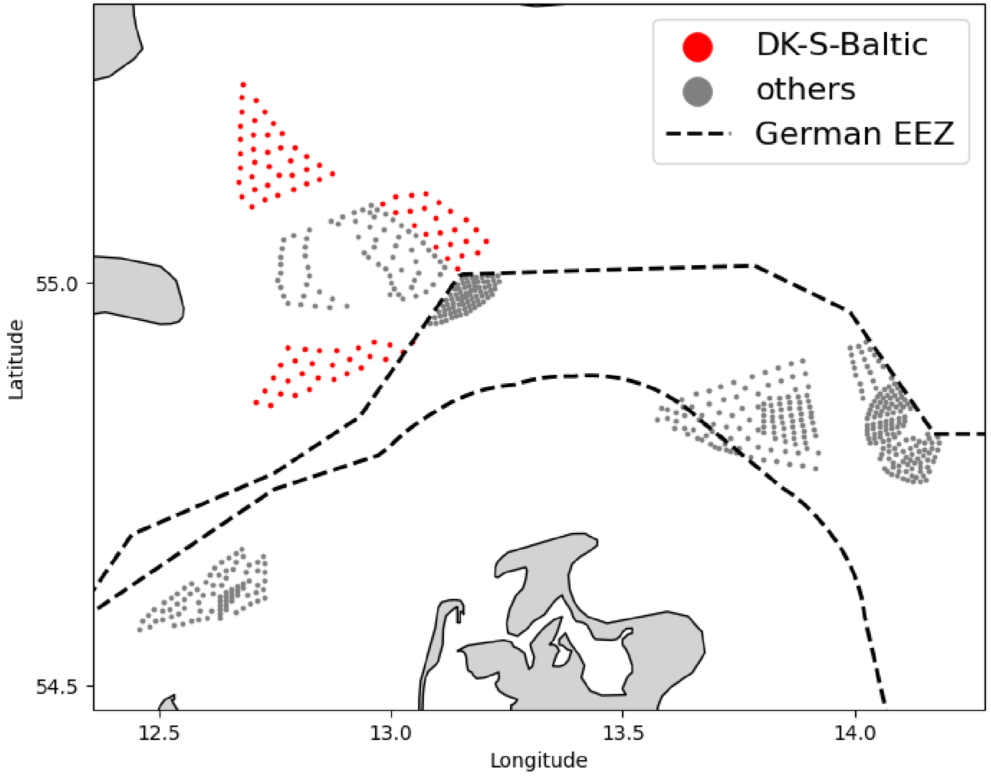
Spatial reallocation of offshore wind capacity (Scenarios 1 & 2)



Scenario 2 with 18 GW capacity (indicated in red) reallocated to the Danish North Sea



2 GW capacity (indicated in red) reallocated to the Danish and Swedish Baltic Sea in Scenario 1 and Scenario 2

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General assumptions

Time Horizon & System Scope

- Fully developed state in 2045
- Relevant offshore wind projects in neighbouring EEZs (DE, DK, NL) considered
- Weather year 2012

Technology & Costs

- 22 MW offshore wind turbines
- Cost assumptions based on established Fraunhofer IWES studies

Operations & Availability

- Identical O&M service concept across all areas (SOV + helicopter, seasonal reinforcement)

Scenario Consistency

- Same assumptions applied to all scenarios
- Results reflect relative differences, not absolute optimization

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CAPEX assumptions

CAPEX and installation for **offshore wind turbine generators** is calculated as the sum of three cost components:

- **Logistics costs** derived from OffshoreTIMES simulations
- **Soft costs** of **0.9 million € per MW**, corresponding to approximately **20 million €** for the **22 MW** turbines used in the new-build scenarios
- **Material costs** of **2.3 million € per MW**, corresponding to approximately **50 million €** for the **22 MW** reference turbine (including monopiles, transition pieces, inter-array cables, and scour protection)

CAPEX and installation for **offshore grid connection systems**:

