

ERA 5 calibration to Elexon power

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Calibration to power

Updates

New

- Curtailment data to obtain potential generation
- Outage data to exclude periods where capacity is constrained
- Updated power curve comparison to data
- ERA 5 wind speed conversion to power

Next steps

- Learn power curve from data
- Benchmark models: Quantile mapping, GAMs
- Calibration spatiotemporal model

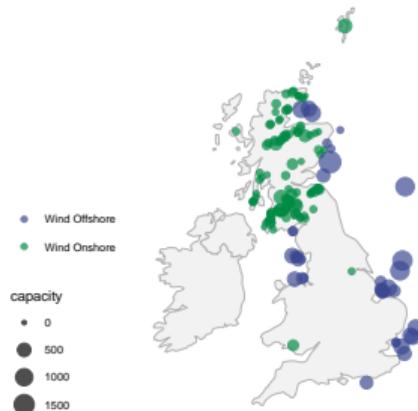
ERA5 vs Elexon generation

Calibrate a ERA5 driven estimate to **potential generation** accounting for spatiotemporal properties.

ERA5 at wind farms



Elexon wind farms map (2025)



Closest grid point to each wind farm location

Overview

Data sources

Wind speed

- ERA5 at wind farms
 - Hourly data
 - Spatial resolution $0.25^\circ \times 0.25^\circ$
 - 10m and 100m heights

Wind power

- Elexon BMU data (since 2019)
 - Half hourly data
 - Generation, curtailment, potential, capacity
 - Outage data (REMIT)
- REPD database
 - Location, turbine height, capacity

Overview

1. ERA 5 to wind farm

Vertical interpolation to turbine height h .

$$w(h) = w_{100} \left(\frac{h}{100} \right)^{\alpha}, \text{ where } \alpha = 1/7$$

2. Wind speed to power

Generic power curves rescaled to wind farm capacity.

$$\hat{PC}_i(w) = PC_i(w) \times \frac{C_i}{\text{Rated power}},$$

where C_i is the capacity at location i

Overview of power conversion

3. Potential generation

Curtailment and outages are two main events that impact observed generation o_{it}

- Curtailment is added giving rise to potential generation:

$$p_{it} = o_{it} + \text{curt}_{it}$$

- Outage data shows additional limits on capacity
- Currently outage periods are excluded

Calibration

4. Calibration

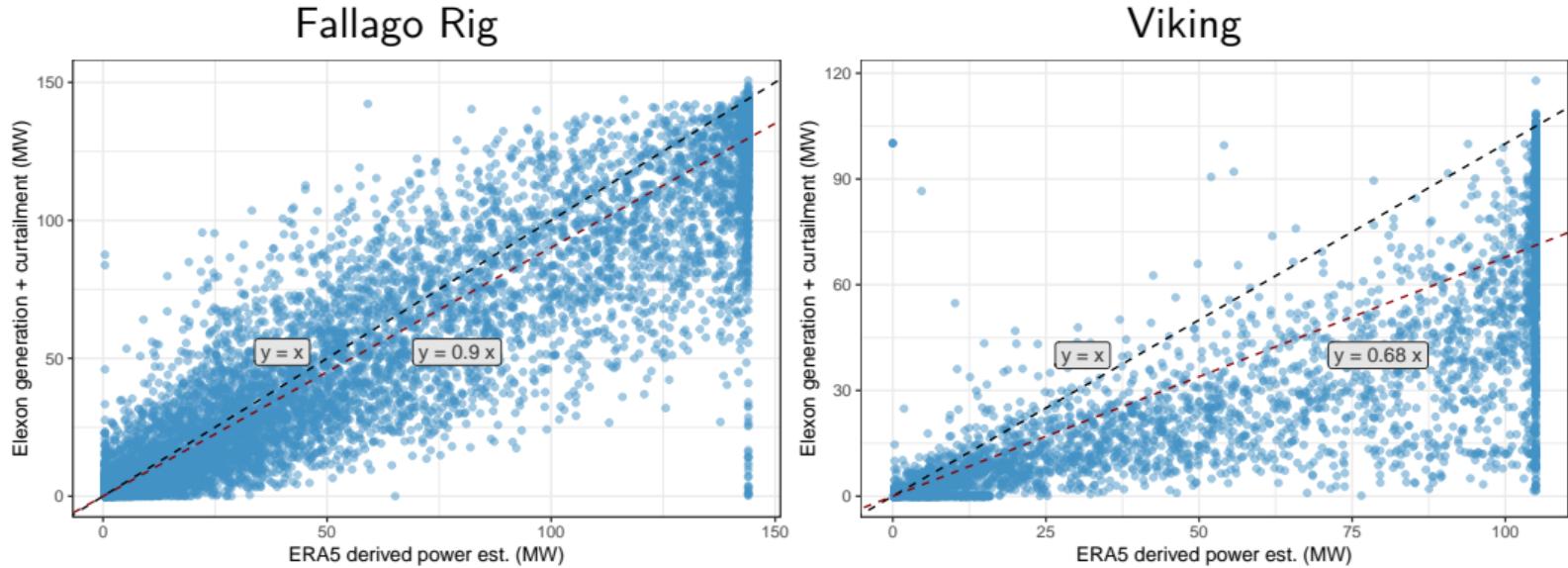
ERA5-derived power estimate \hat{p}_{it} is compared versus potential power p_{it}

