Hybrid Offshore Energy

Forecasting, Layout Optimisation & Complementarity

Transatlantic forecasting & spatial yield mapping

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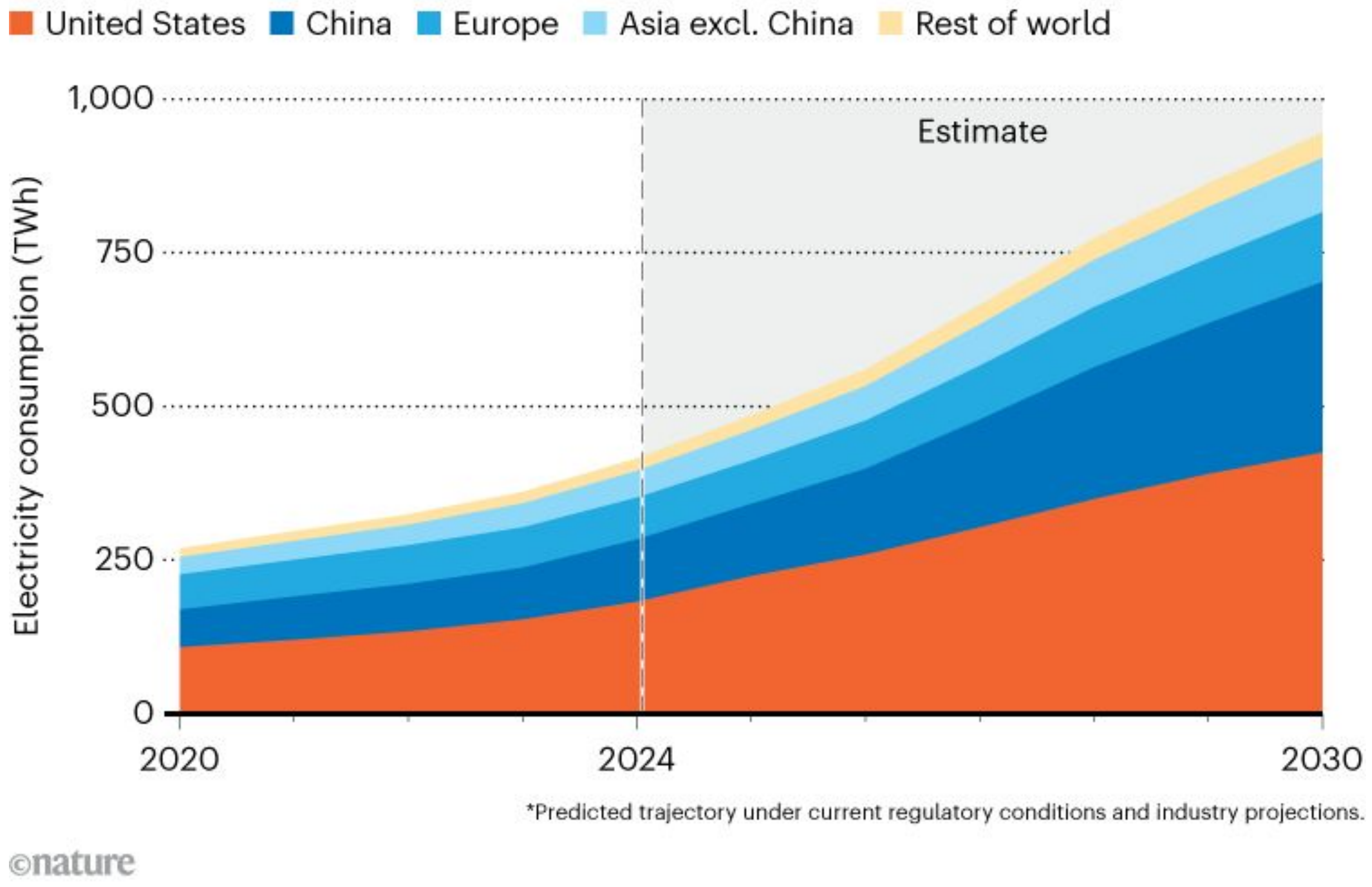
Motivation – Data-Centre Energy Growth

- China and the United States are predicted to account for nearly 80% of the global growth in electricity consumption by data centres up to 2030 *.



Agenda

- Offshore growth
- Forecasting & data
- Layout optimisation
- Hybrid resources
- Conclusions

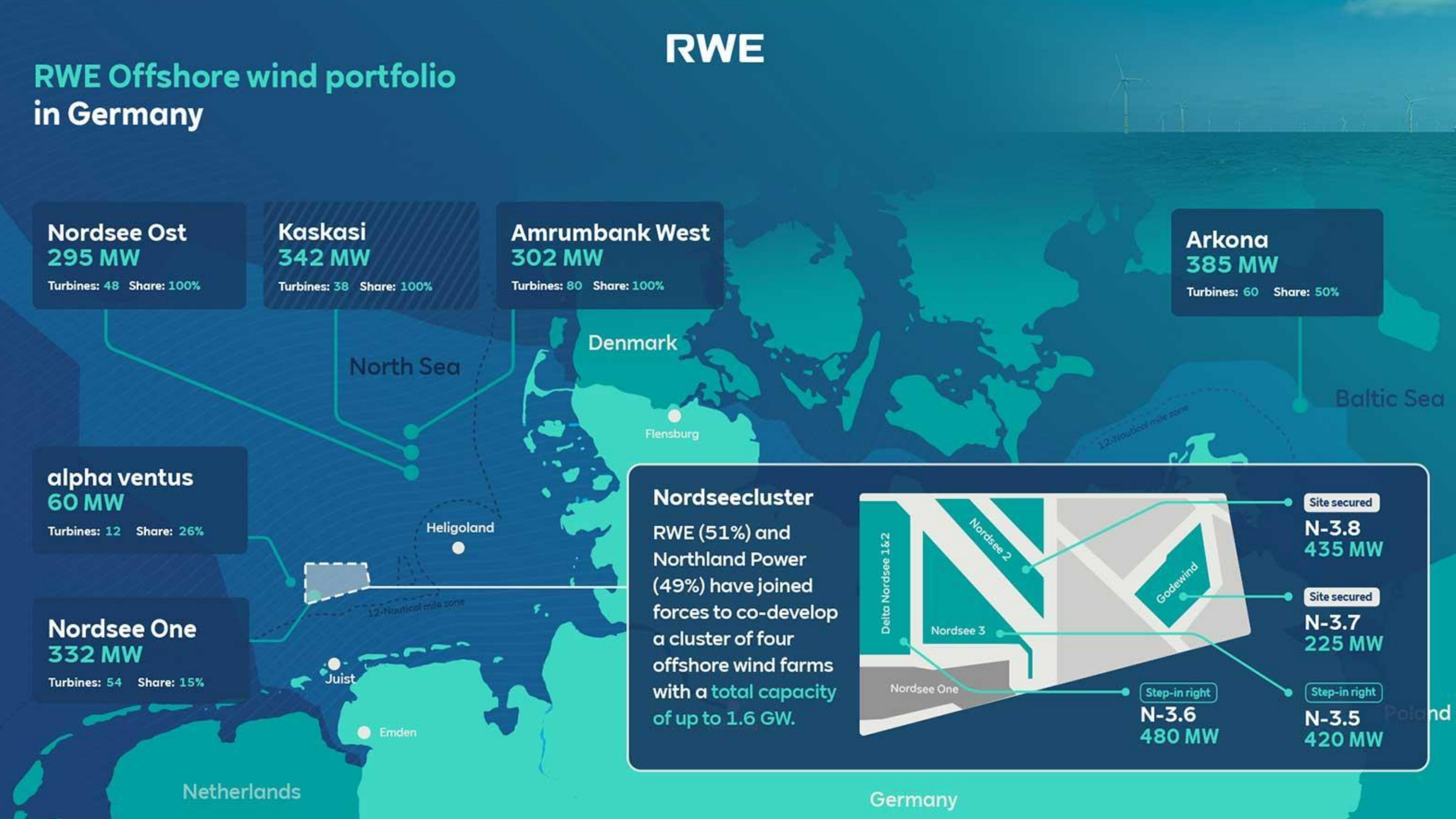
Offshore Wind Expansion & Projects

Germany’s growing offshore wind fleet

- Nordsee cluster: four farms totalling up to 1.6 GW
- Rapid capacity growth driven by ambitious 2030 targets
- Larger turbines and tighter spacing improve economics

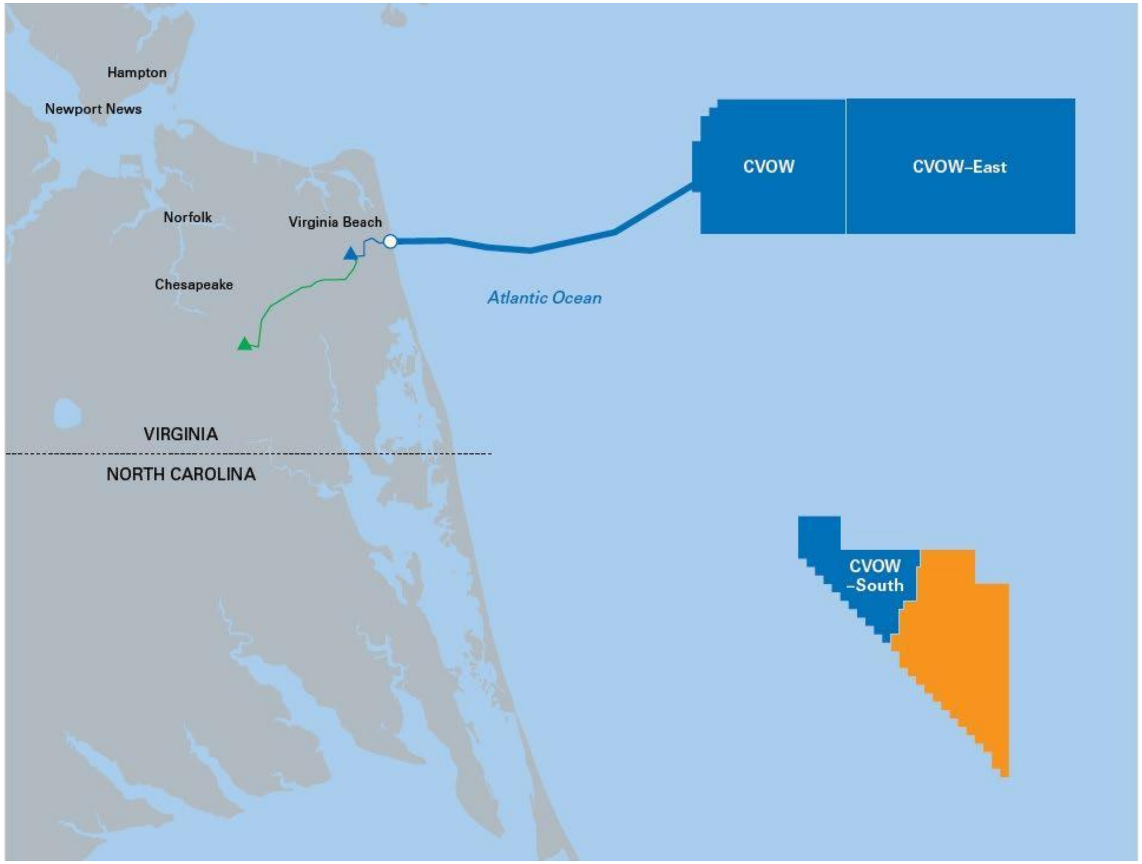
Coastal Virginia Offshore Wind (CVOW)