- Based on **NEP 2023**, with adjustments by the TSOs
- Costs for offshore export cables **(6 million € per km**) and converter platforms (onshore and offshore combined) amounting to **1 billion € per GW**

Assumptions for failure rates, offshore processes, and logistics costs are based on: "Evaluation of various lifetime extension and repowering scenarios of offshore wind farms and offshore grid connection systems in the German Bight"

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Relative cost-efficiency metric for scenario comparison

- Evaluation of scenarios at area level based on:
  - Energy yield (full load hours)
  - Cost index [€/MWh]   not the same as a complete LCoE;
    for simplification, the cost index is defined as:

$$\text{Cost index} = \frac{\left(\text{construction cost}^{1} + \text{O\&M cost}_{\text{OWF}}{}^{2} + \text{O\&M cost}_{\text{offshore grid connection systems}}\right)}{\text{energy yield}^{3}}$$

- For all relevant areas in the three scenarios, energy yield and operating costs are evaluated over a 35-year lifetime
- The cost index is normalized to the average cost index of the base scenario
- Relevant areas: Zone 3, 4 and 5, area N-5 as well as the new areas in the Danish North and Baltic Sea

1 sum of installation cost and CAPEX as defined on the previous slide
2 computed with Fraunhofer IWES *OffshoreTIMES*
3 computed with the Weather Research & Forecasting (WRF) model