$$\begin{aligned}\hat{p}_{it} &= \hat{P}C_i(w_{it}) \\ p_{it} &= \beta_0 + \beta\hat{p}_{it} + s_i + u_t,\end{aligned}$$

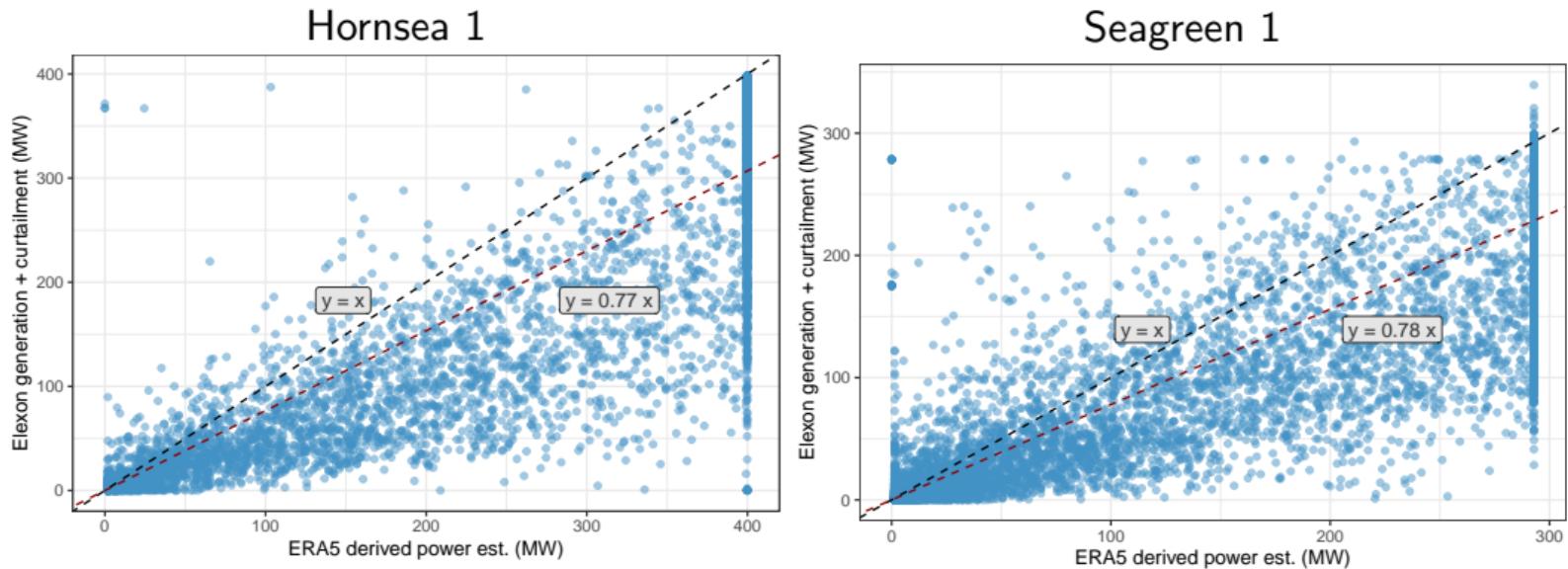
where s_i and u_t represent spatial and temporal effects.