- 2.6 GW project with 176 Siemens Gamesa 14–222 DD turbines
- Enough zero-carbon energy to power ~660,000 homes
- Construction underway – completion expected in 2026


RWE
RWE Offshore wind portfolio
in Germany
Nordsee Ost
295 MW
Turbines: 48 Share: 100%
Kaskasi
342 MW
Turbines: 38 Share: 100%
Amrumbank West
302 MW
Turbines: 80 Share: 100%
Arkona
385 MW
Turbines: 60 Share: 50%
alpha ventus
60 MW
Turbines: 12 Share: 26%
Nordsee One
332 MW
Turbines: 54 Share: 15%
North Sea
Denmark
Baltic Sea
Flensburg
Heligoland
12-Nautical mile zone
Juist
Emden
Netherlands
Germany
Poland
Nordseecluster
RWE (51%) and Northland Power (49%) have joined forces to co-develop a cluster of four offshore wind farms with a total capacity of up to 1.6 GW.
Delta Nordsee 1&2
Nordsee 2
Nordsee 3
Godewind
Nordsee One
Site secured
N-3.8
435 MW
Site secured
N-3.7
225 MW
Step-in right
N-3.6
480 MW
Step-in right
N-3.5
420 MW

CVOW Lease Areas

- Leveraging Dominion Energy's proven regulated offshore wind development expertise
- **CVOW South**
  - Up to 800 MW of capacity
  - Could serve up to 200,000 homes
  - Located off Kitty Hawk, NC
- **CVOW East**
  - Estimated up to 4,000 MW of capacity
  - Could serve up to 1,000,000 homes
  - Located directly east of CVOW



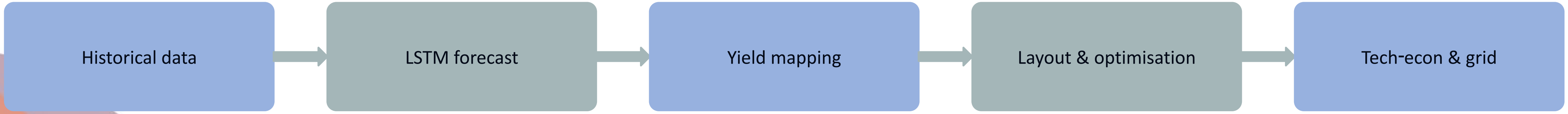
Data & Forecasting Approach

Data sources

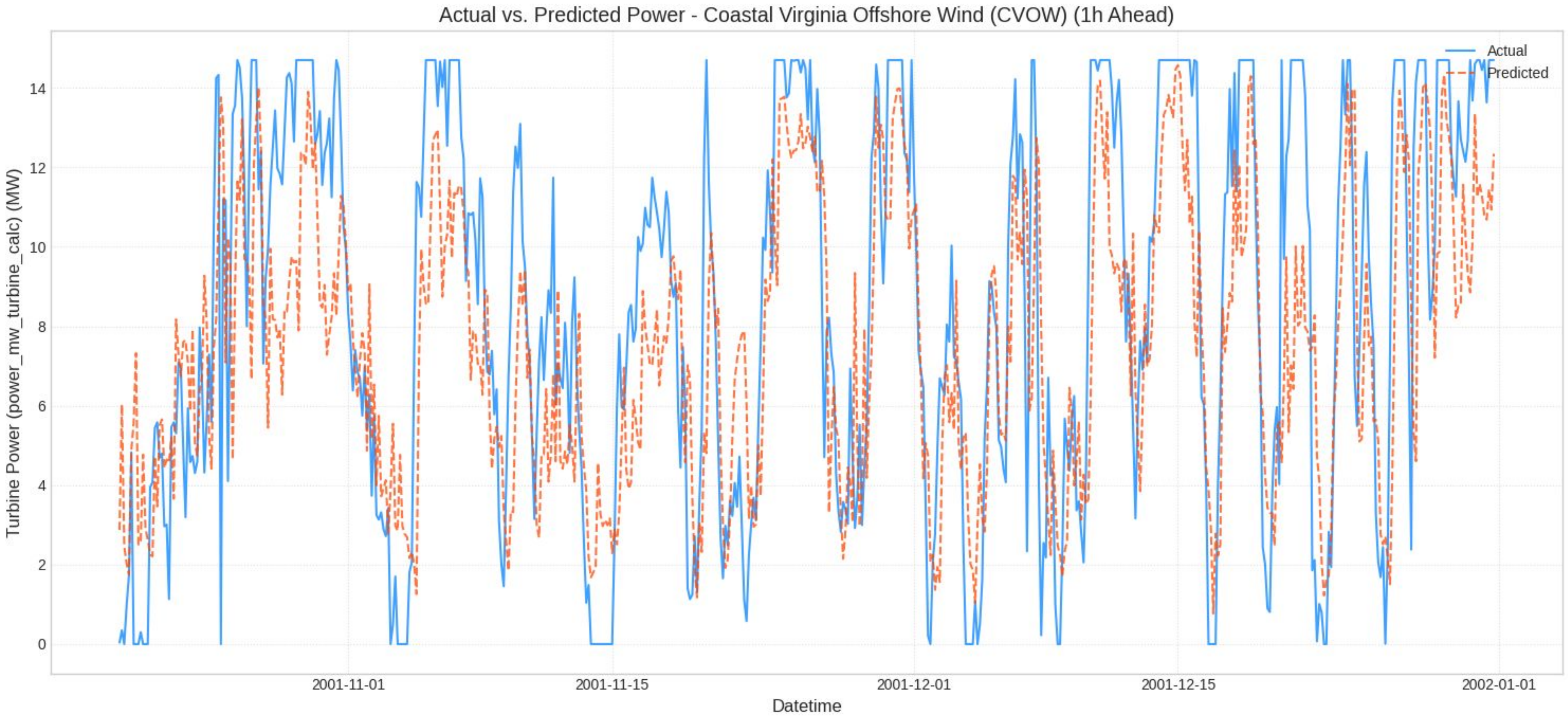
- ERA5 meteorological reanalysis & buoy measurements
- Historical power production from multiple sites
- Turbine characteristics (cut-in/rated/cut-out speeds)

Deep learning forecast

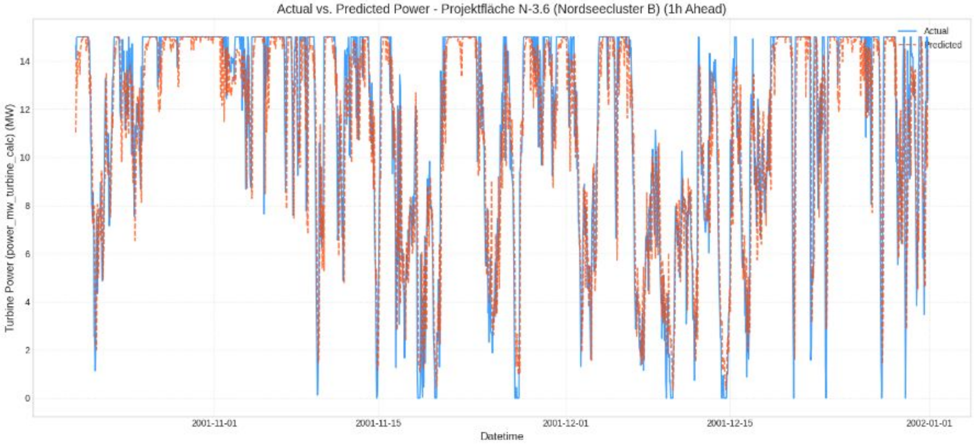
- LSTM models per site predict 1h ahead power output
- Utilises temporal patterns and exogenous weather inputs
- Forms the basis for spatial yield mapping