Results

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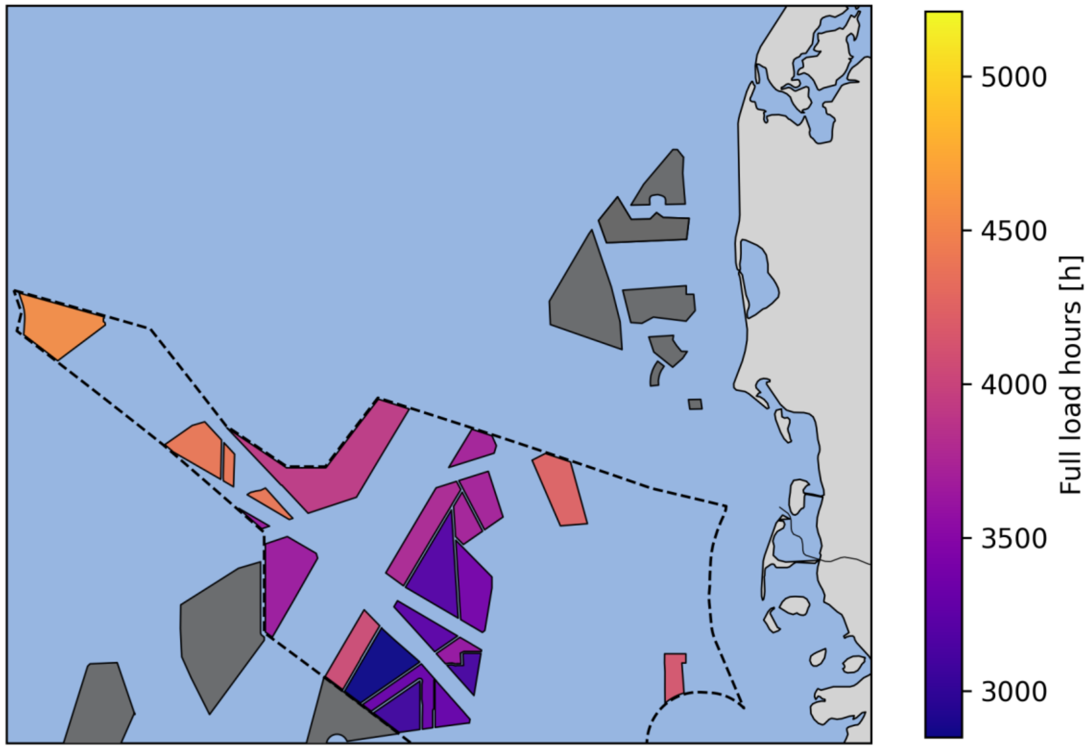
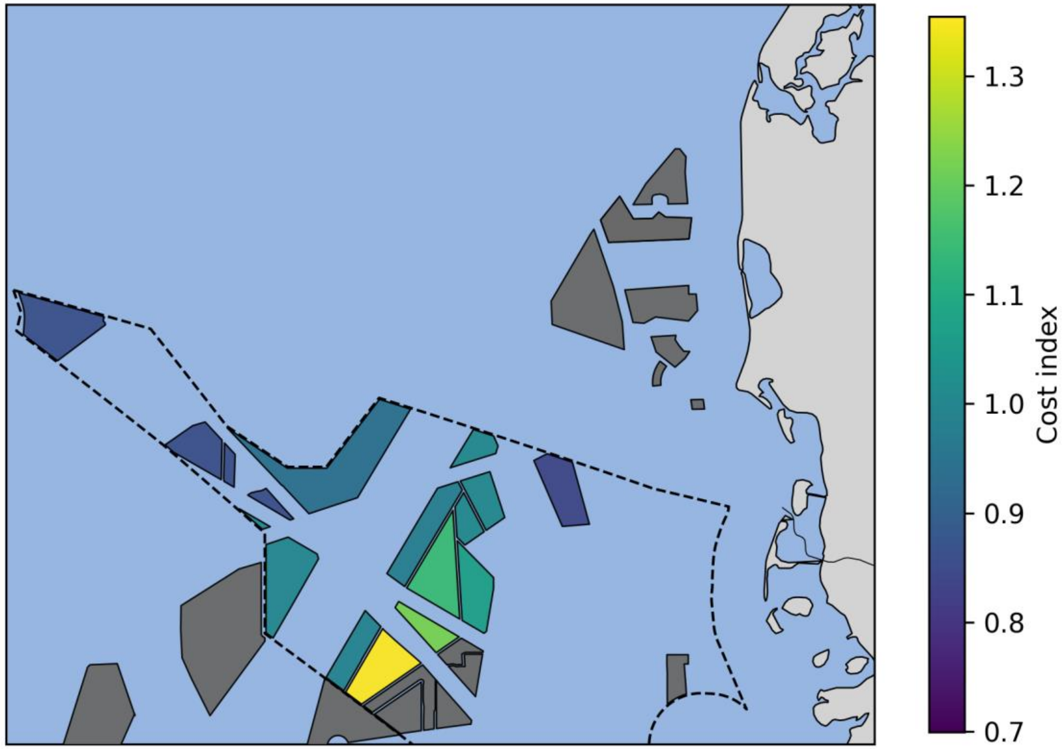
Base Scenario: Full load hours (excl. availability) & cost index per area

