Improving Cost Efficiency in Offshore Wind Through Optimal Overplanting

frontier economics

Study for the Bundesverband der Windenergie Offshore (**BWO**) and the Bundesverband der Energie- und Wasserwirtschaft (**BDEW**)

12 March 2026 **English convenience translation**

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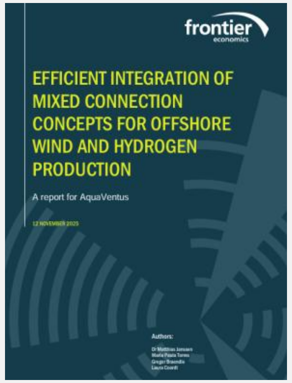

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A report for AquaVentus

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Studie für das Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg

16. SEPTEMBER 2024

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Client: Baden-Württemberg MINISTERIUM FÜR UMWELT, KLIMA UND ENERGIEWIRTSCHAFT

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INSTRUMENTE FÜR EINE SYSTEMDIENLICHE INTEGRATION VON BATTERIESPEICHERN

Kurzpapier für TenneT TSO GmbH

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Executive Summary

Objective and Approach

- Background: Overplanting of offshore wind farms (OWFs) – i.e. lower grid grid connectionnection capacity relative to installed wind capacity — is being discussed as a tool for efficiency. It increases the utilisation of the grid connection and can reduce system costs but leads to curtailment during periods of peak generation.
- Objective: **Analysis of the economically optimal overplanting** of offshore wind farms relative to grid connection systems (grid connection).
- Approach: **modelling the combination of OWFs and grid connection capacity that minimises the economic costs (investment and capital costs minus electricity revenues)** for four offshore areas and two expansion scenarios.

Results

Economically optimal overplanting lies in the range between 5 to 10%, depending on the area and . The associated curtailment amounts to approximately 3 to 4%.

The optimal level of overplanting **depends on the generation profile, the grid connection length, and the ratio between OWF and grid connection costs**. Given this, future market developments could also lead to a higher or lower optimal overplanting.

The commercially (firm-level) optimal **level of overplanting** is around **2.5 to 5%.** From the perspective of an OWF, there are therefore already incentives for overplanting, albeit to a lesser extent than what is economically optimal.

Conclusions

Overplanting is systemically beneficial to a certain extent and can enhance the efficiency of offshore expansion. A blanket requirement or one set to high, by contrast, would generate additional economic costs.

The optimal level of overplanting depends on the location and costs. If overplanting is made mandatory, it should be based on site characteristics (generation profile, distance, grid connection costs) and relative cost ratios.

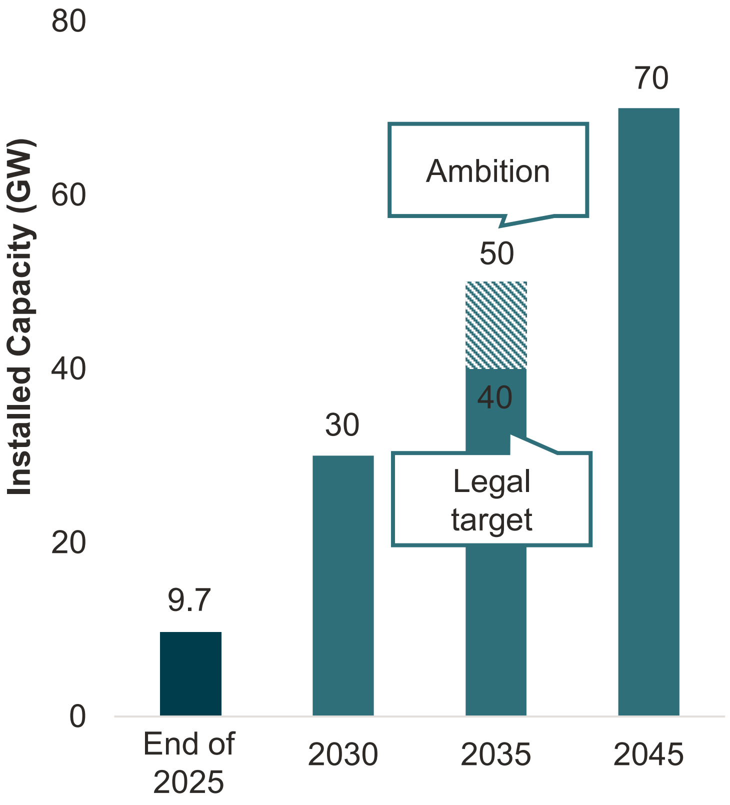
Economically optimal overplanting **detracts from the commercial prospects of the OWF operator**, which could necessitate a compensation mechanism.

Agenda

Agenda

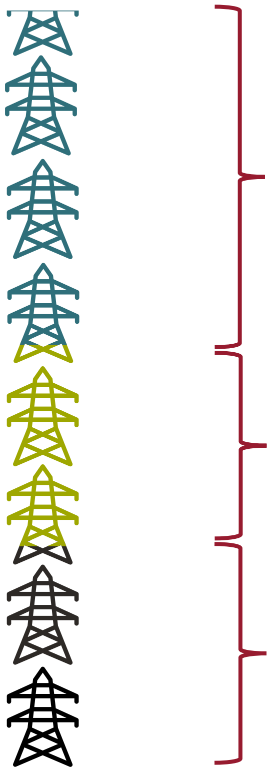
Germany's offshore wind expansion is currently caught between ambition and reality

Ambitious targets



… but high grid costs

362 - 386bn €



153 - 171bn € for an offshore grid*

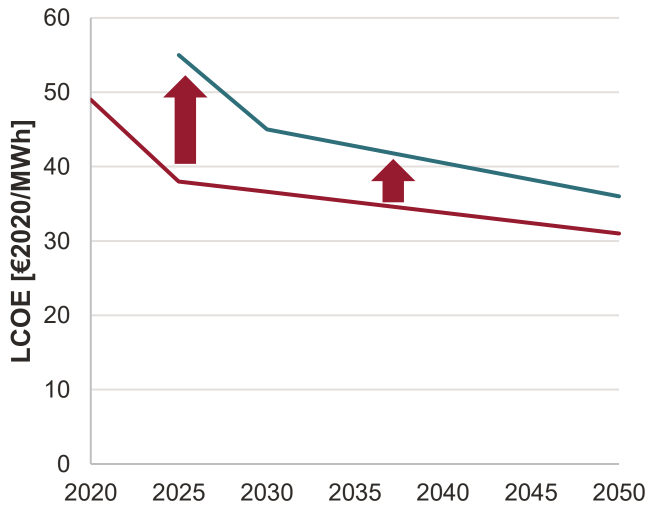
95 - 101bn € for an additional onshore grid

114bn € for an “initial grid”

Grid Development Plan for 2037 / 2045

… and a challenging environment for offshore wind farms (OWF)

LCOE projections for offshore wind in Denmark, **2022** vs **2025**



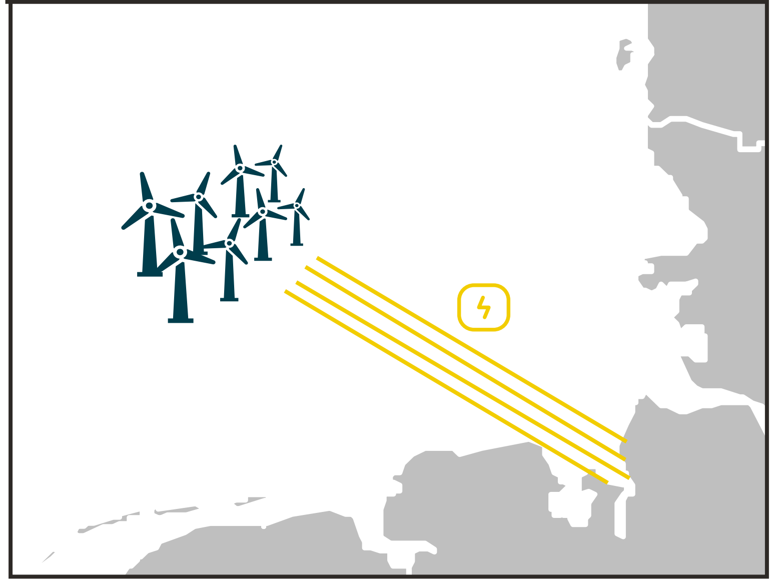
LCOE for grid-connected offshore wind farms (AC), based on the Danish Energy Agency's Technology Catalogue. 3.5% WACC (real)

Sources: WindGuard - Status des Offshore-Windenergieausbaus Jahr 2025, NEP 2025 (1.Entwurf), Danish Energy Agency (2025) Technology Brief,

The responsible planning authority (BSH) therefore proposes limited grid connections , i.e. “overplanting” in connection with “curtailment” during peak wind hours

Current Expansion

Wind farm capacity = Grid connection capacity



BSH’s proposals in FEP 2025 to increase grid utilisation

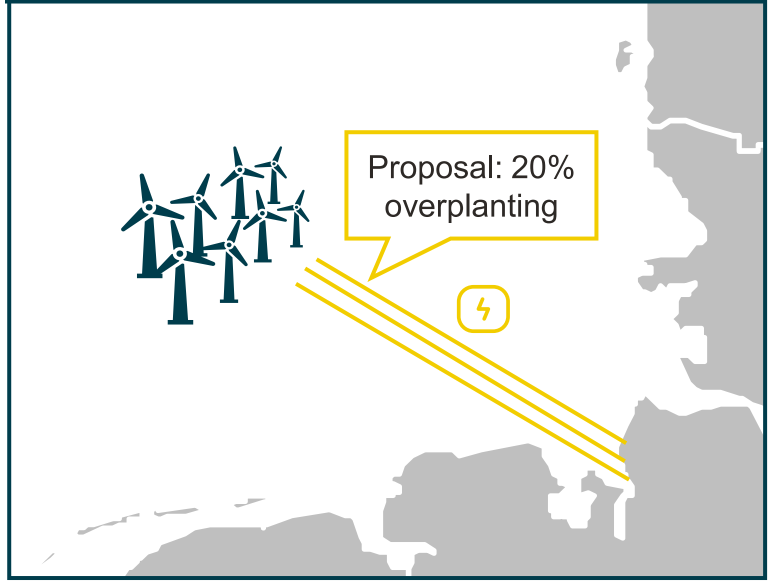
Focus on Zones 4 and 5:

- **Reduce grid connection capacity relative to wind farm capacity (“overplanting” of 20%)**
- Redesign of the sites with lower power density to reduce wake effects
- Increase in the transmission capacity of grid connection from the current 2 GW to 2.2 GW

➔ **Achieve a reduction of five grid connection systems compared to the Network Development Plan (NDP) 2037/2045.**

BSH proposal: overplanting

Wind farm capacity > Grid connection capacity



BWO and BDEW commissioned Frontier Economics to contribute to the ongoing discussion by analysing the economic effects of overplanting

Objective

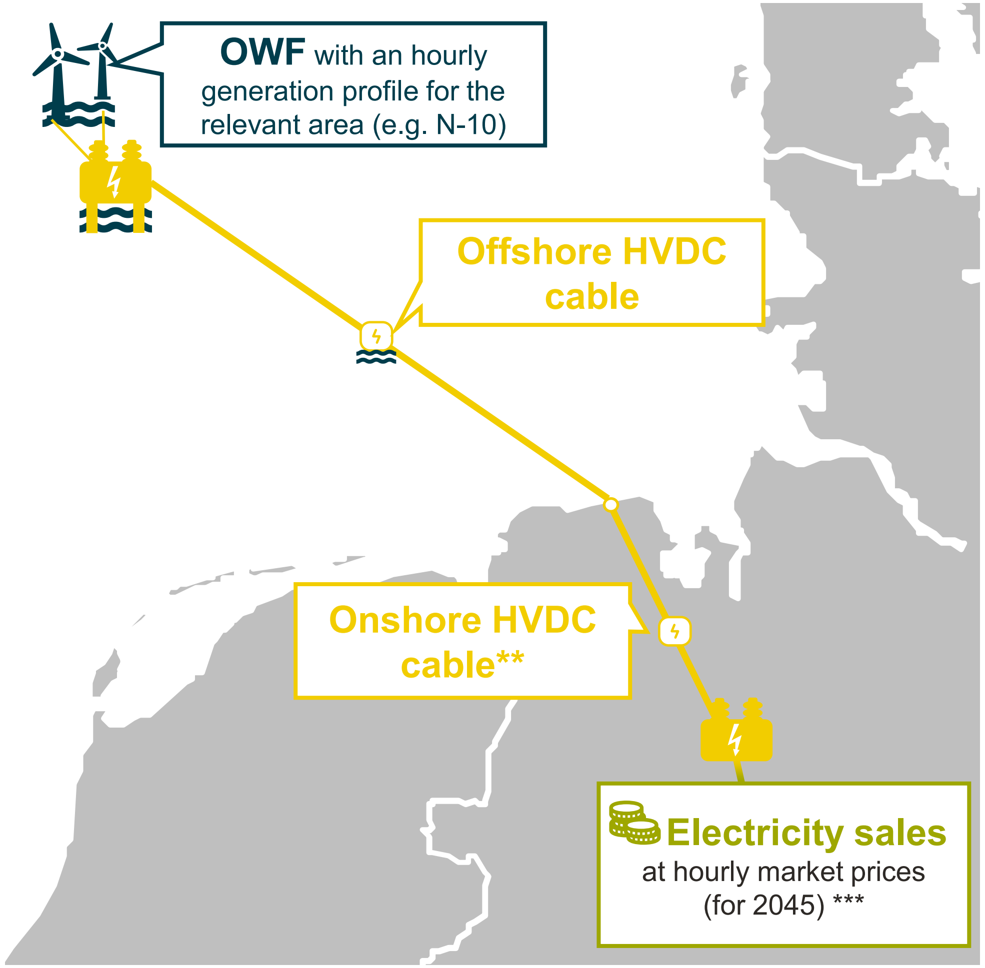
- **Quantitative analysis** of **optimal overplanting levels** from an economic and offshore wind farm perspective.

Drivers

- **Sensitivity analysis** to test the robustness of the results and identify the **factors** that **influence optimal overplanting**.

Agenda

Model-based approach: we minimise infrastructure costs while considering the value of the electricity produced



OWF with an hourly generation profile for the relevant area (e.g. N-10)

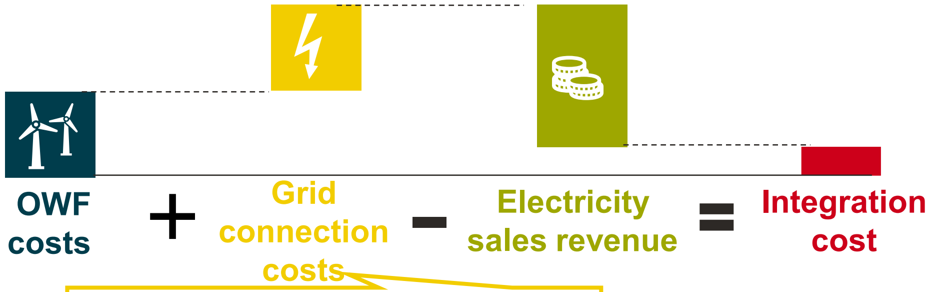
Offshore HVDC cable

Onshore HVDC cable**

Electricity sales at hourly market prices (for 2045) ***

	Economic Optimum	Firm-level Optimum OWF Perspective
OWF Capacity	Optimised*	Optimised*
Grid connection Capacity (up to grid connection point)	Optimised*	Exogenously specified
Min. electricity volume	Exogenously specified	No constraint

The model optimises infrastructure investments to minimise integration costs



OWF costs + **Grid connection costs** − **Electricity sales revenue** = **Integration cost**

Excluded from the OWF perspective

"Integration cost" = total costs less electricity sales revenue:
Remaining economic costs of integrating offshore wind. The ratio of OWF capacity to grid connection capacity that minimises integration cost determines the **optimal level of overplanting**.

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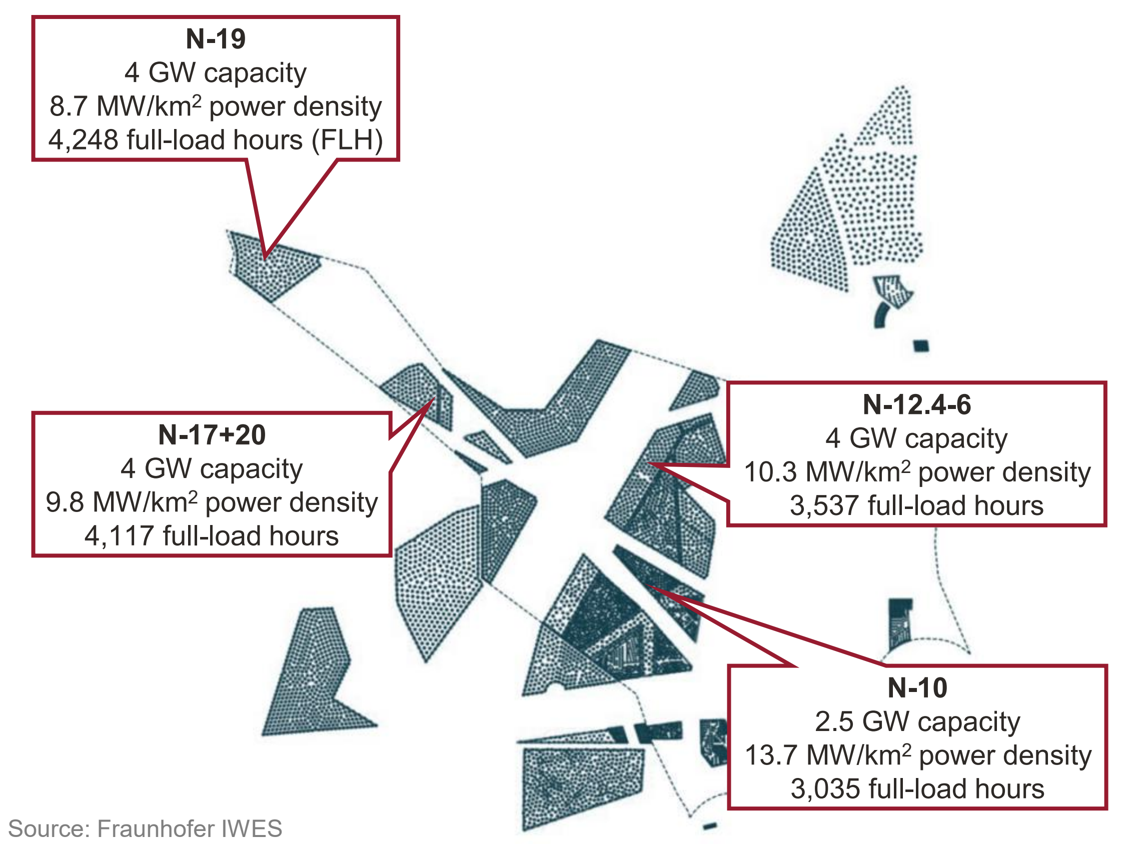
*To enable the most accurate optimisation possible, we assume that grid connection and OWF capacities can vary continuously (the optimum abstracts from real-world standardisation, such as a 2 GW grid connection system or a 22 MW wind turbine).

** As the analysis considers entire areas, we assume the average distance to all grid connection points within a given area.

*** Prices at the grid connection point. The analysis does not consider the AC grid:(1) AC grid costs are not included in the modelling; i.e. grid costs include grid connection up to injection into the AC grid.(2) Curtailment due to (local) AC grid congestion, and its effect on the optimal level of overplanting, is not considered.