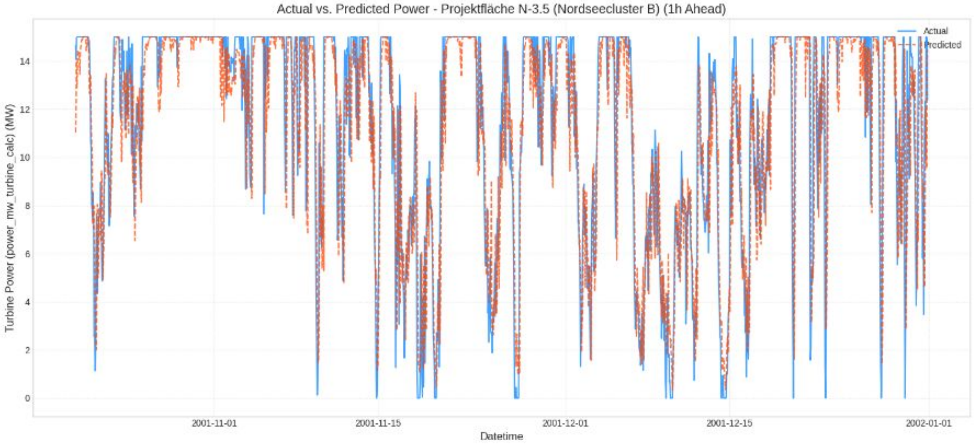


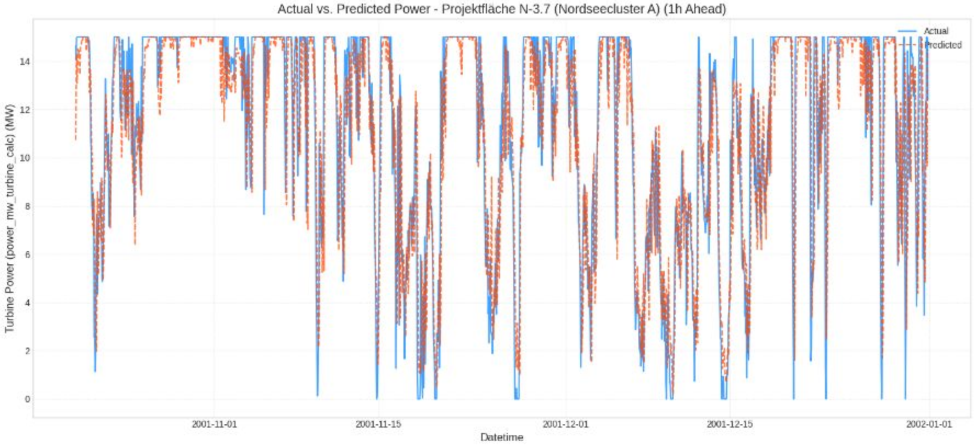
CVOW Power Prediction – Rolling Window

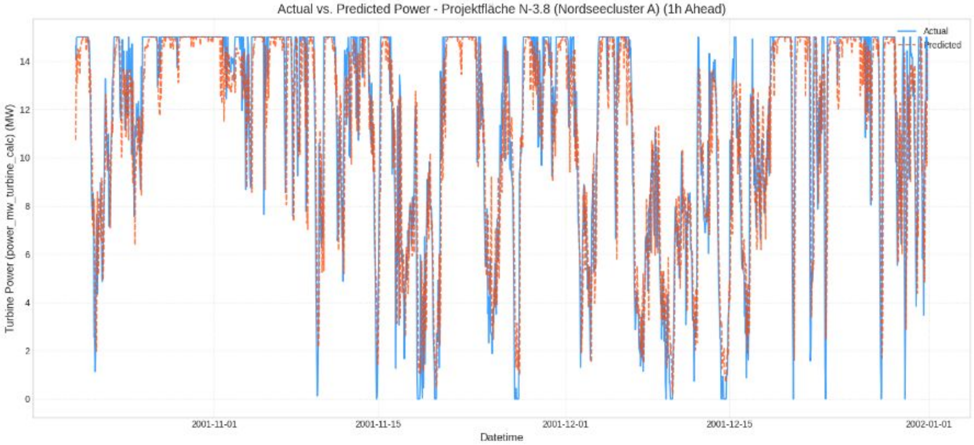


Nordseecluster Power Prediction – Rolling Window

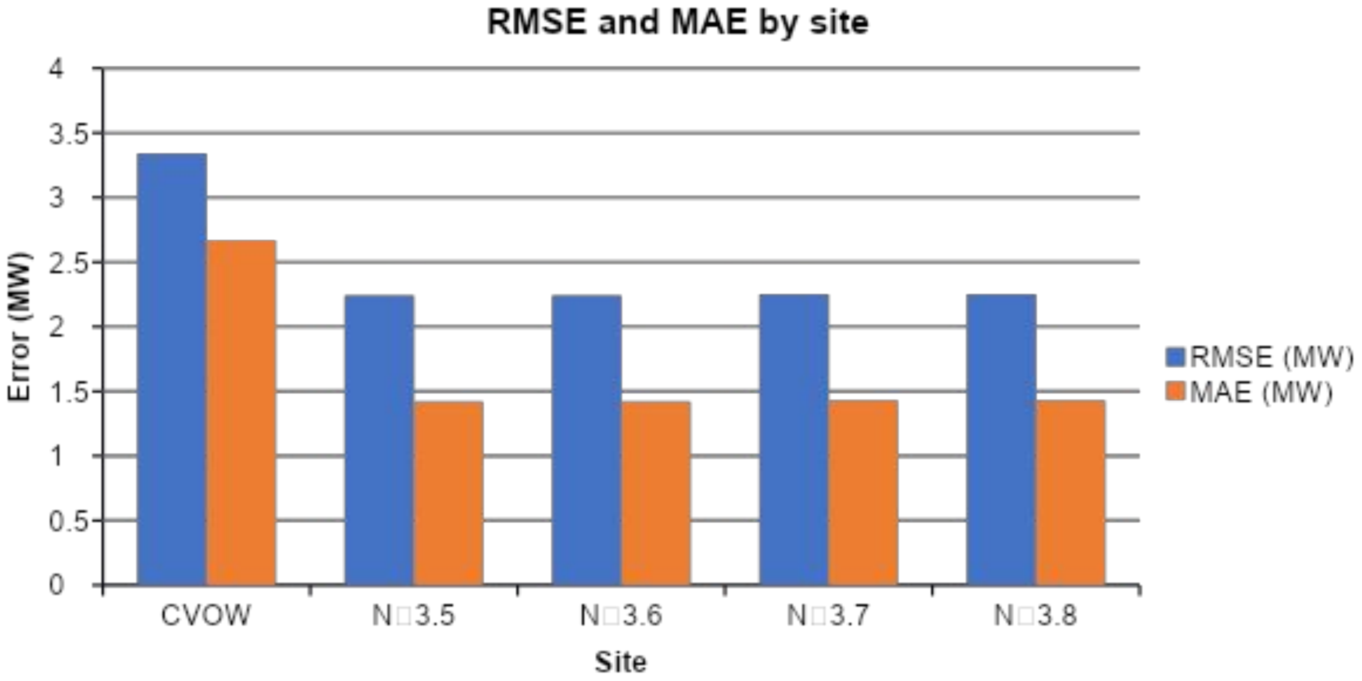






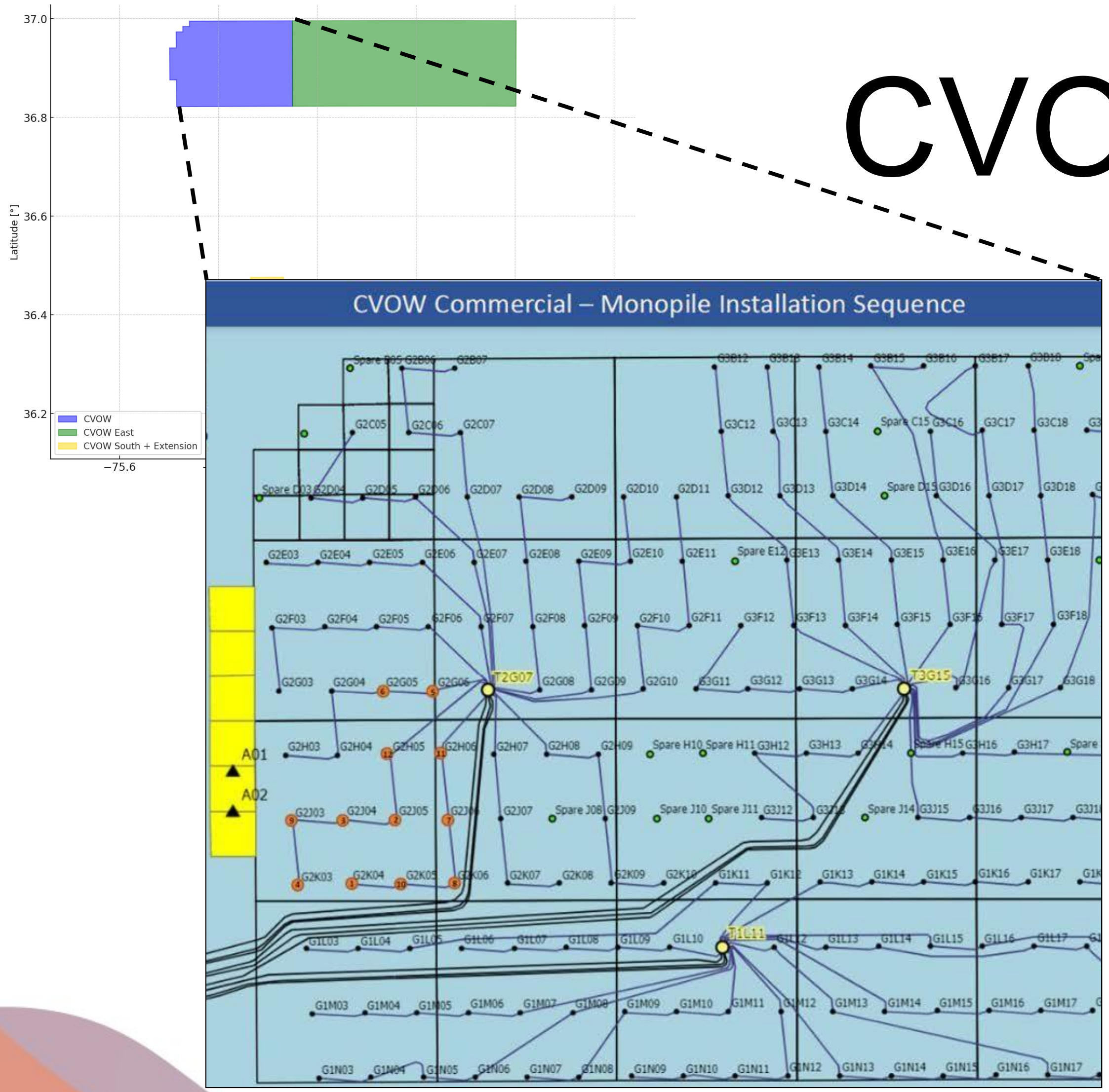


Model Performance – 1h Ahead



Additional metrics:

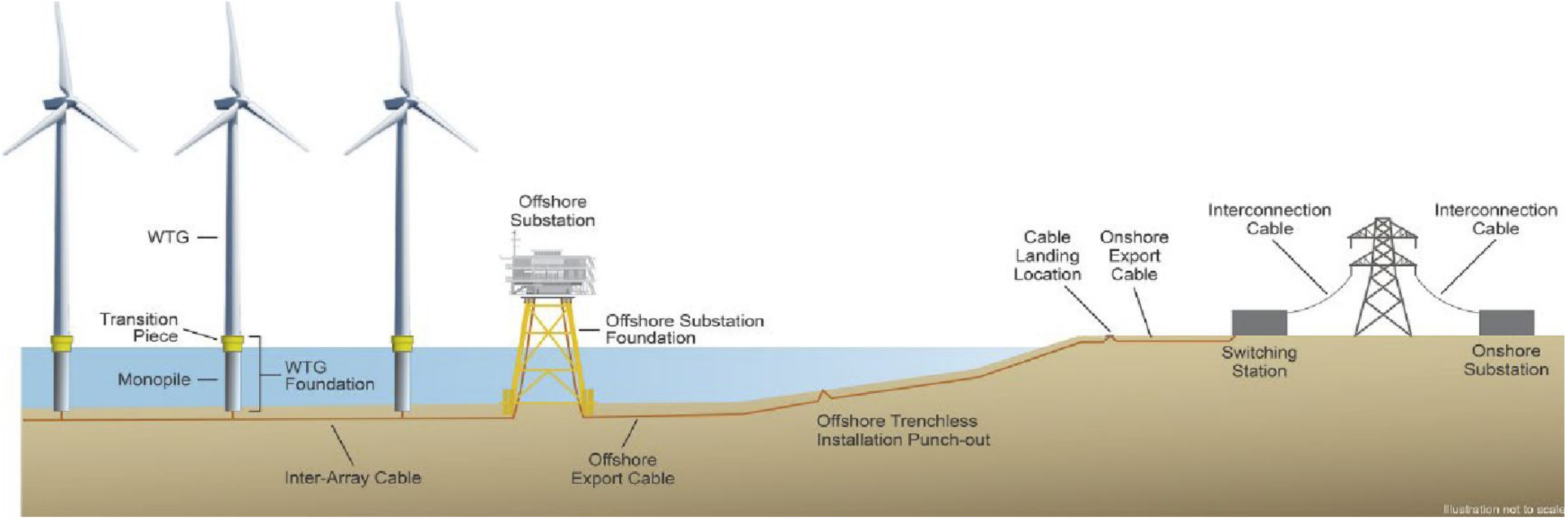
R^2 score range: 0.54 – 0.75
Normalised RMSE: 14–23 %
Models capture site-specific dynamics with high accuracy.



CVOW Site

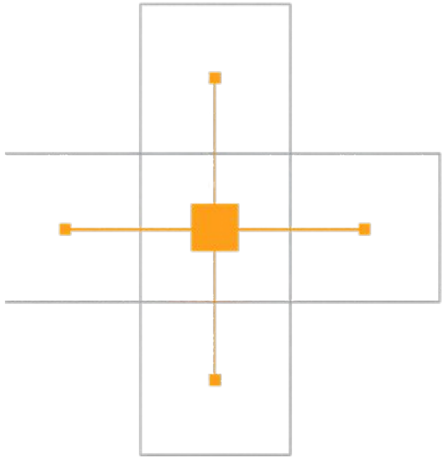
- Builds on success of the two-test turbine pilot project
- Located just east of the pilot project
- 27 to 42 miles offshore in a lease area
  - equal to 85,000 football fields
- 176 X 14.7 MW turbines
- 2.6 GW total capacity
- Power up to 660,000 homes

General OSW Park structure



Wind Turbine Arrangements

$$\rho_{\text{square}} = \frac{1}{d^2},$$



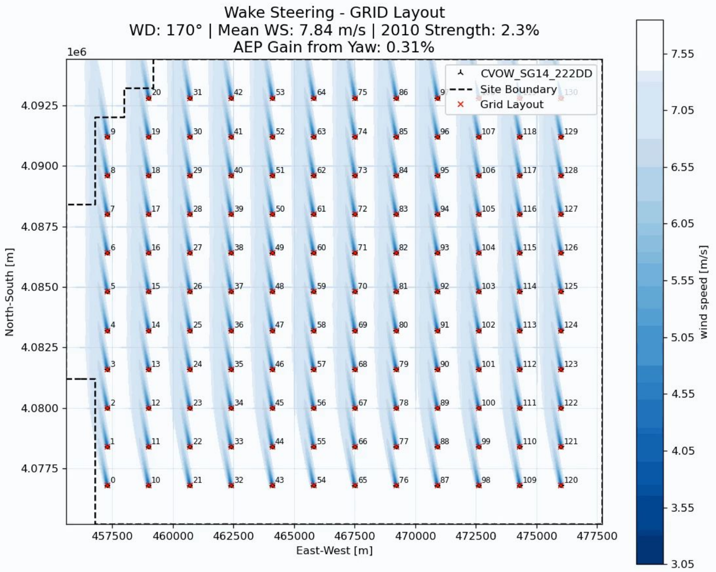
Standard Grid
Grid

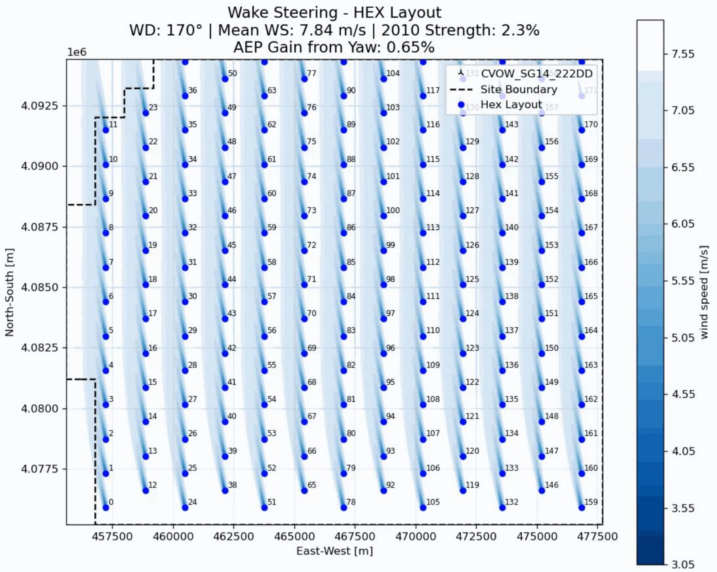
$$\rho_{\text{hex}} = \frac{2}{\sqrt{3}\, d^2} \approx \frac{1.1547}{d^2}.$$

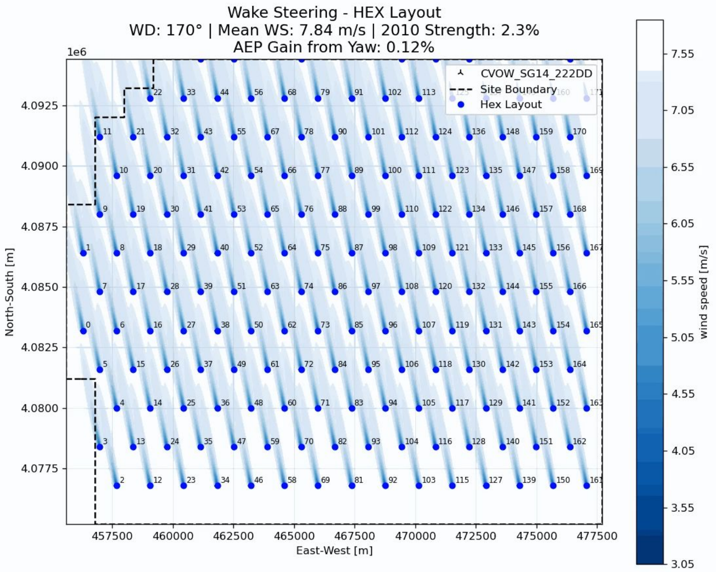
Hex

- **Why hexagon layout?**
- +15.5 % more turbines per area
- Shorter cables → lower cost & losses
- More routing options for feeders