Calibration with linear model

ERA5 based estimates vs Elexon 2024

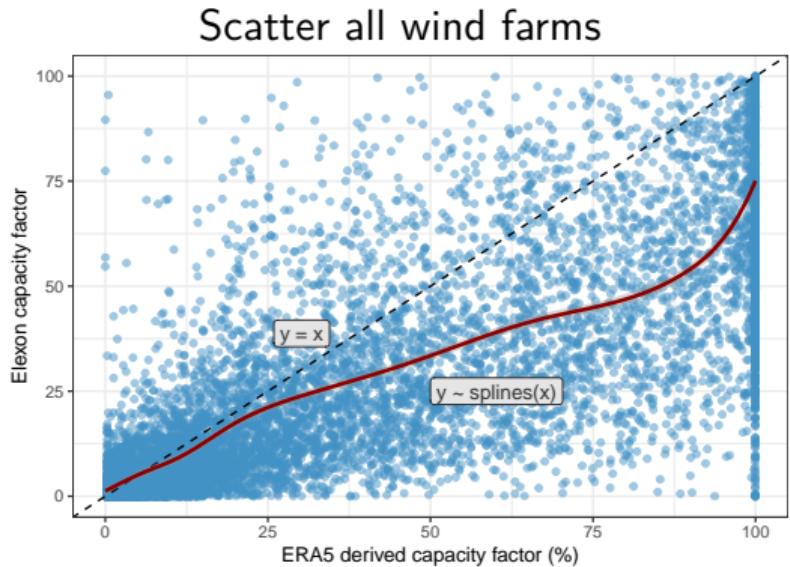


ERA5 based estimates vs Elexon 2024



Comparison for all wind farms

- Working with 2024 data only
- Each point represents one hour and one location
- Showin a sample of points to simplify plotting