We are analysing four reference areas for the currently planned expansion ("baseline scenario") and an optimised scenario with lower power density

Base scenario
Expansion in line with the current site development plan,
70 GW in Germany



N-19
4 GW capacity
8.7 MW/km² power density
4,248 full-load hours (FLH)

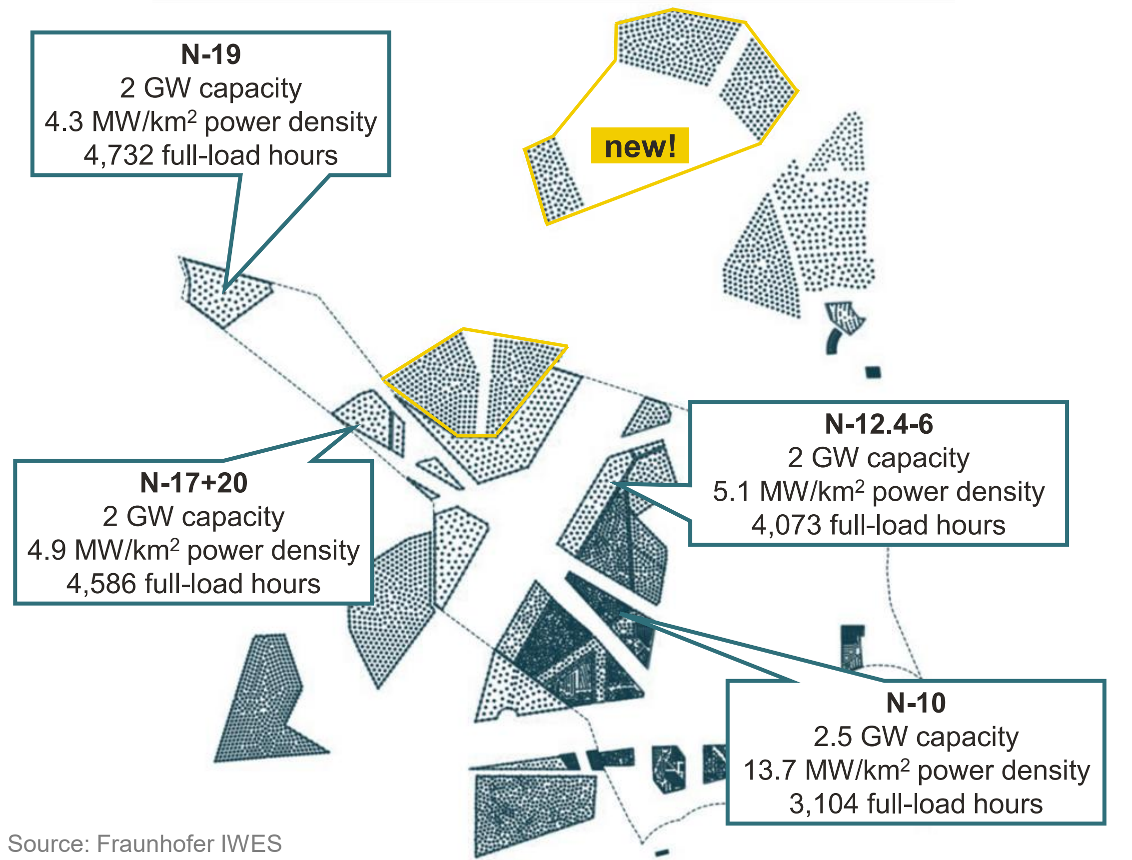
N-17+20
4 GW capacity
9.8 MW/km² power density
4,117 full-load hours

N-12.4-6
4 GW capacity
10.3 MW/km² power density
3,537 full-load hours

N-10
2.5 GW capacity
13.7 MW/km² power density
3,035 full-load hours

Source: Fraunhofer IWES

"Optimised scenario"
Reduced power density, 50 GW in Germany,
relocation of 20 GW to Denmark and Sweden



N-19
2 GW capacity
4.3 MW/km² power density
4,732 full-load hours

N-17+20
2 GW capacity
4.9 MW/km² power density
4,586 full-load hours

N-12.4-6
2 GW capacity
5.1 MW/km² power density
4,073 full-load hours

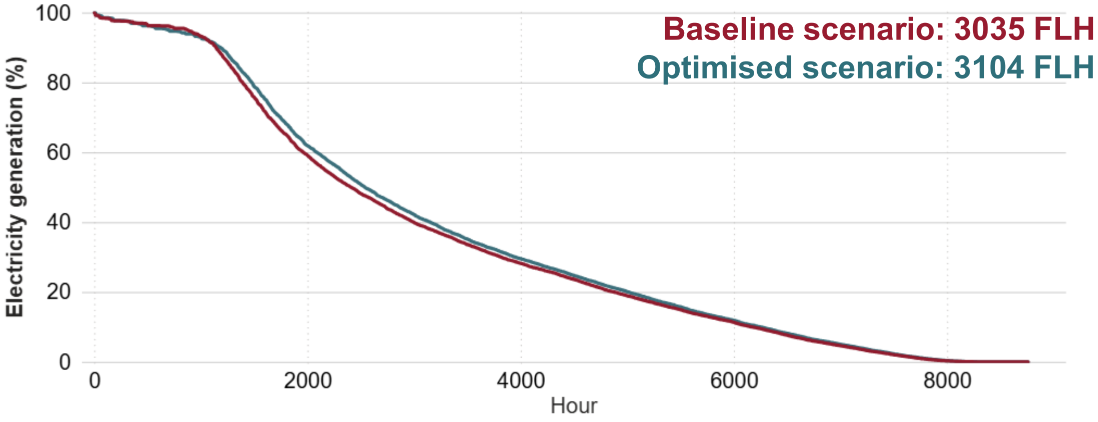
N-10
2.5 GW capacity
13.7 MW/km² power density
3,104 full-load hours

Source: Fraunhofer IWES

The scenarios and the associated wind generation profiles are based on a preliminary study by Fraunhofer IWES (2026)

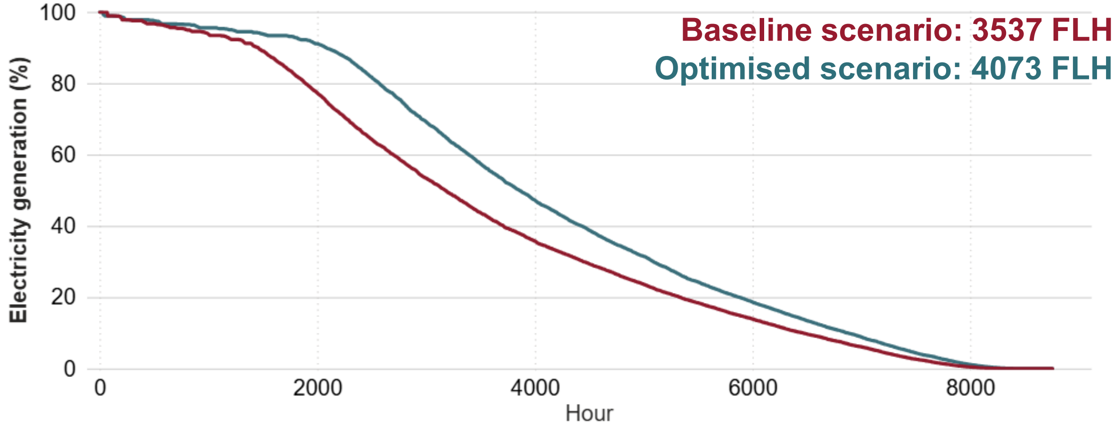
Assumptions from the Fraunhofer IWES preliminary study: optimised expansion changes generation profiles and full-load hours

N-10



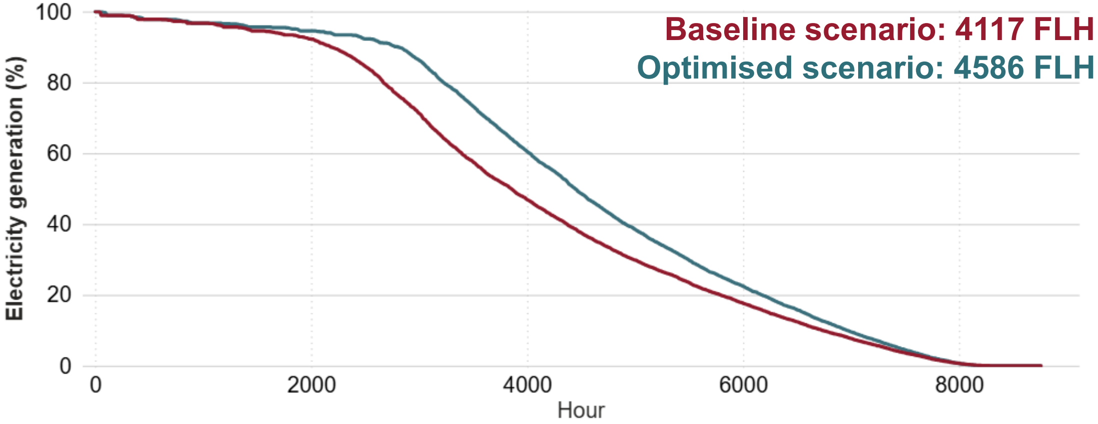
Baseline scenario: 3035 FLH
Optimised scenario: 3104 FLH

N-12



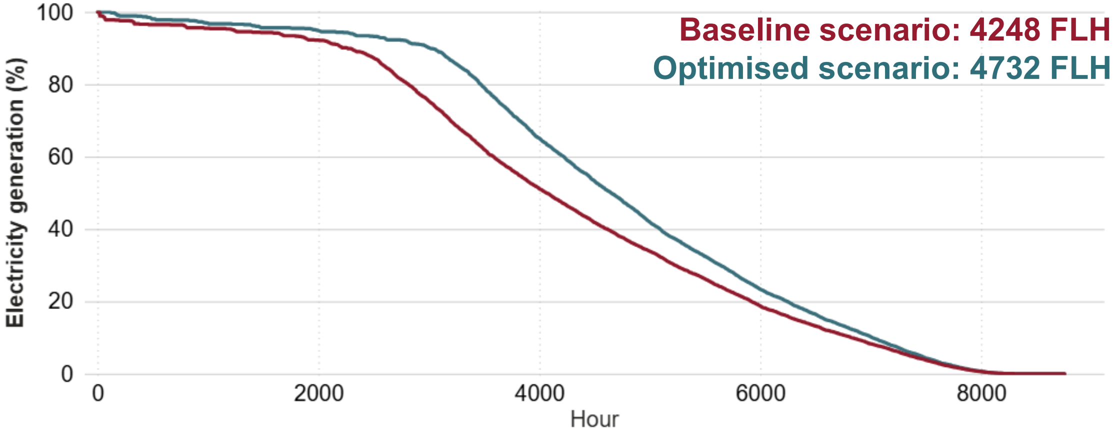
Baseline scenario: 3537 FLH
Optimised scenario: 4073 FLH