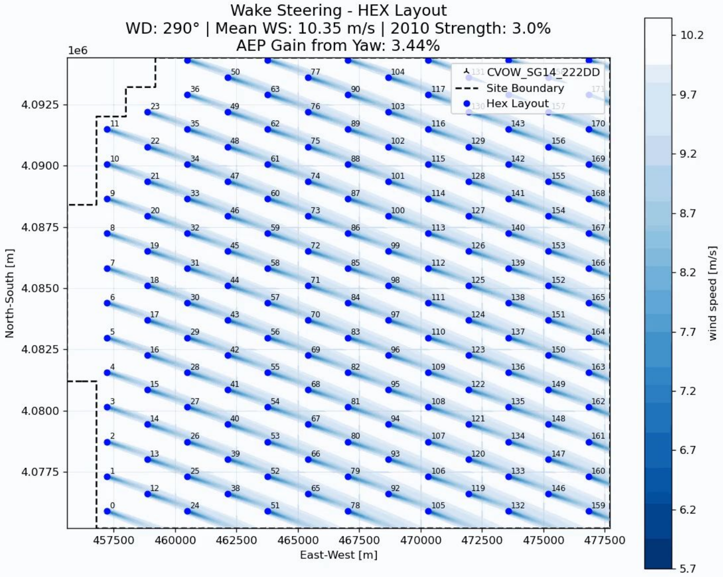
Wind Flow Visualization – SW to S

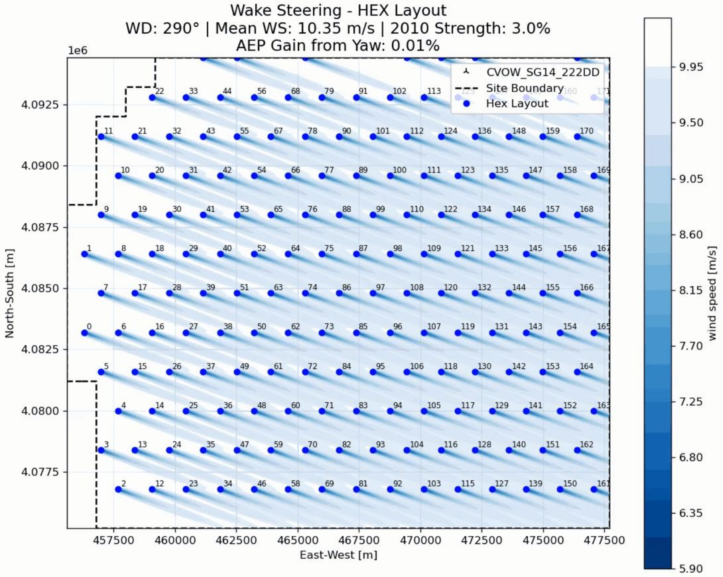


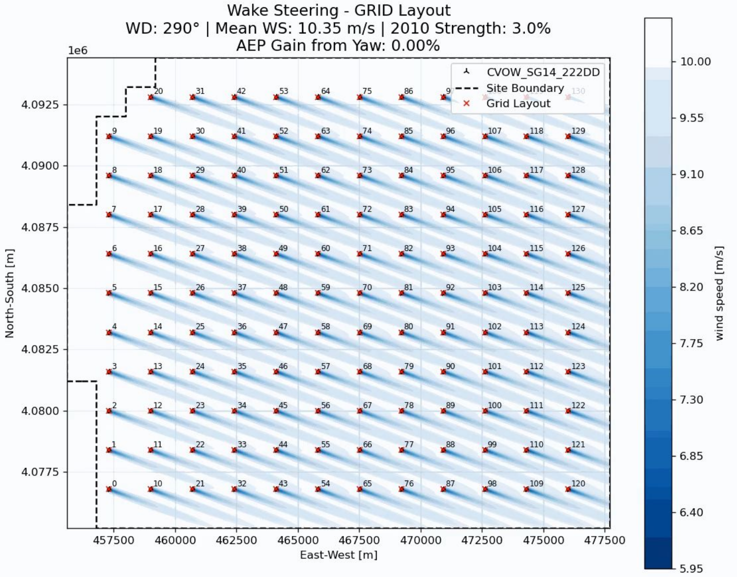




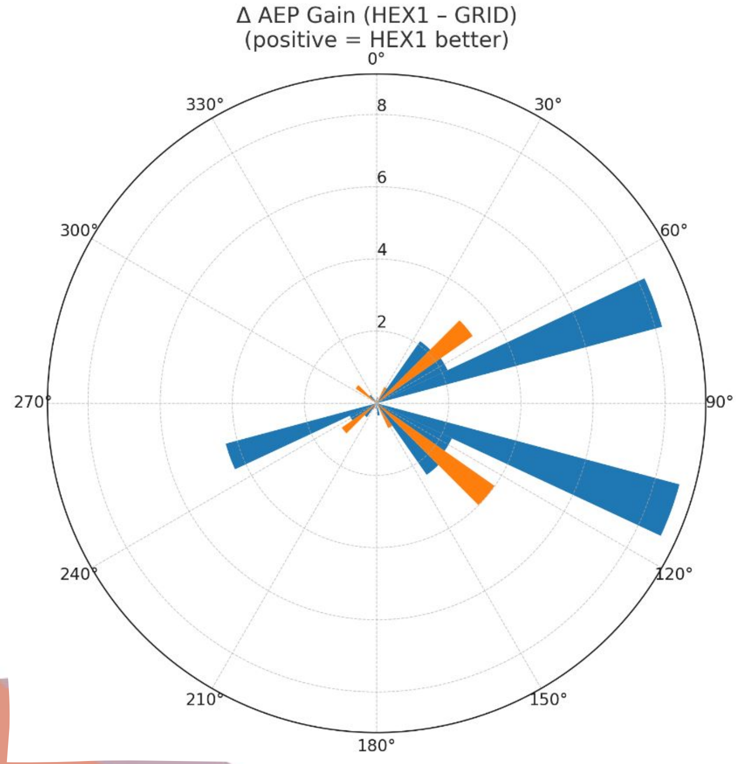
Wind Flow Visualization – NW to N

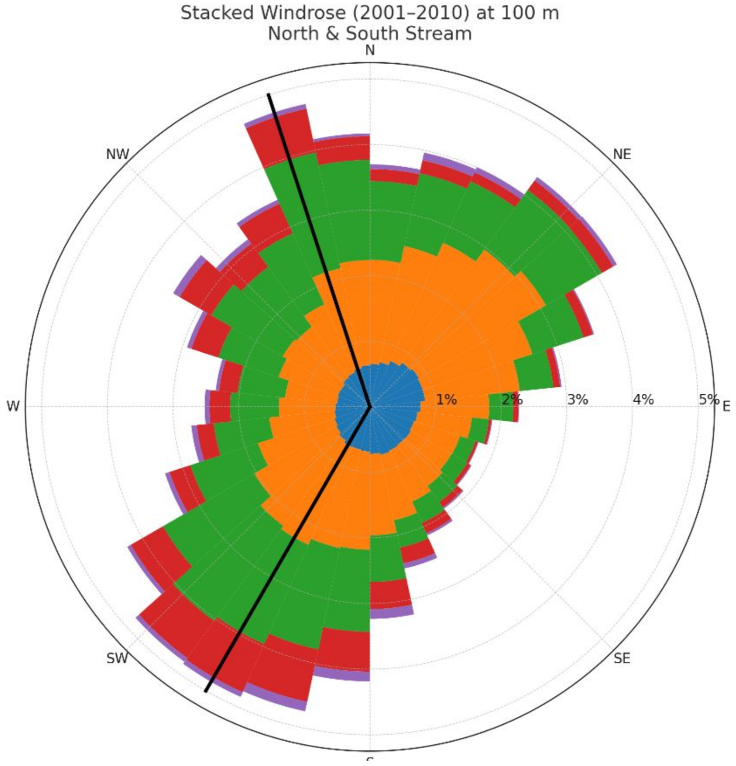


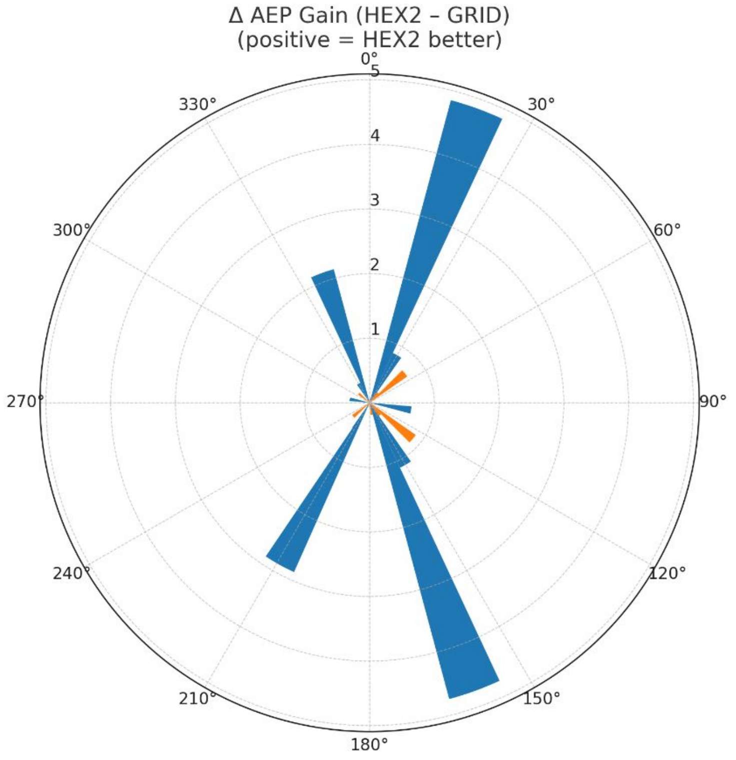




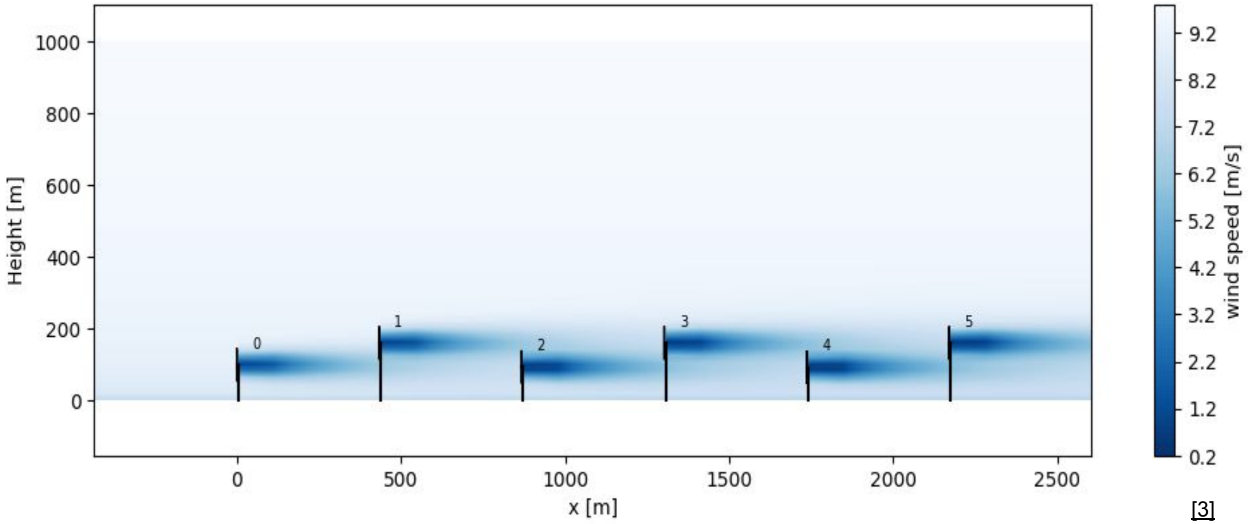
AEP improvements using a HEX structure







Alternating hub heights for increased AEP



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Hexagonal layout advantages

- Reduces wake losses by staggering turbines
- Increases Annual Energy Production (AEP) by ~3 %
- Compact footprint enables more turbines per site

Alternating hub heights

- Taller towers catch higher wind speeds and improve yield
- Alternating heights minimise mutual wake effects
- Combined with hex layout adds +1–2 % AEP

Hub Height Wind Speed Extrapolation

Wind speed generally increases with height above the surface due to reduced frictional drag. This vertical gradient is often modeled using the **wind profile power law**:

$$v_2 = v_1 \left(\frac{h_2}{h_1} \right)^{\alpha}$$

Where: v_2 is the wind speed at the target height h_2, v_1 is the known wind speed at a reference height h_1, and α is the wind shear exponent (typically ~0.12 offshore).