Full load hours



Cost index



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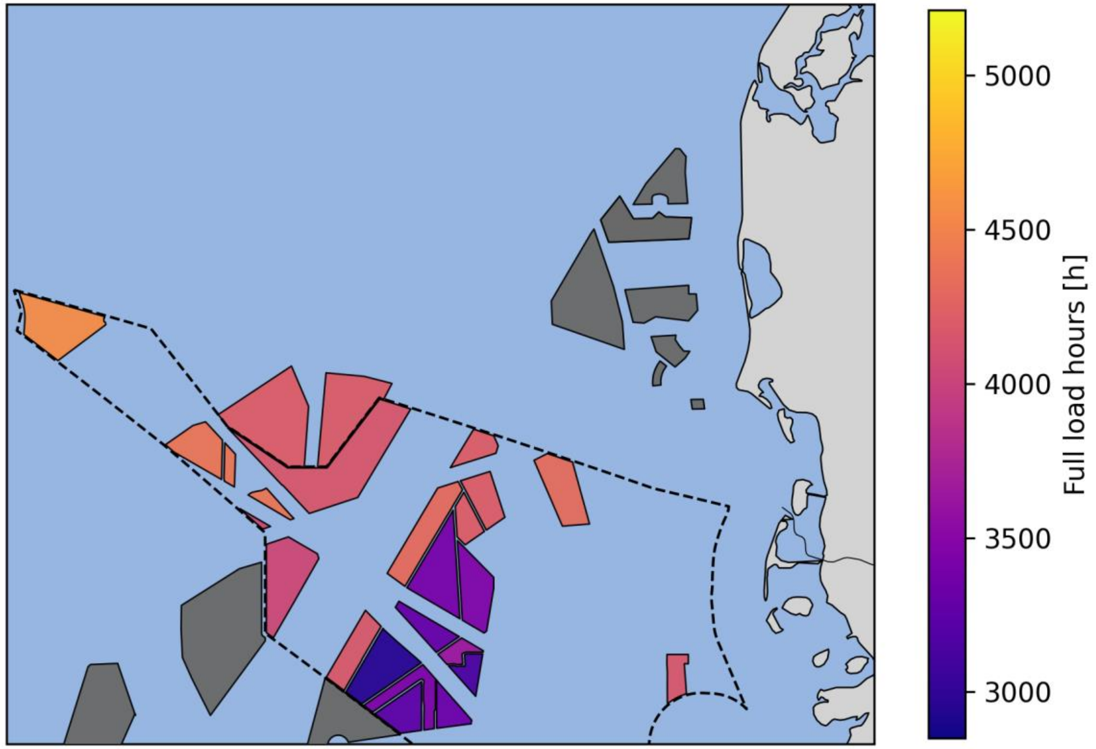
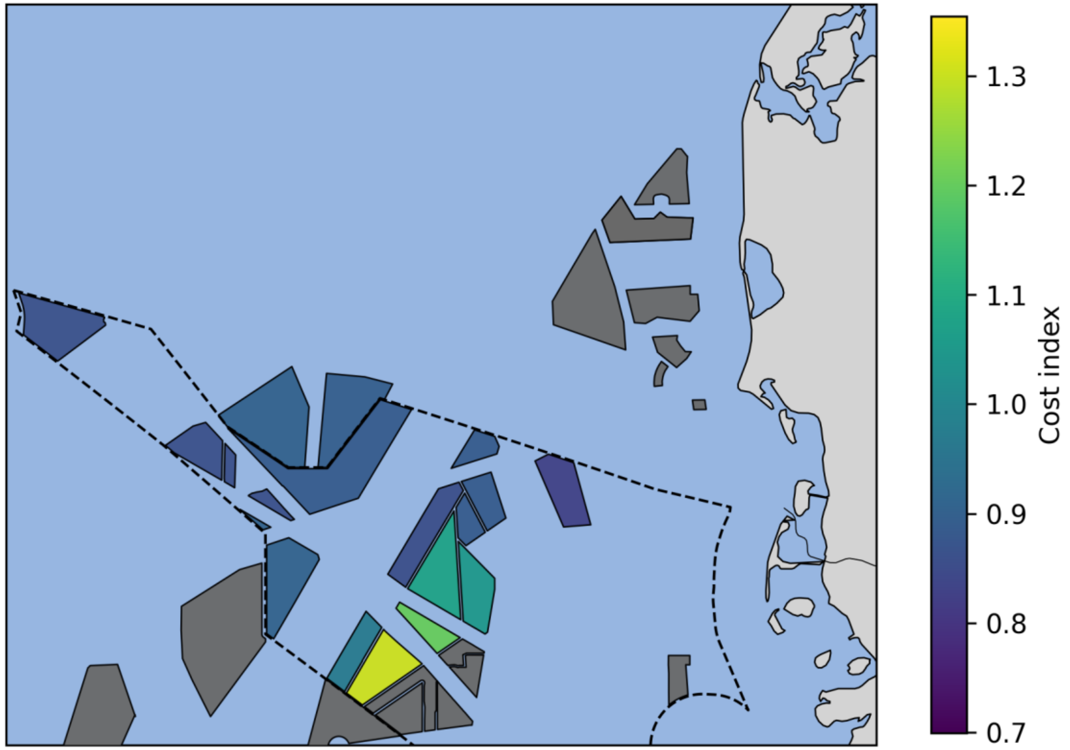
International Optimization of Full Load Hours in the German Bight