N-17+20



Baseline scenario: 4117 FLH
Optimised scenario: 4586 FLH

N-19



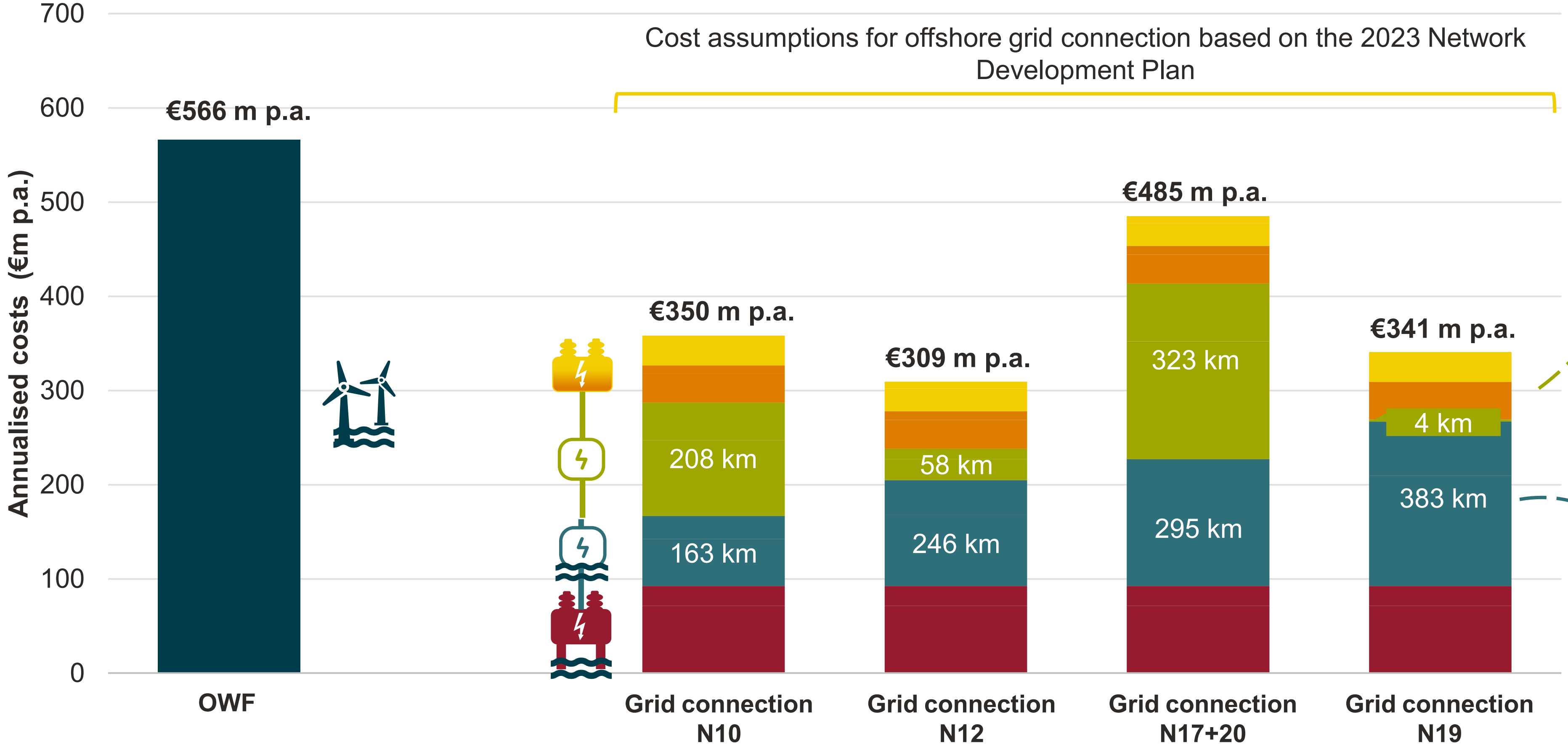
Baseline scenario: 4248 FLH
Optimised scenario: 4732 FLH

Source: Frontier Economics based on Fraunhofer IWES

*The generation profiles reflect full-load hours after accounting for the availability of OWFs. Availability is based on Monte Carlo simulations by Fraunhofer IWES. We use a single time series (one one-year simulation run), with the average annual availability of the wind farms, including the grid connection stations, amounting to 93–94% depending on the area and scenario.

Overview of cost assumptions: the level of grid connection costs strongly depends on the distance to the grid connection point

Annualised costs* for an offshore system without overplanting (2 GW OWF + 2 GW grid connection)



Length of the onshore HVDC cable based on the average distance of all grid connection points of an area in the NDP from the coast. Planning for the cable is part of TSO optimisation and could therefore still change accordingly.

Length of the offshore HVDC cable based on the average distance of the area in the NDP from the coast.

*Costs include CAPEX, OPEX and cost of capital.

Agenda

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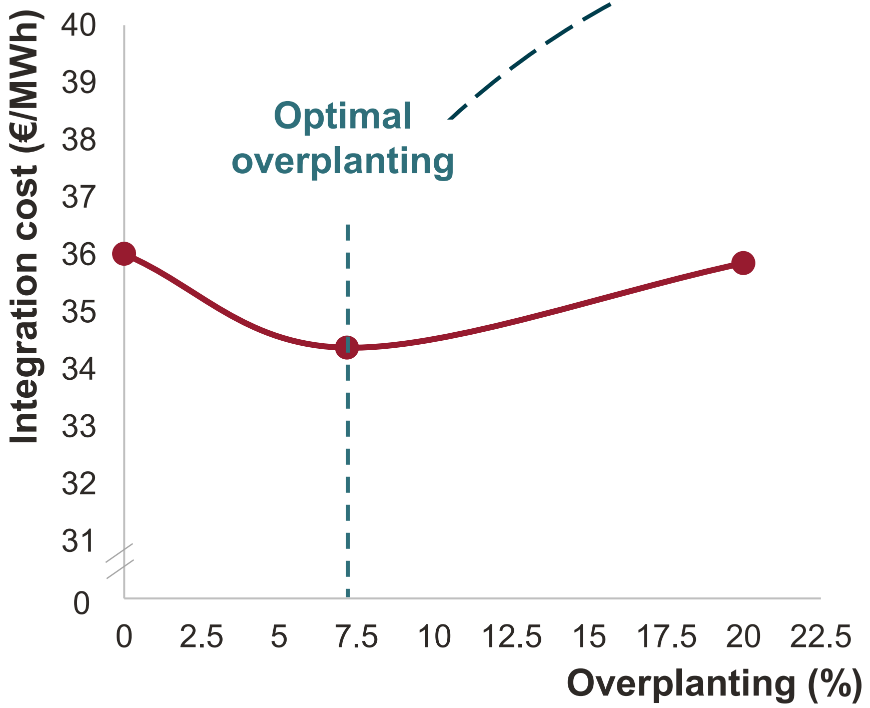
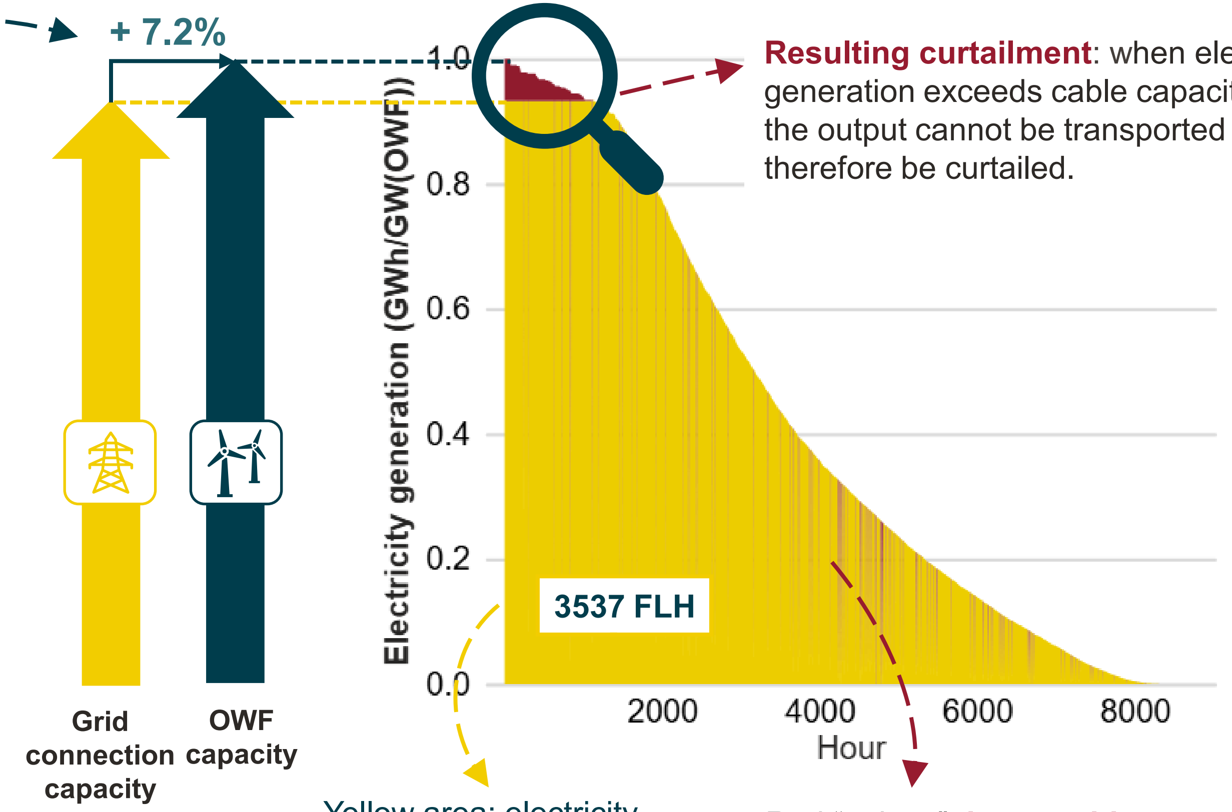
Example results N-12 in the baseline scenario: the model optimum shows that a certain degree of overplanting is efficient from an economic perspective