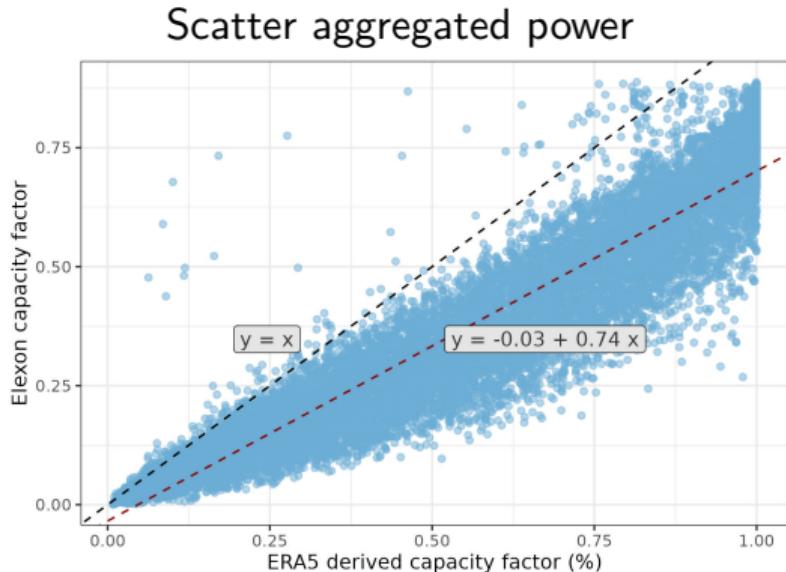
GB level aggregation

GB level aggregation

- Power aggregated at GB level

$$p_{\text{tot},t} = \sum_i p_{it} / \sum_i C_i$$

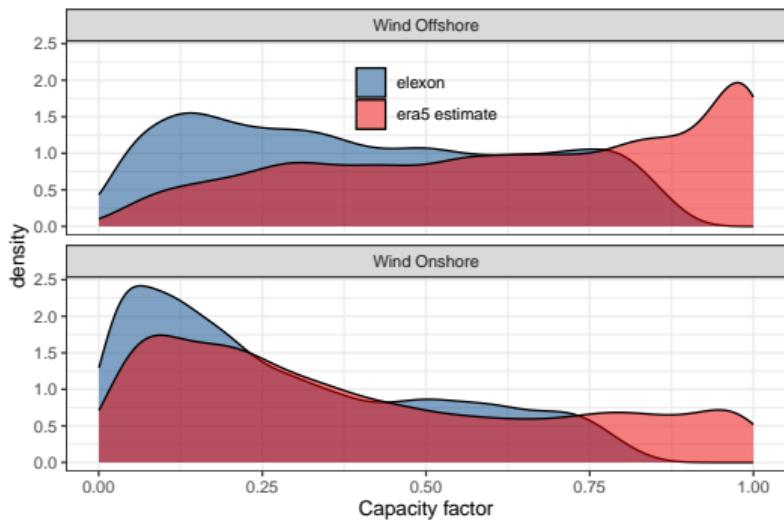
- Each point represents one hour
- Overestimation persists but dispersion is lower now



Density of aggregated power

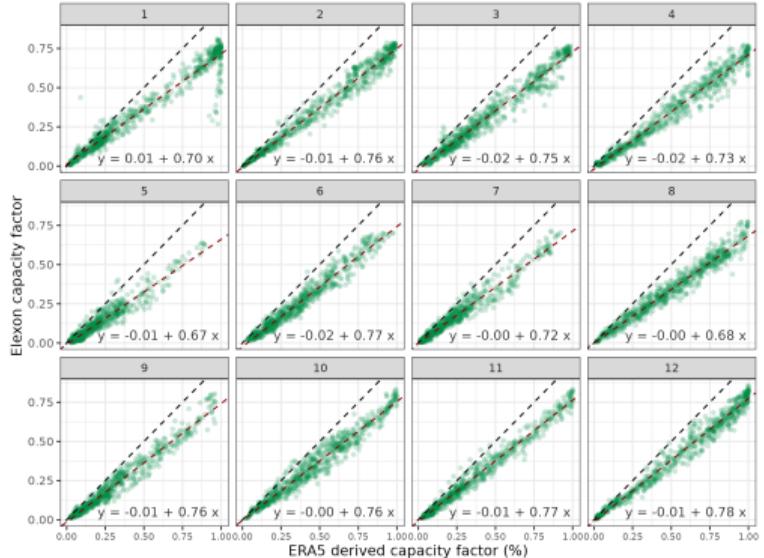
- Cut-off wind speed isn't capture well by generic power curves
- This issue is markedly present in offshore data