Scenario 1: Full load hours (excl. availability) & cost index per area

Full load hours



Cost index



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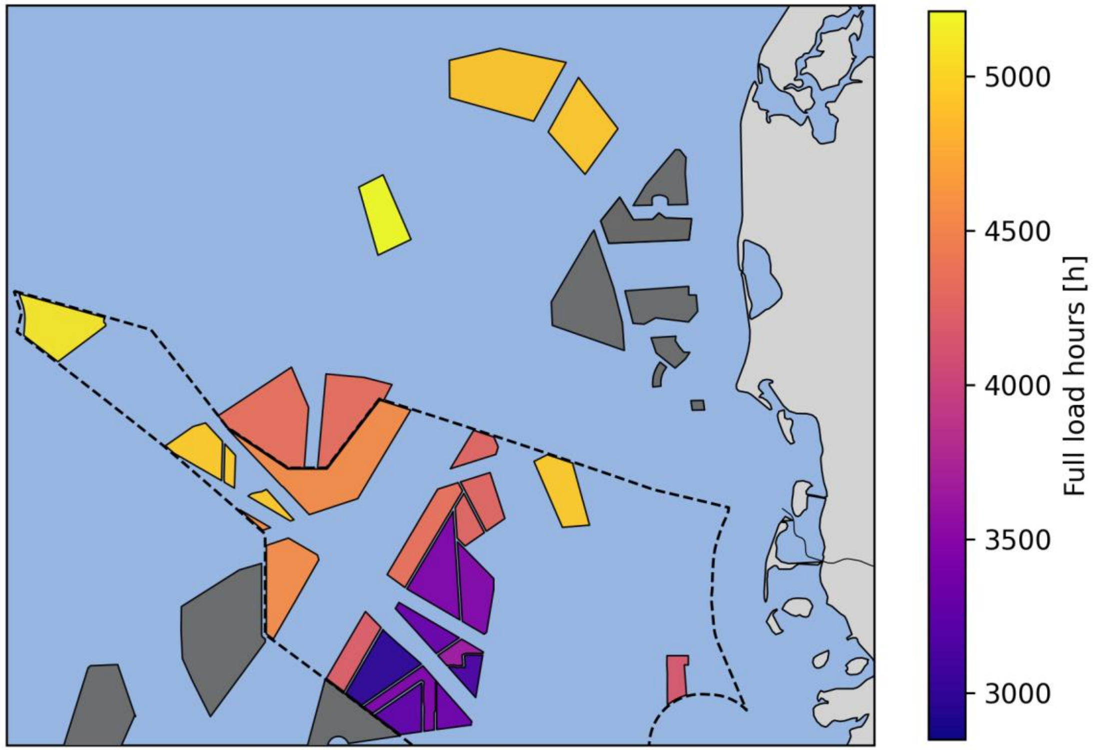
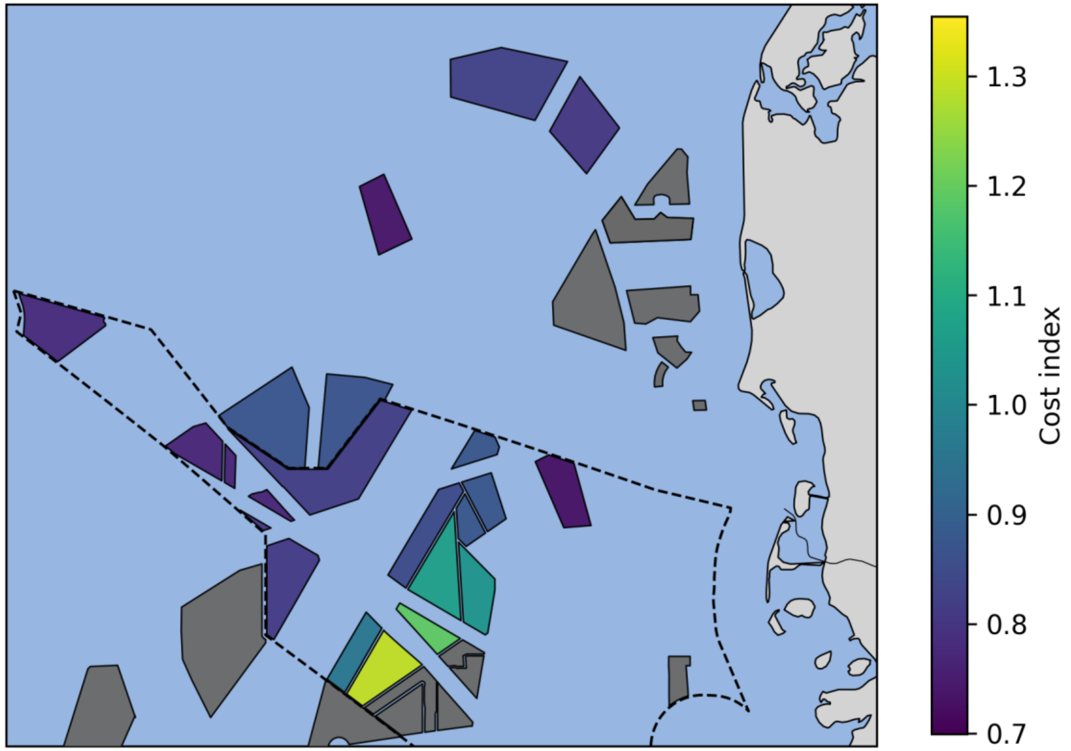
International Optimization of Full Load Hours in the German Bight