Modelling the economic optimum



…results in an optimal economic level of overplanting of 7.2%



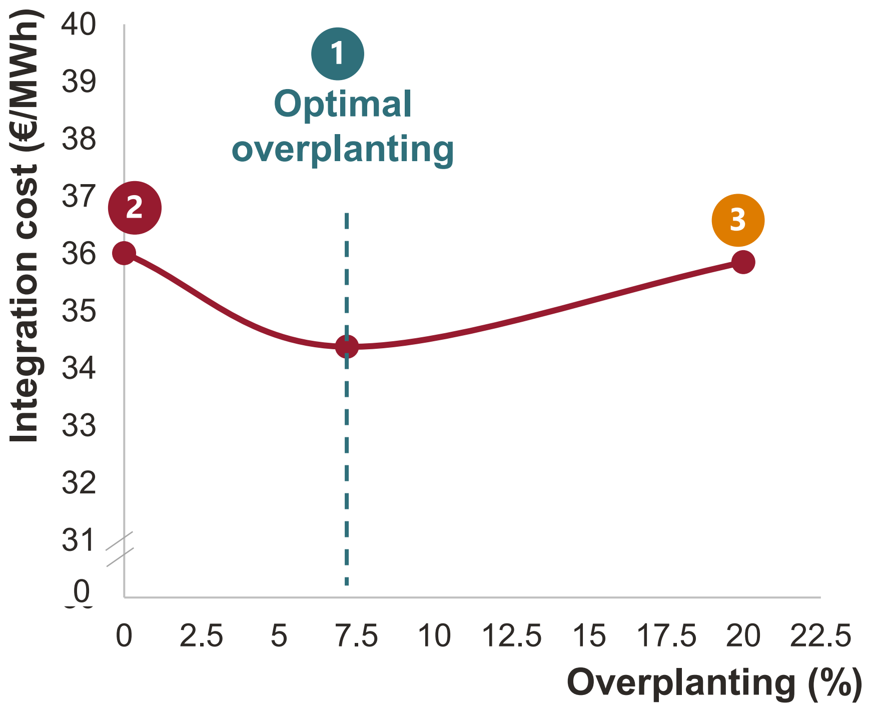
Resulting curtailment: when electricity generation exceeds cable capacity, part of the output cannot be transported and must therefore be curtailed.

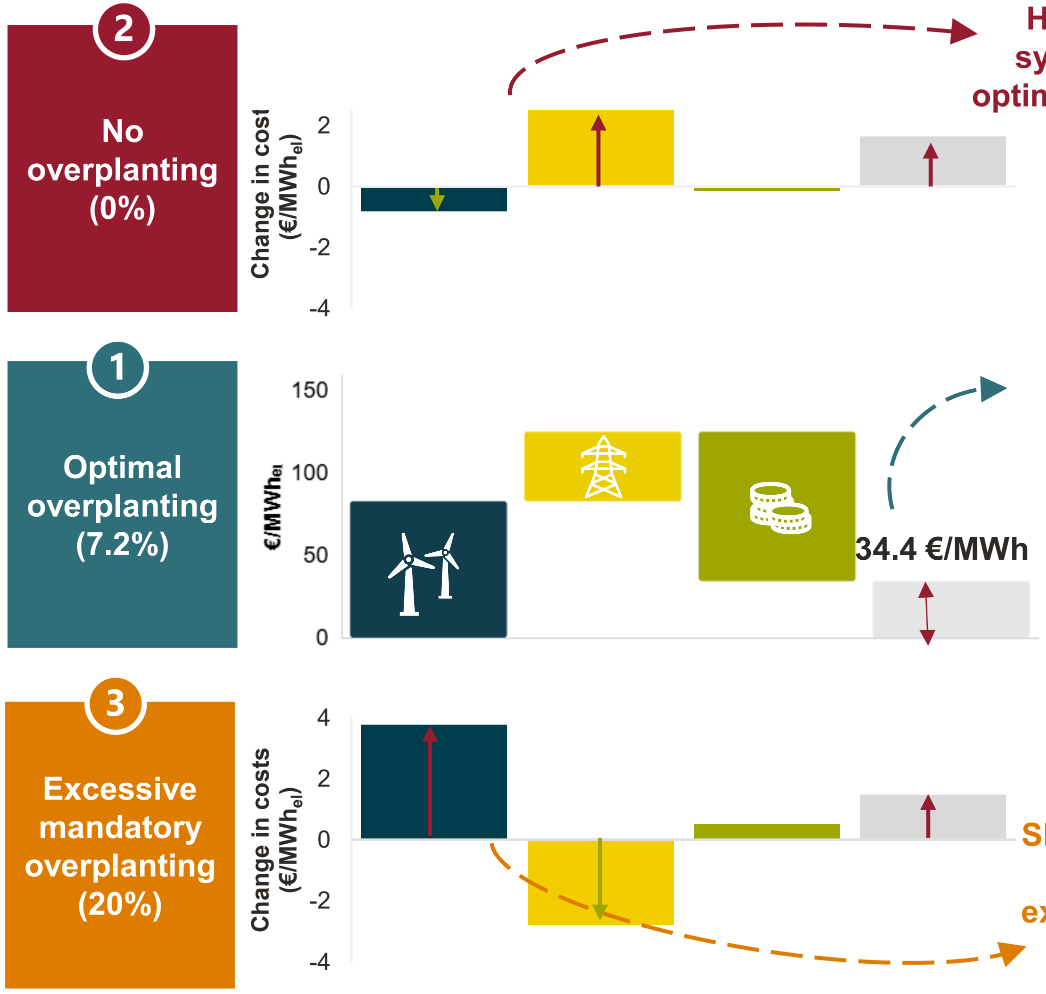
Yellow area: electricity generated and **transmitted to the grid**

Red “stripes”: **hours with non-positive electricity prices**, which are curtailed here due to sufficient transmission capacity

A deviation from the optimum leads to higher economic integration cost

Modelling the economic optimum…





Higher grid connection system costs than at the optimum, only limited savings for OWFs

Lowest integration costs with **optimal overplanting**

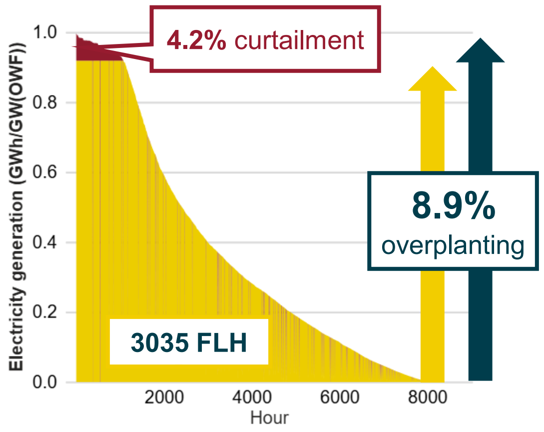
Sharp increase in OWF costs in the case of excessive overplanting

■ OWF costs ■ Grid connection costs ■ Electricity sales revenue ↕ Integration cost

Complete results: the optimal economic level of overplanting for the areas considered in the baseline scenario ranges from 6.1 to 8.9%

Baseline scenario

N-10 (371 km grid connection)

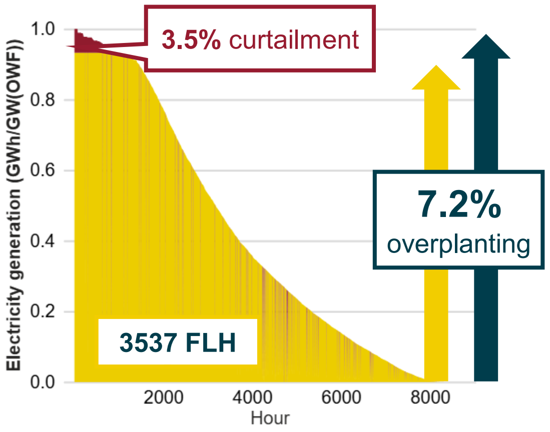


4.2% curtailment

8.9% overplanting

3035 FLH

N-12 (303 km grid connection)

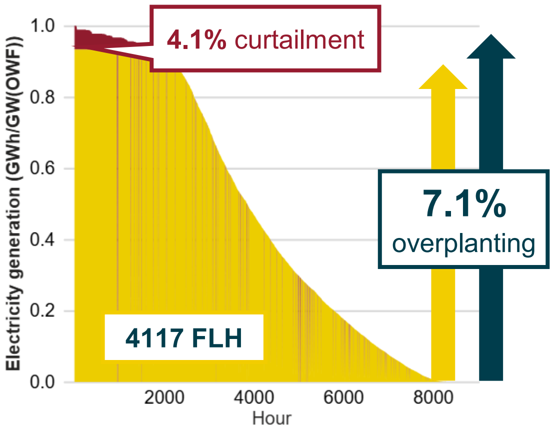


3.5% curtailment

7.2% overplanting

3537 FLH

N-17+20 (617 km grid connection)

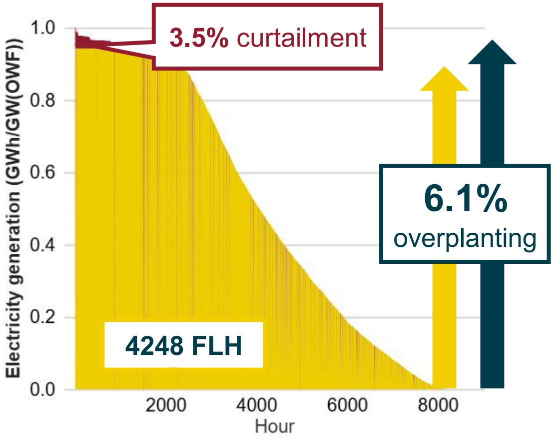


4.1% curtailment

7.1% overplanting

4117 FLH

N-19 (387 km grid connection)