Density of Elexon and ERA5 based estimate

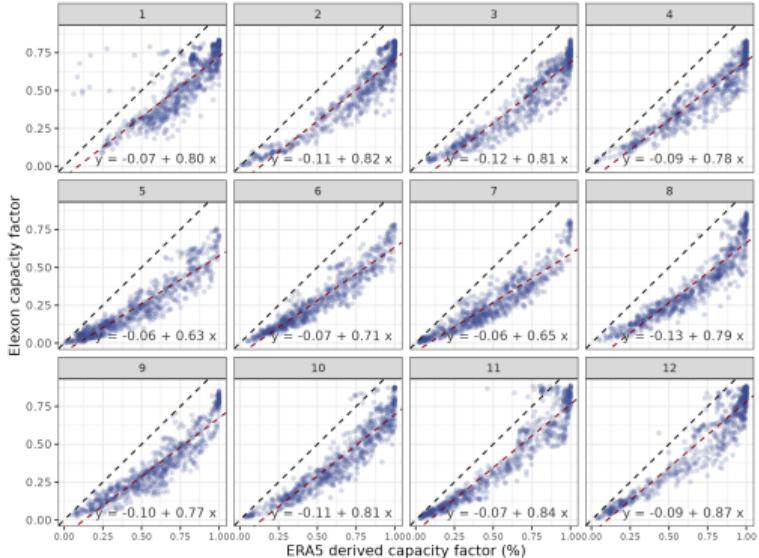


Scatter by season - Offshore

Scatter aggregated power



Scatter aggregated power



Next Steps

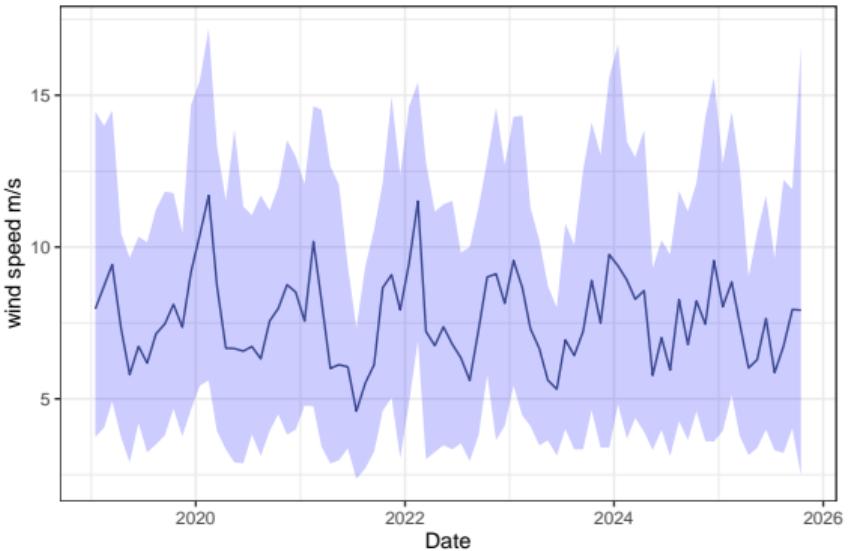
- Learn power curve from history
- Model for calibration
- Quantile mapping calibration

Appendix

ERA5 data

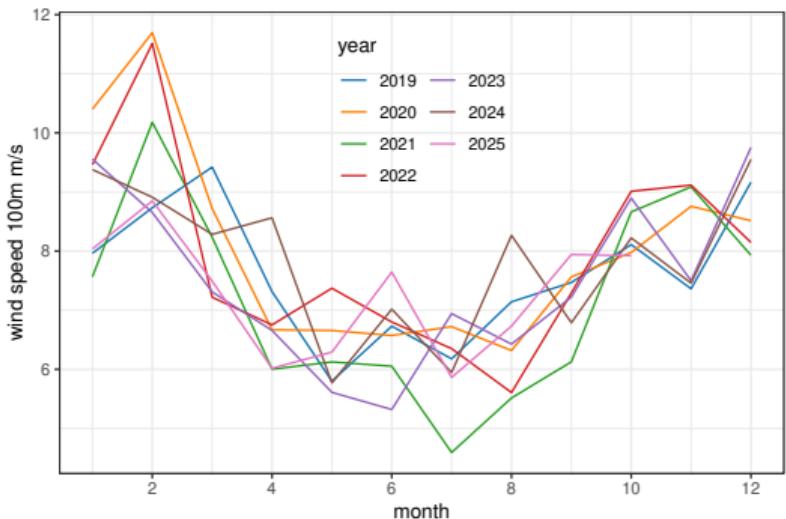
- 5th generation of ECMWF's global reanalysis
- Spatial resolution $0.25^\circ \times 0.25^\circ$ (31km \times 31 km at equator)
- Hourly temporal resolution
- Heights: 10m, 100m