Scenario 2: Full load hours (excl. availability) & cost index per area

Full load hours



Cost index



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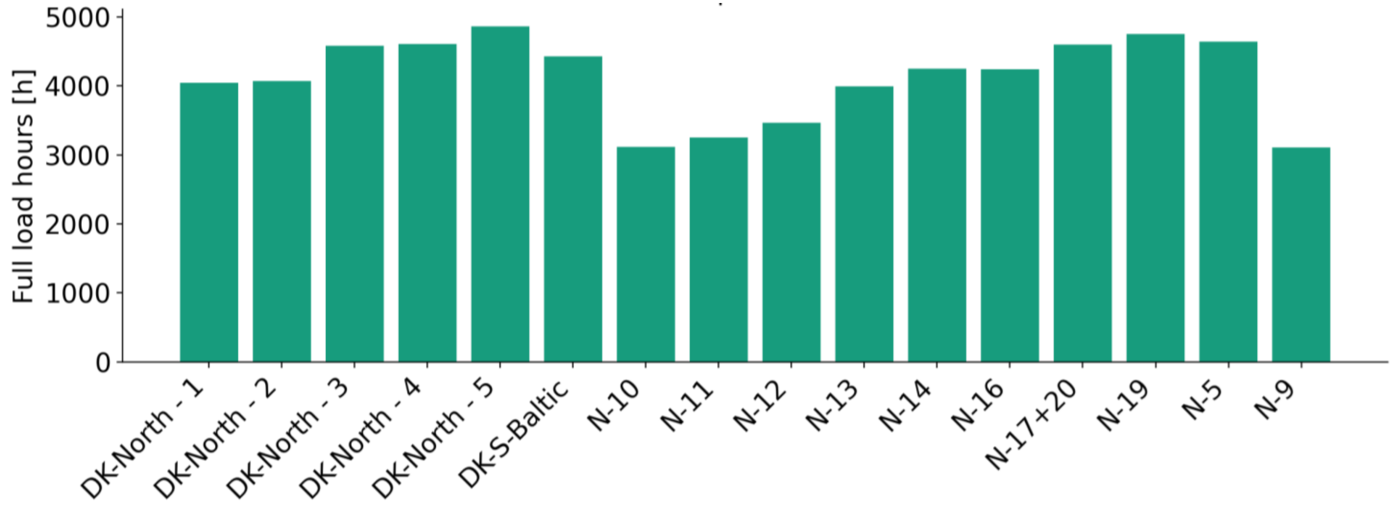
Energy yield increases due to reduced wake losses and lower power density