3.5% curtailment

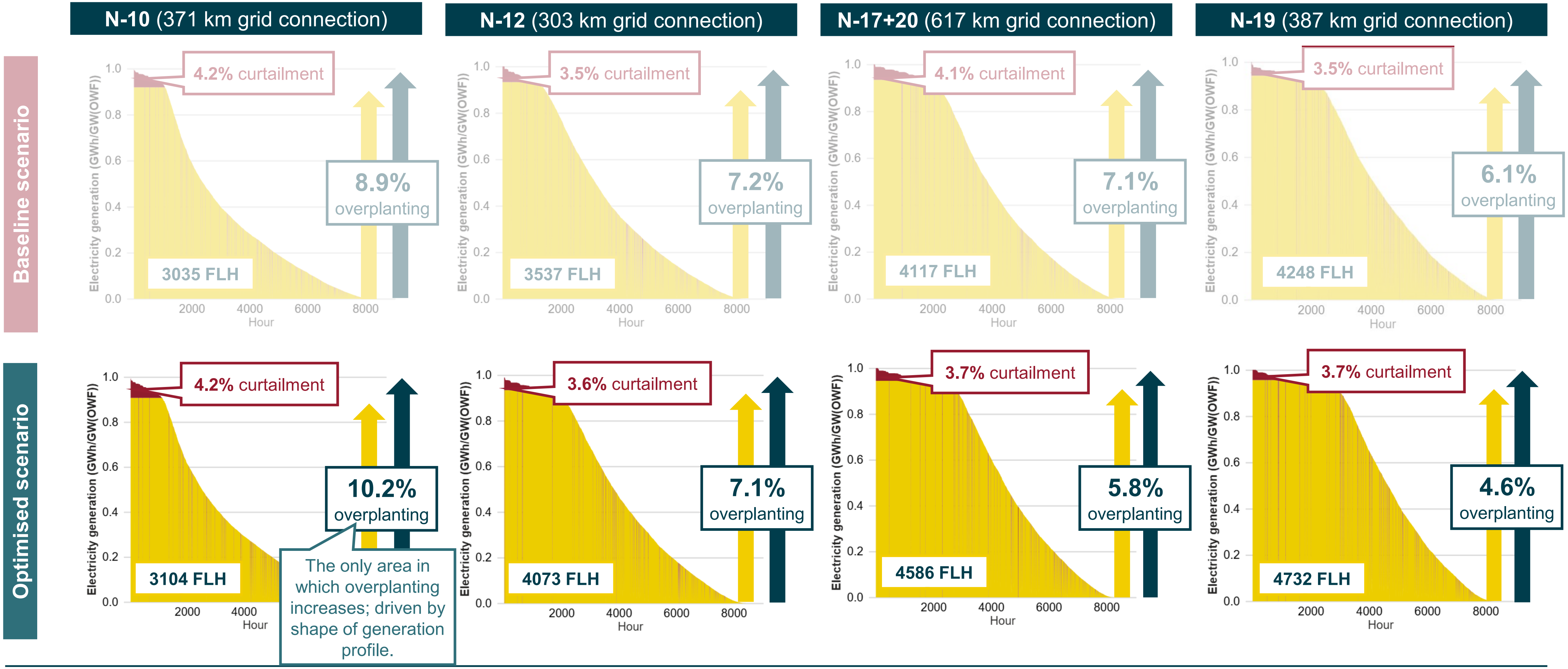
6.1% overplanting

4248 FLH

■ OWF capacity

🟨 Grid connection capacity

Optimised scenario: higher full-load hours tend to lead to a lower optimal level of overplanting



The only area in which overplanting increases; driven by shape of generation profile.

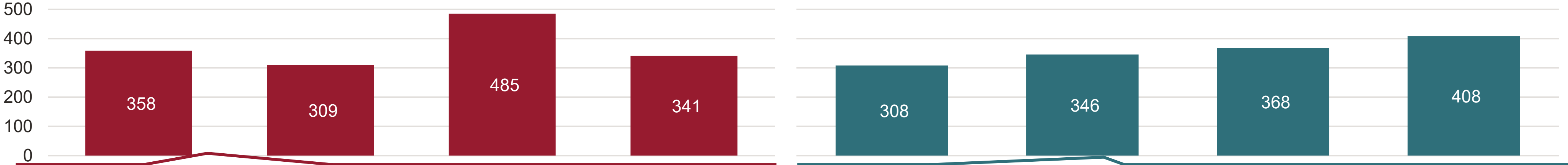
■ OFW capacity

■ grid connection capacity

The location of the grid connection point in the network development plan (NDP) impacts the optimal level of overplanting for an area

	Baseline scenario: grid connection distance from the NDP				Uniform onshore grid connection distances			
	N-10	N-12	N-17+20	N-19	N-10	N-12	N-17+20	N-19
Optimal over-planting	8.9% overplanting	7.2% overplanting	7.1% overplanting	6.1% overplanting	↓ 6.5% overplanting	↑ 8.3% overplanting	↓ 5.8% overplanting	↑ 7.1% overplanting
FLH	3035 FLH	3537 FLH	4117 FLH	4248 FLH	3035 FLH	3537 FLH	4117 FLH	4248 FLH
Offshore HVDC	163 km	246 km	295 km	383 km	163 km	246 km	295 km	383 km
Onshore HVDC	208 km	58 km	323 km	4 km	↓ 121 km	↑ 121 km	↓ 121 km	↑ 121 km

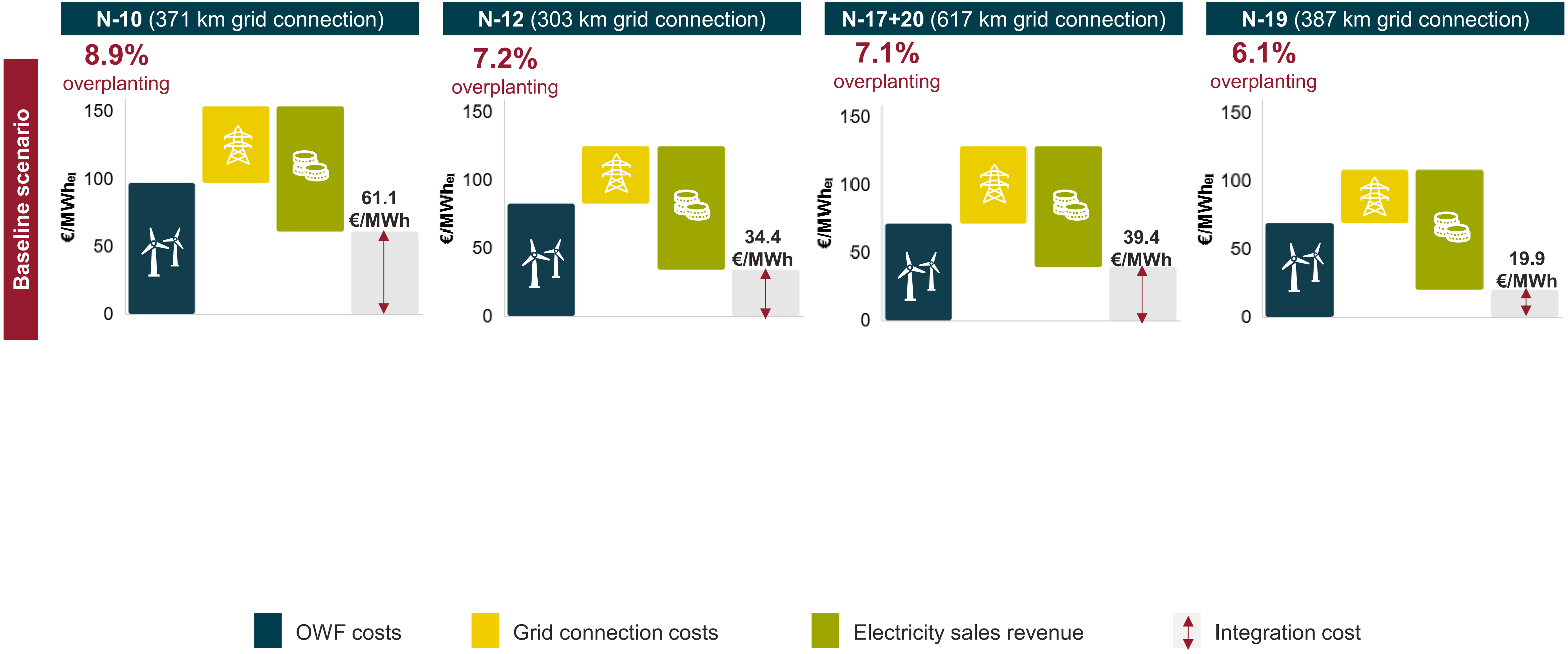
Annualised costs for 2 GW grid connection (€m)



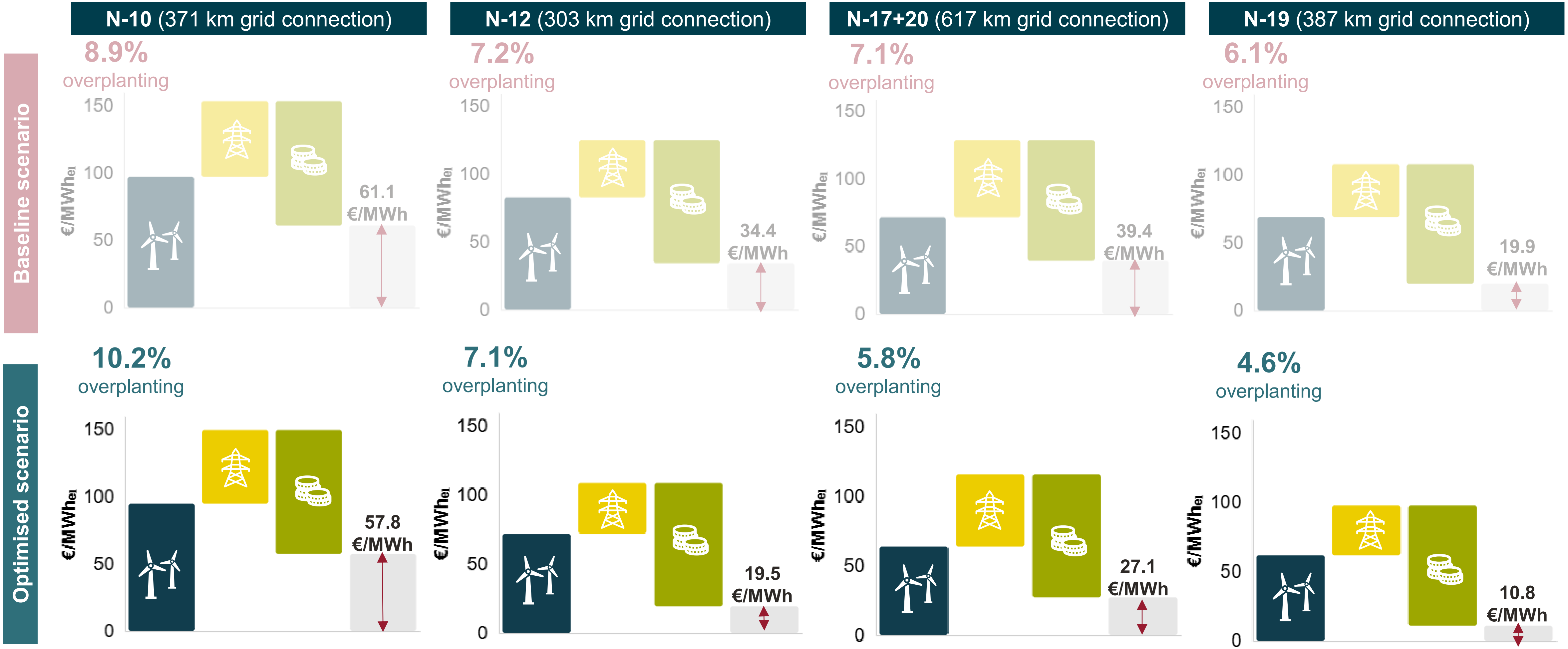
grid connection costs are more strongly driven by onshore cable lengths to the grid connection point than by the distance of the area from the coast.

grid connection costs are driven more by the distance between area and coast than by onshore lengths to the grid connection; further areas incur higher costs.