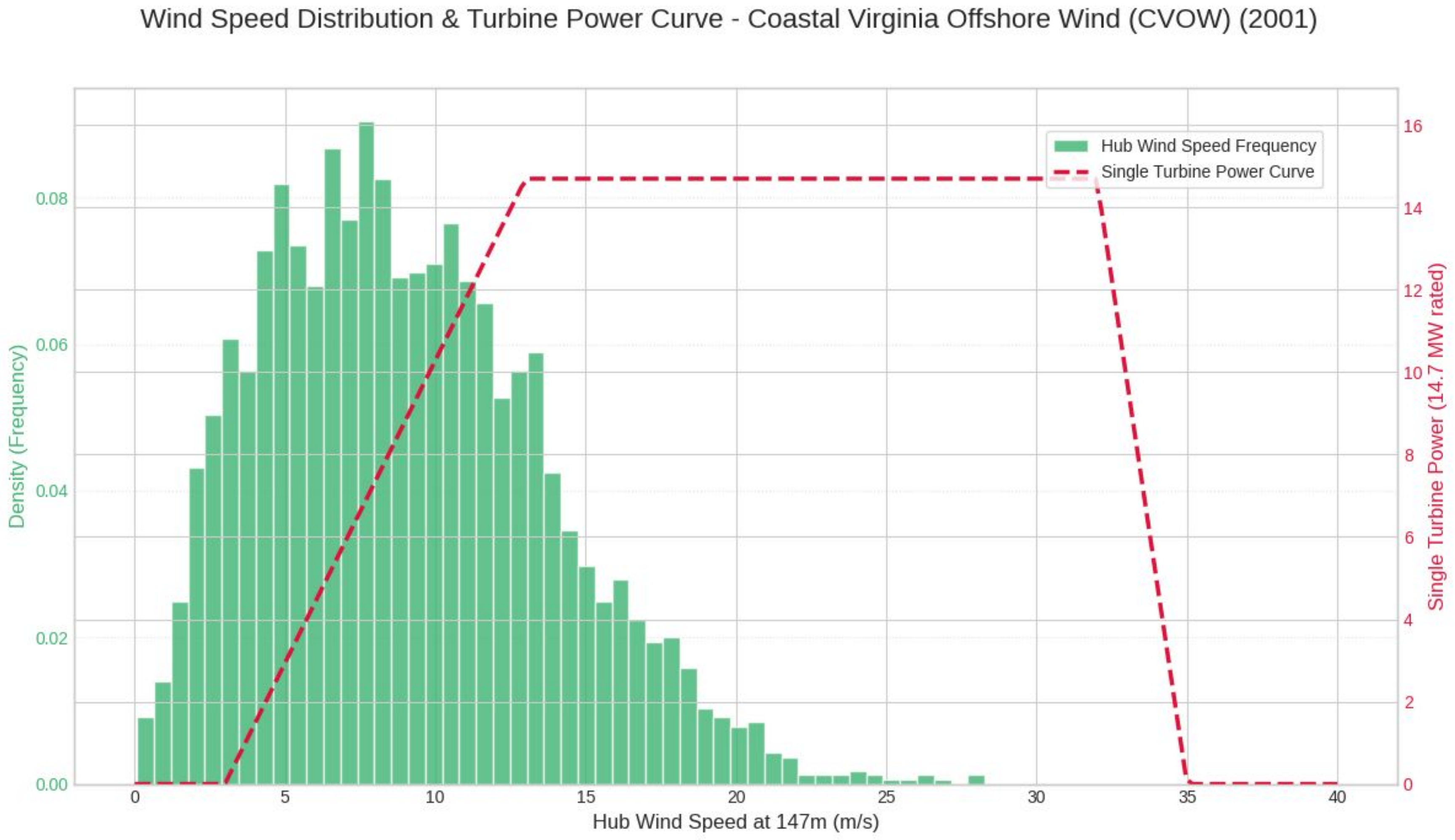
Theoretical Turbine Power Output

The power output (P) of a wind turbine is primarily a function of the wind speed (v) at its hub height:

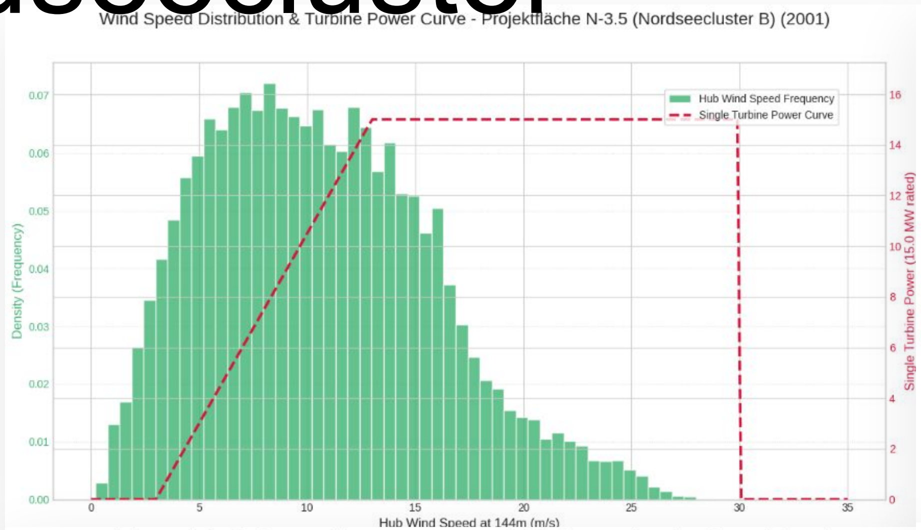
1. **Cut-in Wind Speed (v_{cin}):** Min speed to start generation.
2. **Rated Wind Speed (v_{rated}):** Speed for max power (P_{rated}).
3. **Cut-out Wind Speed (v_{cout}):** Max speed before shutdown. For turbines with High Wind Ride Through (HWRT), this is the speed at which power output becomes zero after a gradual ramp-down. HWRT starts derating power at $v_{HWRTstart}$. Model:

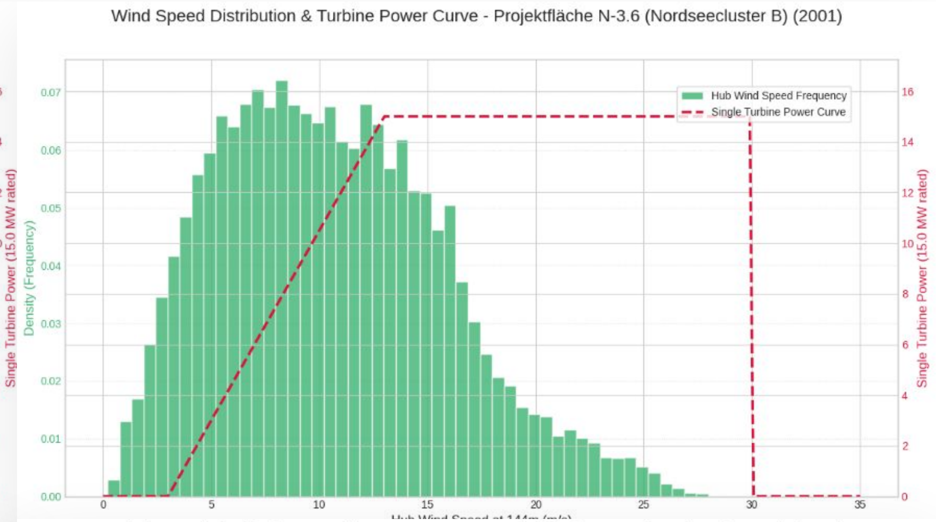
- If $v < v_{cin}$: $P = 0$
- If $v_{cin} \leq v < v_{rated}$: $P = P_{rated} \times \frac{v - v_{cin}}{v_{rated} - v_{cin}}$ (Ramp-up)
- If HWRT is NOT enabled:
  - If $v_{rated} \leq v < v_{cout}$: $P = P_{rated}$ (Rated Power)
  - If $v \geq v_{cout}$: $P = 0$ (Cut-out)
- If HWRT IS enabled:
  - If $v_{rated} \leq v < v_{HWRTstart}$: $P = P_{rated}$ (Rated Power)
  - If $v_{HWRTstart} \leq v < v_{cout}$: $P = P_{rated} \times \left(1 - \frac{v - v_{HWRTstart}}{v_{cout} - v_{HWRTstart}}\right)$ (HWRT Ramp-down)
  - If $v \geq v_{cout}$: $P = 0$ (Final Cut-out)