Scenario 2



Total capacity of the relevant areas listed above is 56 GW.

Scenario	Energy Yield	Change vs. Base [%]
Base	196 TWh	0.0
Scenario 1	208 TWh	6.2
Scenario 2	222 TWh	13.3

- Reducing power density and wake interactions leads to higher full load hours
- Significant differences between areas reflect local wake exposure
- Zones 4, 5 and N-5 are less affected by wakes and show higher yields
- Danish and Swedish areas also achieve high full load hours
- Aggregated effect: total energy yield increases by 6% (S1) and 13% (S2)

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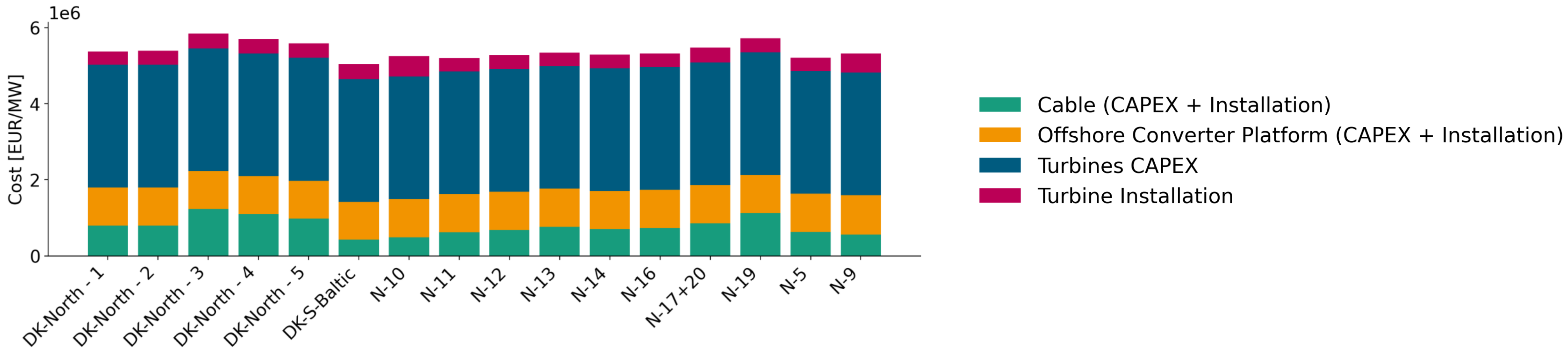
Installation costs: moderate differences driven by cable length

Scenario 2



- Differences in distance to shore directly drive export cable costs
- The Baltic Sea area shows the lowest installation cost due to short cable length
- Scenario 1 shows a slightly lower total installation cost than the base scenario
- Scenario 2 shows a higher total installation cost due to longer export cables to Danish areas

Scenario	Total Installation Cost	Change vs. Base [%]
Base	299.18 billion €	0.0
Scenario 1	298.78 billion €	- 0.13
Scenario 2	302.55 billion €	1.13