Costs and revenues in the baseline scenario: high full-load hours and shorter grid connection length lead to lower economic integration cost



Economic costs decline in the optimised scenario



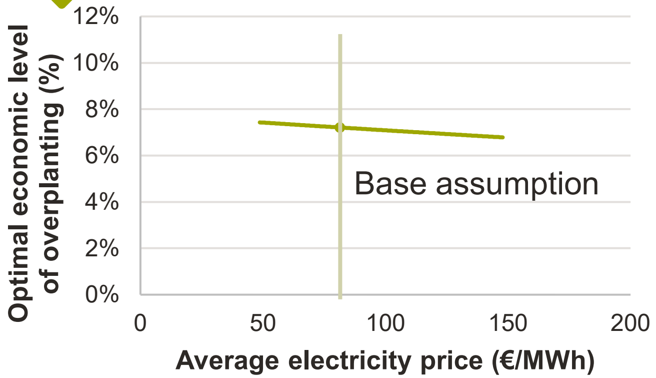
■ OWF costs
🟨 Grid connection costs
🟩 Electricity sales revenue
↕ Integration cost

Example N-12, baseline scenario

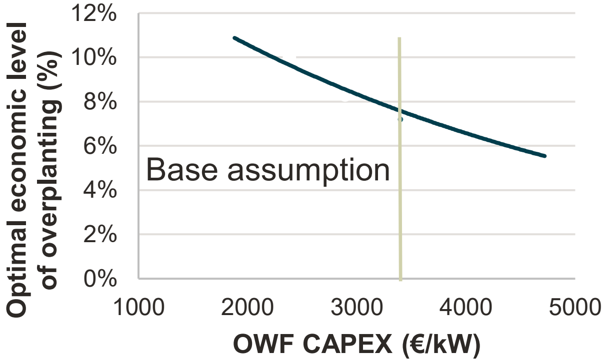
Assumptions and area characteristics significantly influence optimal overplanting

The charts show optimal overplanting as a function of...

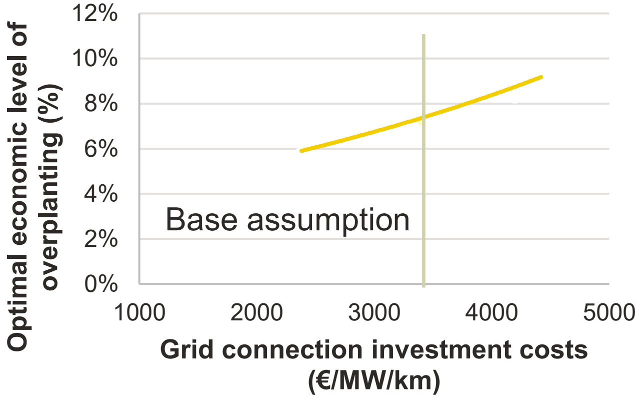
Electricity price level



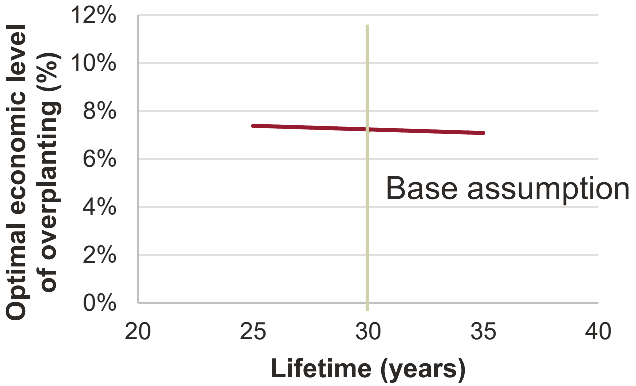
OWF investment costs



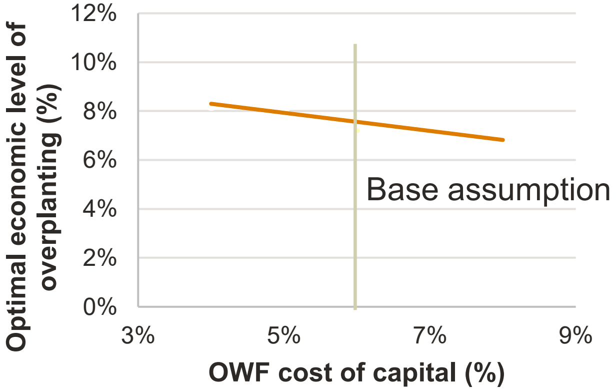
Grid connection investment costs*



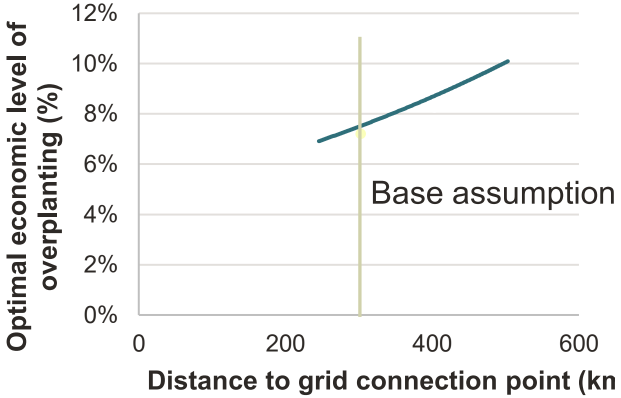
Asset lifetime (OWF and grid connection)



OWF cost of capital



Grid connection length**



*Average value of onshore and offshore CAPEX; ** the total distance from the OWF to the grid connection point is shown here. In the sensitivity analysis, only the onshore route length varies.

The sensitivities consider variation in a single factor. Varying multiple factors could result in even higher or lower optimal overplanting. Outside the sensitivities, onshore grid congestion (not considered in this study), as well as stronger cannibalisation of offshore wind generation, could lead to higher optimal overplanting.

A higher level of overplanting is efficient from an economic perspective than is commercially viable for OWF operators

N-10 (371 km grid connection)

N-12 (303 km grid connection)

N-17+20 (617 km grid connection)

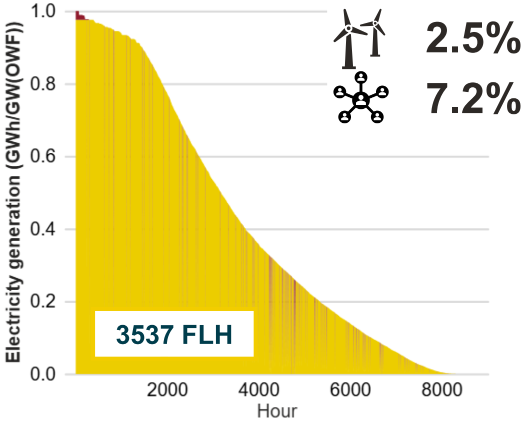
N-19 (387 km grid connection)