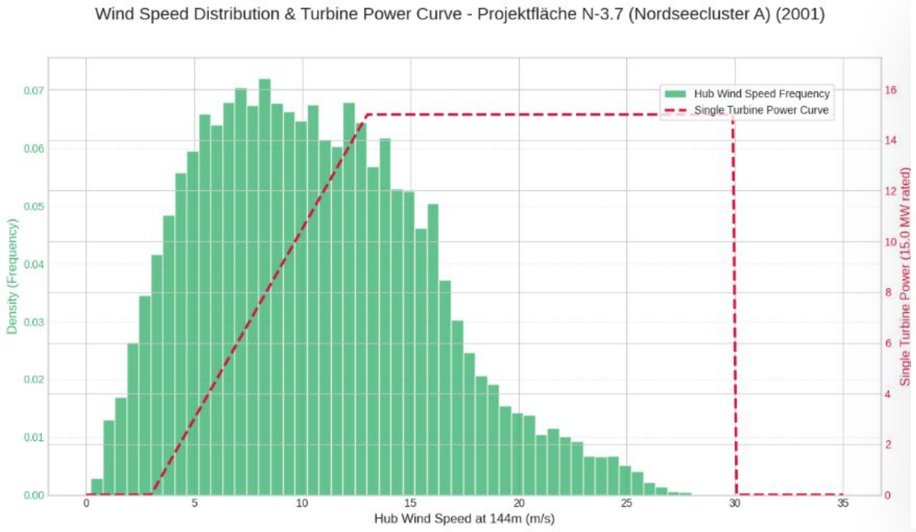
Unused Wind Turbine Potential for CVOW

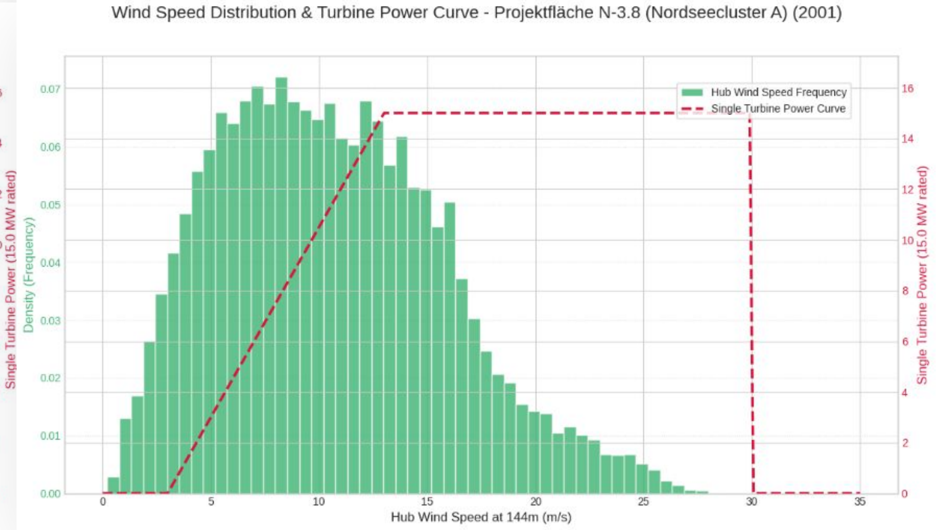


Wind Speed Distributions – Nordseecluster





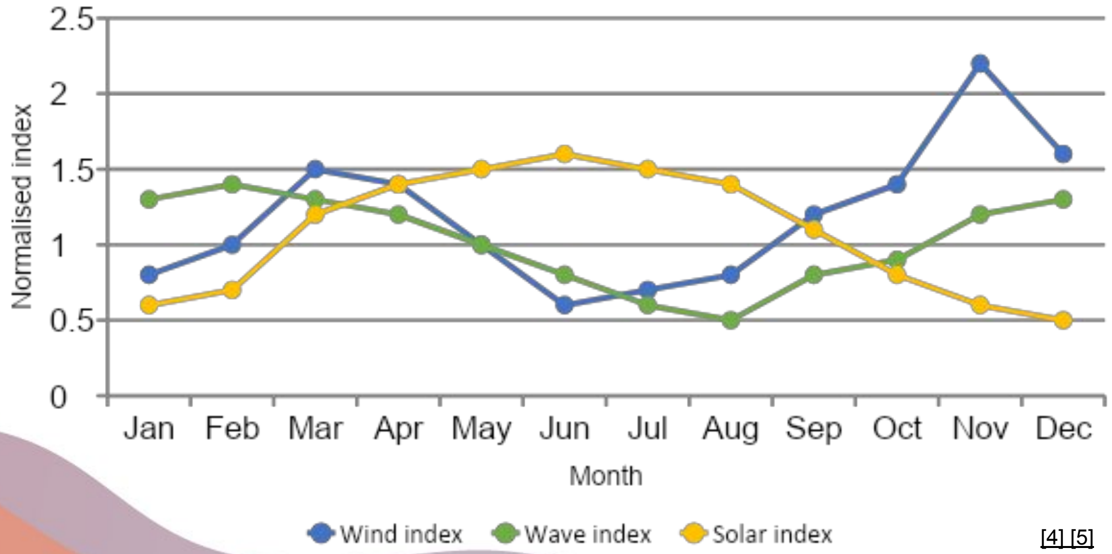




Hybrid Offshore Energy & Complementarity

Why combine wind, wave & solar?

- Wind provides the largest resource but is highly variable
- Solar peaks in summer and complements winter wind
- Wave energy offers continuous power during wind/solar lulls



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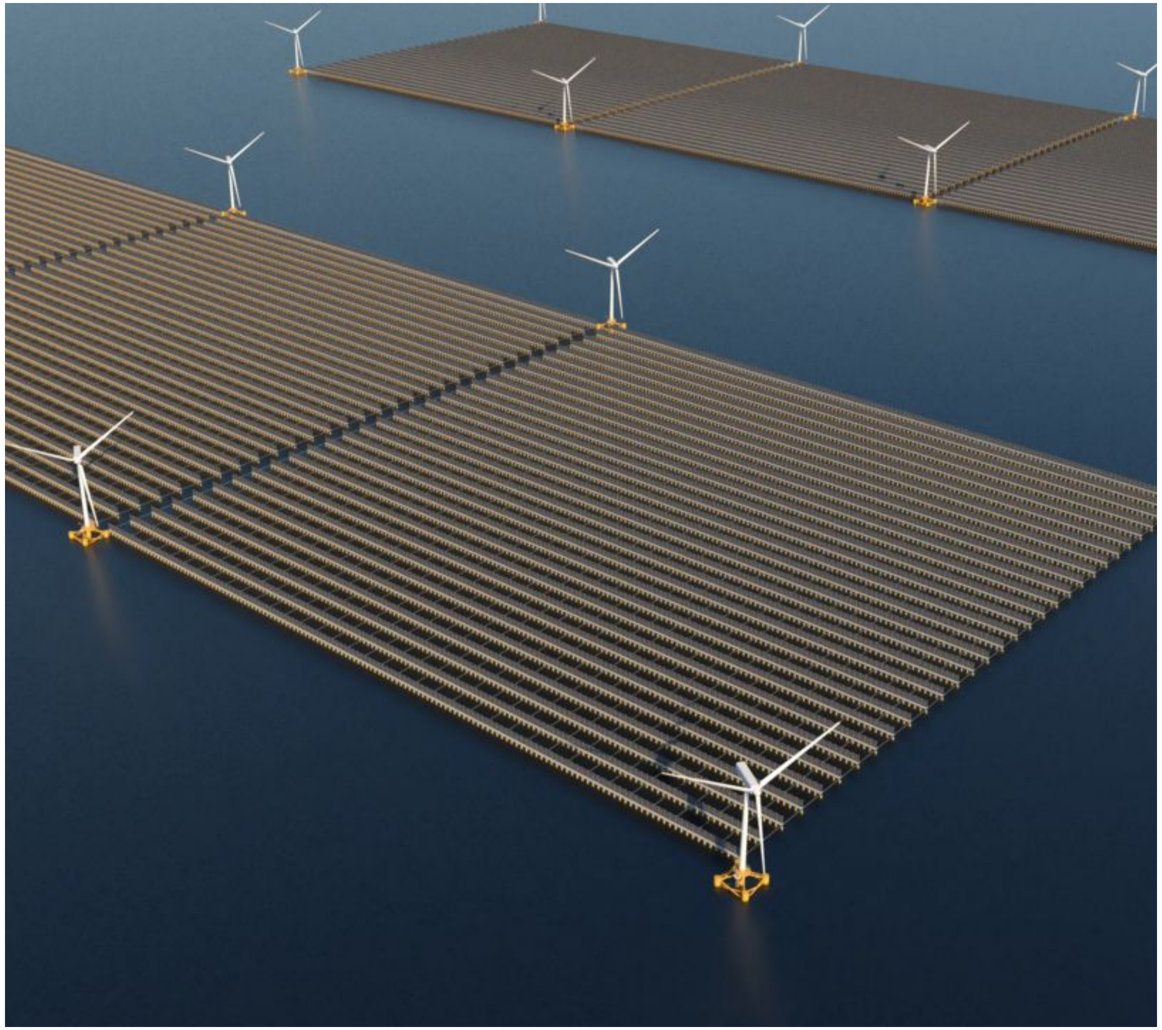
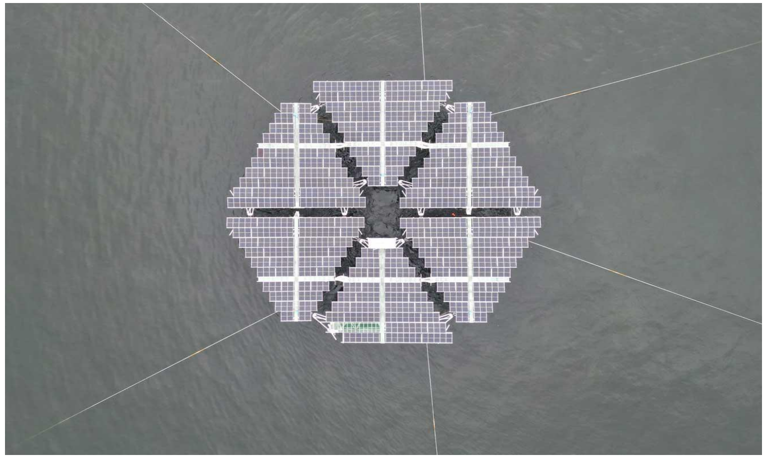
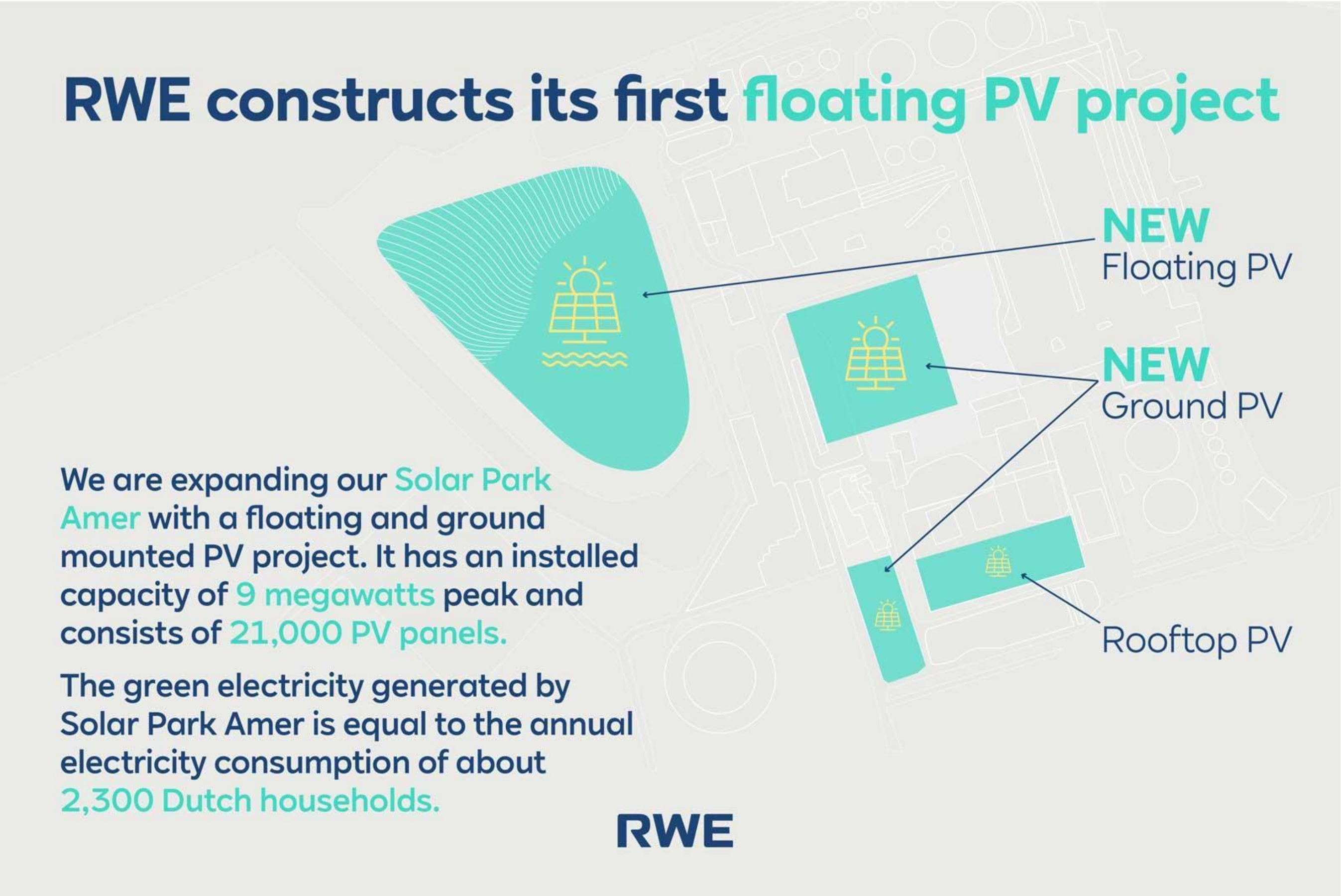