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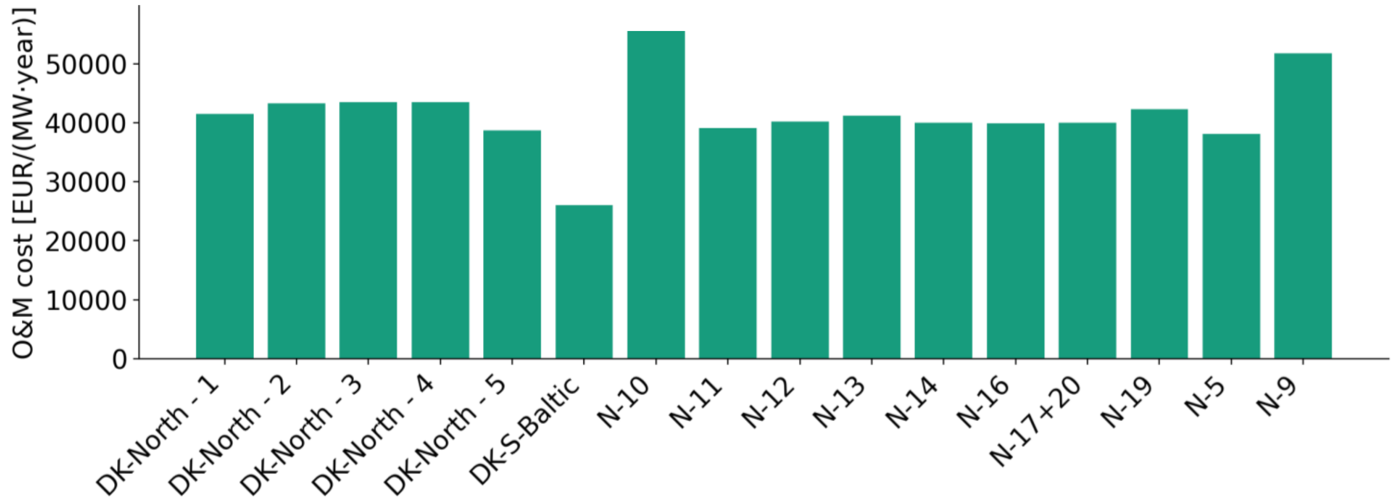
O&M costs: modest increase with distance to shore

Scenario 2



- O&M costs increase with distance to shore for OWFs in the Danish North Sea
- The new Baltic Sea wind farms show the lowest O&M cost due to a CTV-based service concept
- In Scenario 1, total O&M costs remain almost unchanged compared to the base scenario
- In Scenario 2, total O&M costs increase by 2.5%

Scenario	O&M per (MW·year)	Change vs. Base [%]
Base	41,693 €	0.0
Scenario 1	41,791 €	0.24
Scenario 2	42,717 €	2.46

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Summary of the results

	Base Scenario				Scenario 1				Scenario 2			
	Capacity [GW]	Energy Yield [TWh]	FLH [h]	Cost Index	Capacity [GW]	Energy Yield [TWh]	FLH [h]	Cost Index	Capacity [GW]	Energy Yield [TWh]	FLH [h]	Cost Index
N-5	4	16.0	4,000	0.840	4	16.2	4,050	0.828	2	9.3	4,640	0.728
Zone 3	28	89.2	3,190	1.106	24	79.8	3,330	1.063	24	80.6	3,360	1.053
Zone 4	20	73.8	3,690	0.938	14	54.9	3,920	0.885	8	34.7	4,330	0.802
Zone 5	4	17.0	4,260	0.861	4	17.0	4,250	0.863	2	9.5	4,750	0.777
Total DE	56	196.1	3,500	**1.000**	46	167.9	3,650	**0.962**	36	134.1	3,730	**0.946**
DK-S-Baltic	-	-	-	-	2	8.9	4,430	0.699	2	8.9	4,430	0.699
DK-N	-	-	-	-	8	31.4	3,930	0.900	18	79.3	4,390	0.828
Total	56	196.1	3,500	**1.000**	56	208.2	3,720	**0.941**	56	222.3	3,970	**0.894**

- Reallocating capacity to Denmark and Sweden increases full load hours in German wind farms and reduces their cost index
- Additional Danish and Swedish areas achieve even higher full load hours and lower cost indices, leading to a net improvement in system-level energy yield and cost efficiency [€/MWh]

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