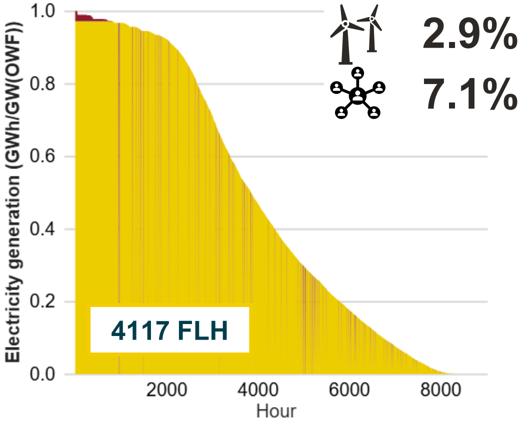
Baseline scenario

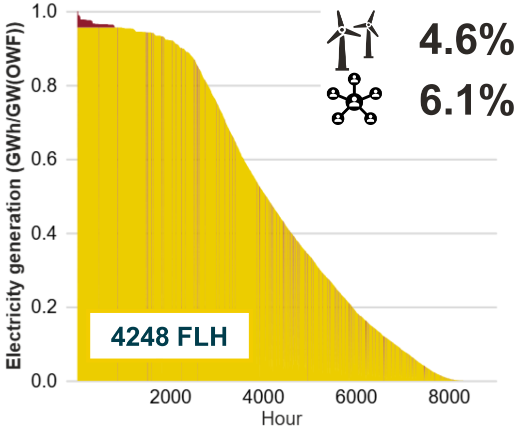
N-10

Not profitable

8.9%





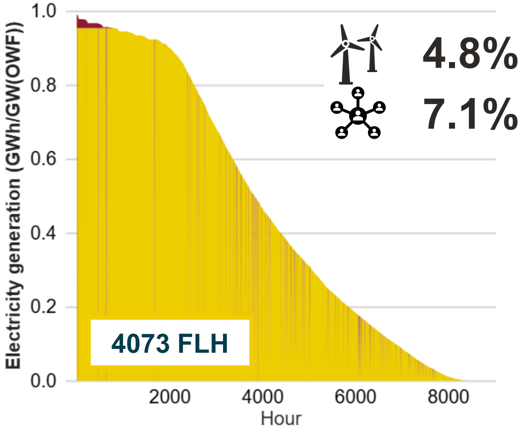


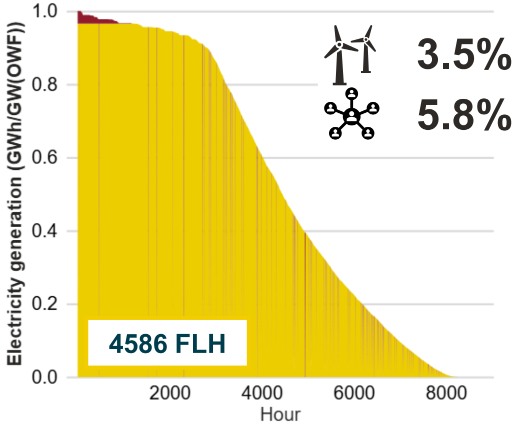
Optimised scenario

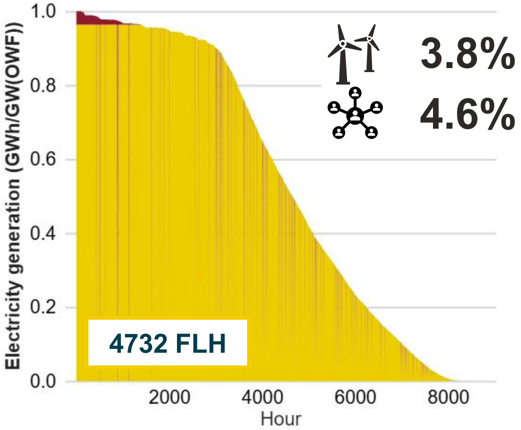
N-10

Not profitable

10.2%







🟥 Optimal curtailment from a firm-level perspective

🟨 Electricity transmission via grid connection

Optimal overplanting from firm-level perspective

Optimal overplanting from an economic perspective

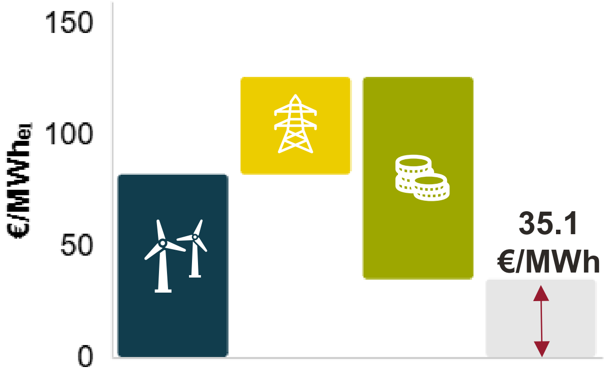
Comparison of cost and revenue: the business case for OWF operators deteriorates under the optimal economic level of overplanting

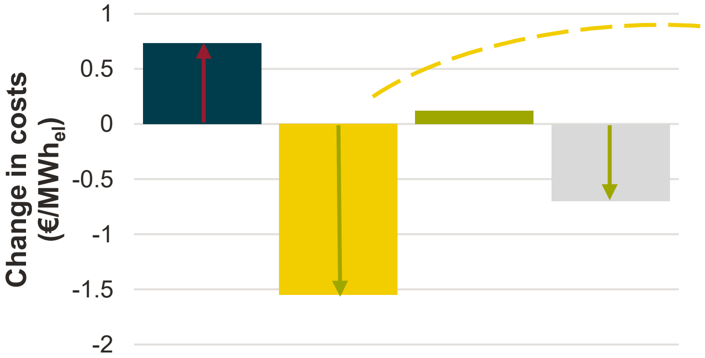
Example N-12 Baseline scenario

Costs and revenue at the commercially optimal level: 2.5% overplanting

Change in costs and revenue from overplanting to the economic optimum (7.2%):

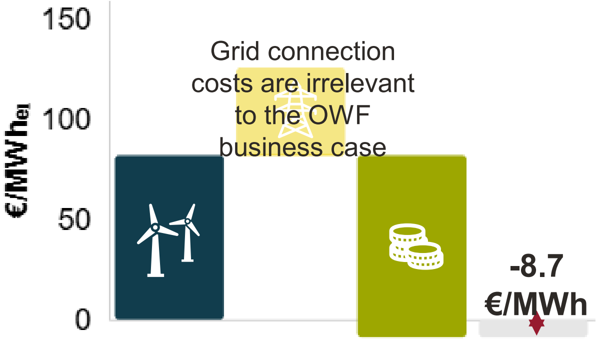
Economic perspective



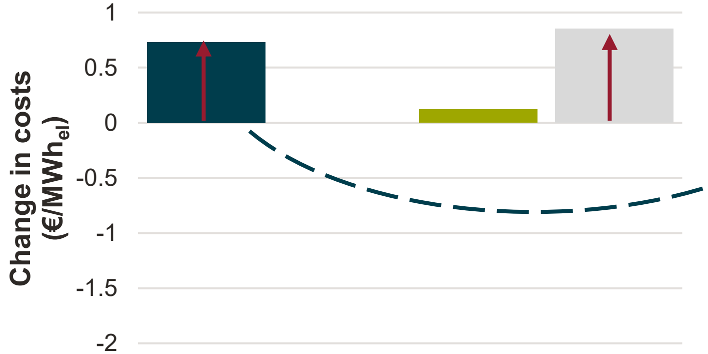


Grid connection costs decline under the optimal economic level of overplanting; overall, this results in lower economic costs

OWF operator perspective



Grid connection costs are irrelevant to the OWF business case



Operators bear **higher OWF costs**, but do not benefit from savings in grid connection costs → weaker commercial outcome

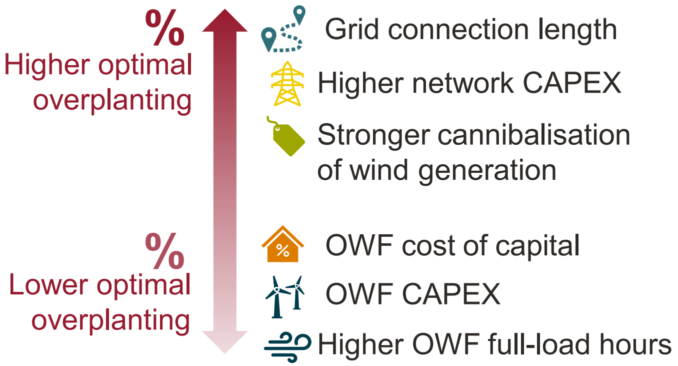
Agenda

Key results and conclusions

5 to 10%
economic overplanting

- **Overplanting** is efficient from an economic perspective up to a certain point because it reduces costs
- The **optimal economic level of overplanting** for the areas considered is **5 to 10%**
- An **excessively high mandatory overplanting requirement (e.g. 20%)** leads to **additional economic costs** under the assumptions used in this study

The optimal economic level of overplanting is
site-specific



- The optimal economic level of overplanting depends on
  - the characteristics of the respective site
  - assumptions on costs and price developments
- When multiple sensitivities are combined or possible market developments are taken into account, it may also be higher or lower than 5 to 10%
- A **mandatory overplanting requirement (e.g. 20%)** does not do justice to this

3 to 5%
Firm-level optimal overplanting

- There are also incentives for overplanting from the OWF perspective: **3 to 5%** for the areas considered
- An overplanting requirement set well above the **economic optimum therefore worsens the OWF business case** → a **compensation mechanism** may be required

Limitations of the study and areas for further analysis

Assumptions subject to uncertainty

- We do not consider **onshore grid costs and congestion** beyond the costs of the onshore connection line. In practice, structural grid congestion could limit offshore wind potential and increase the optimal level of overplanting.
- **Capture prices for offshore wind** and the ratio of OWF to grid connection costs are key factors for the optimal level of overplanting. Their future development is uncertain.
- The values for optimal overplanting identified in the study are based on **grid connection lengths up to the planned grid connection points** in the NDP. The choice of grid connection point (and thus the length of the onshore cable) is a separate optimisation task for the TSOs and may still change – and with it the optimal level of overplanting for individual areas.

Comprehensive optimisation of offshore wind is needed

Overplanting can be a **useful tool for improving the efficiency** of offshore wind – but it is not the only one:**:**

- **Increasing wind yield** by reducing power density (including through international cooperation).
- **Focusing on energy delivered** rather than purely on capacity targets (e.g. 70 GW).
- Measures to **de-risk** projects and achieve economies of scale in production in order to reduce costs.
- Analysis of further measures beyond direct use of wind energy in the power system, e.g. **offshore sector coupling**, where transport of **hydrogen** could reduce costs.

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Overview of the key assumptions in the model

	INPUT	ASSUMPTIONS			SOURCES
Areas + Wind profiles	Areas with installed capacity and hourly wind profiles	Outputs from the Fraunhofer IWES study “International Optimization of Full Load Hours in the German Bight” for weather year 2012: **energy yields** by area and scenario, **availability** based on Monte Carlo simulations, of which we use one simulation run in each case			Fraunhofer IWES (2026)
Costs	OWF	**CAPEX** (logistics costs, soft costs, material costs): 3.4m €/MW	**OPEX**: ~0.036m €/MW (1.1% CAPEX p.a.)	**Asset life**: 30 years	Fraunhofer IWES (2026)
	DC cable system*	**CAPEX** (2-GW-grid connection): Offshore: 6.0m €/km Onshore: 7.6m €/km	**OPEX**: 2.5% (CAPEX p.a.)	**Asset life:** 30 years (identical to OWF)	CAPEX: NEP 2023, AC substation from ENTSO-E ONDP (cost set 3); OPEX: ENTSO-E ONDP Methodology 2024
	Converter*	**CAPEX**: DC Offshore: 0.7m €/MW DC Onshore: 0.3m €/MW AC-Substation: 0.24m €/MW	**OPEX**: 1.5% (CAPEX p.a.)		
	Cost of capital	**3%** for grid connection components, **6%** for OWFs (real)			Grid: BNetzA (2024) for new investments; OWFs: Fraunhofer ISE LCOE Study (2024)
Prices	Hourly power prices	Modelled for target year 2045 based on weather year 2019			Frontier‘s European energy model *COMET*

*100% efficiency assumed.