RWE constructs its first floating PV project
NEW
Floating PV
NEW
Ground PV
Rooftop PV
We are expanding our Solar Park Amer with a floating and ground mounted PV project. It has an installed capacity of 9 megawatts peak and consists of 21,000 PV panels.
The green electricity generated by Solar Park Amer is equal to the annual electricity consumption of about 2,300 Dutch households.
RWE

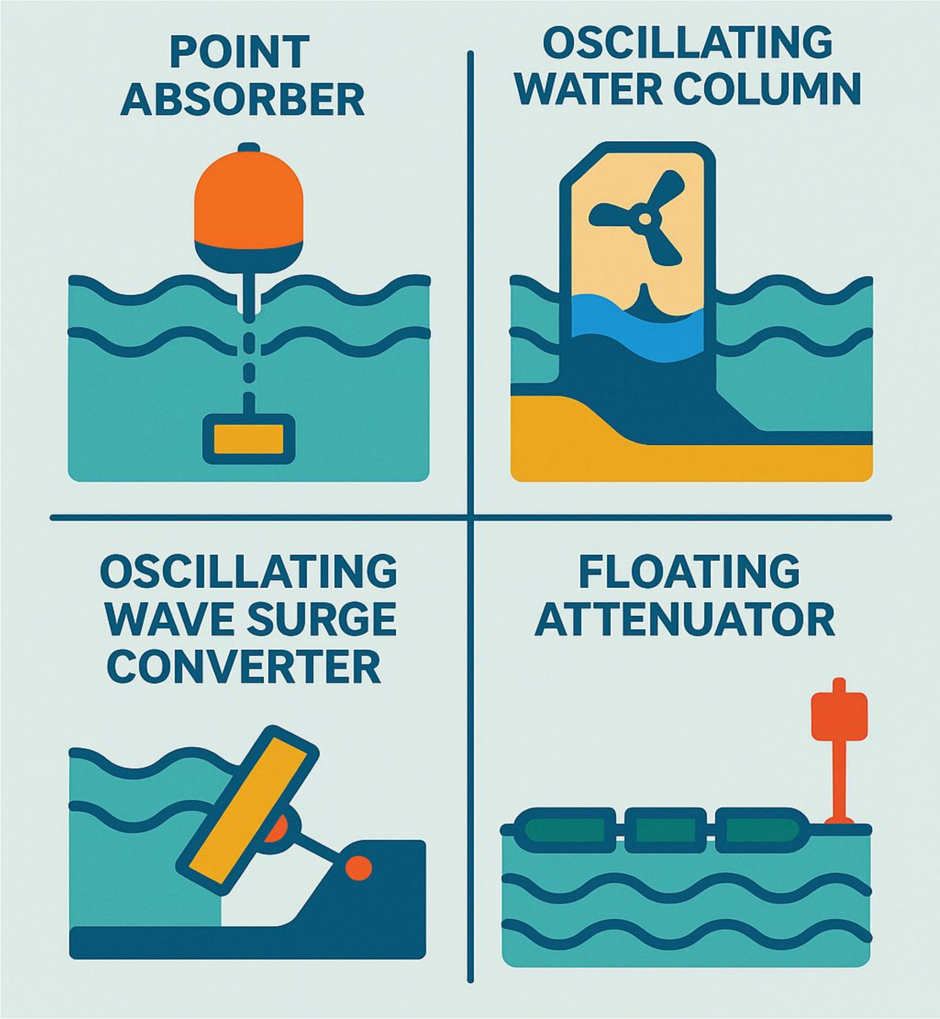
[6] [7] [8]

Wave Energy Converters & Costs

Wave energy converters (WECs) exist but remain costly

- Devices like point absorbers, attenuators and oscillating water columns capture wave motion
- High capital and maintenance costs keep LCOE well above wind and solar

Technology	Typical LCOE ($/MWh)
Offshore Wind	≈ 90
Solar PV	≈ 55
Wave (WEC)	≈ 300



[9] [10] [11]

Takeaways

Key findings

- Forecast models deliver accurate short-term predictions for wind & wave power
- Hex layouts and alternating tower heights yield 3–5 % AEP gains
- Hybrid platforms (wind–wave–solar) minimise variability and maximise output

Outlook

- Extend forecasts to longer horizons & incorporate WEC performance
- Conduct techno-economic and grid-integration assessments for hybrid wind–wave–solar farms
- Study storage solutions, environmental impacts & optimised siting for multi-use platforms

Thank you for your attention.

Questions, remarks?

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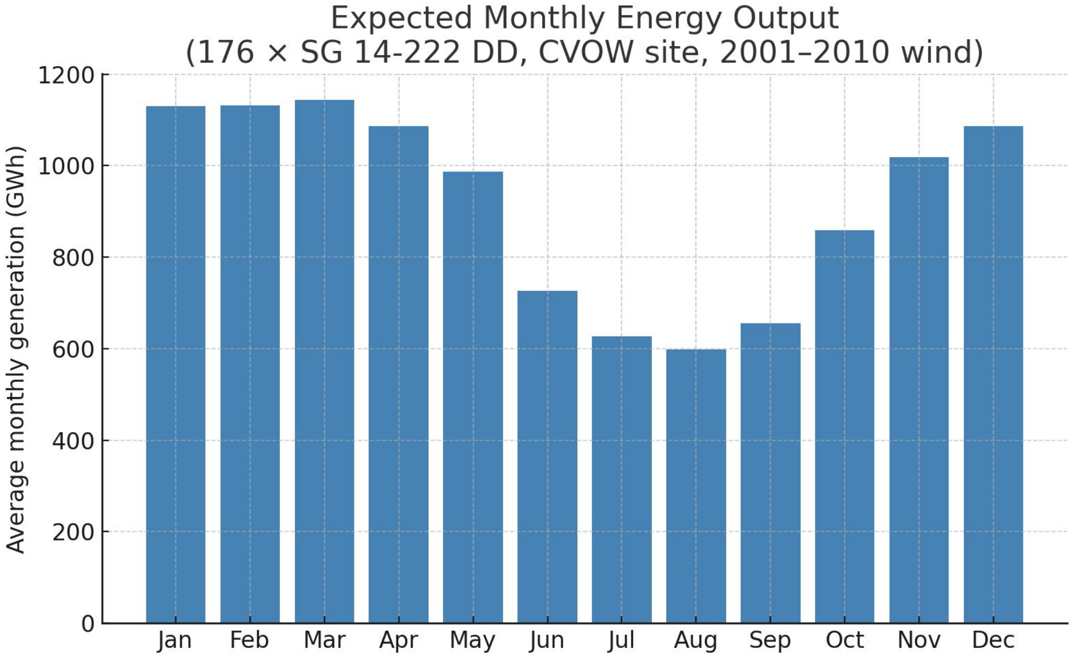
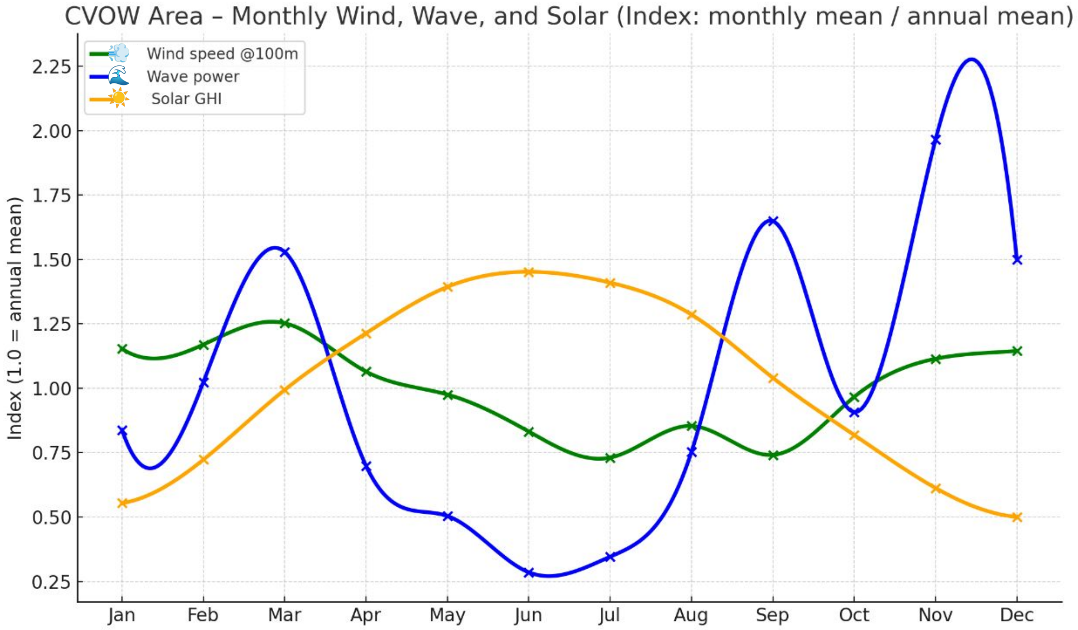
BACKUP

Expected Energy Yield CVOW





Changes in Wind Park Designs