Average monthly wind speed and 90 CI

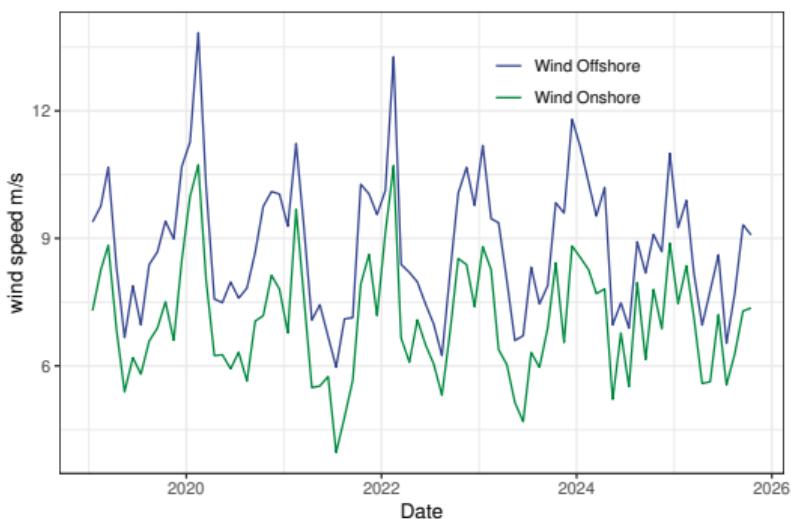


ERA5 series

Wind speed seasonality



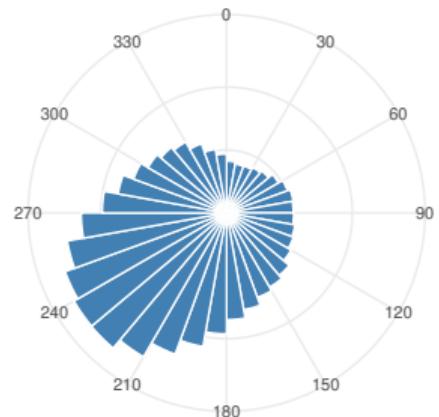
Wind speed by location type



ERA5 wind direction at wind farms

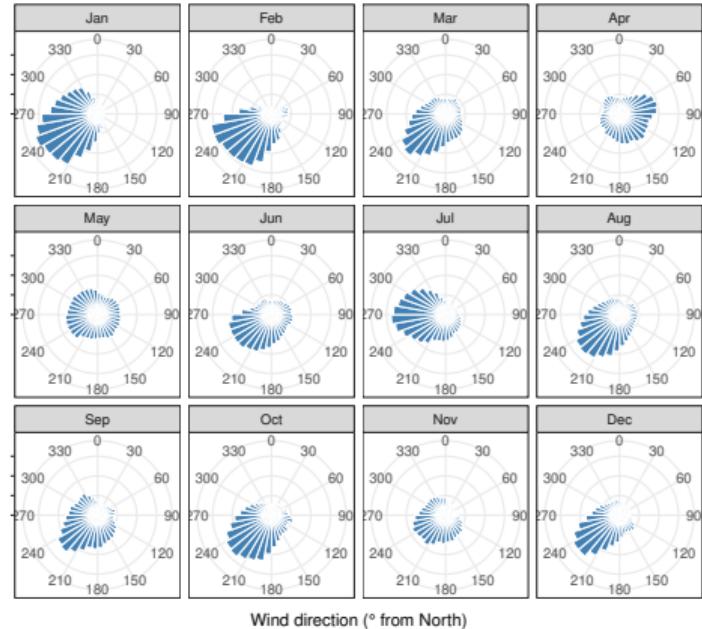
Wind direction frequency

Radial Histogram of Wind Direction (100 m)



Seasonal patterns

Radial Histogram of Wind Direction (100 m)

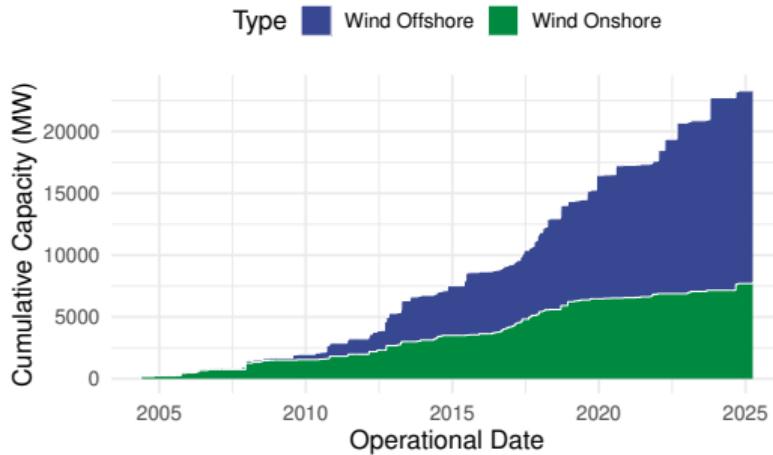


Elexon data

BMU wind data

- 150 wind farms split in over 216 units
- Total capacity: 27 GW
- Half hourly resolution
- Records starting in 2019
- Curtailment and outage data available
- Location / turbine data unavailable

Wind installed capacity

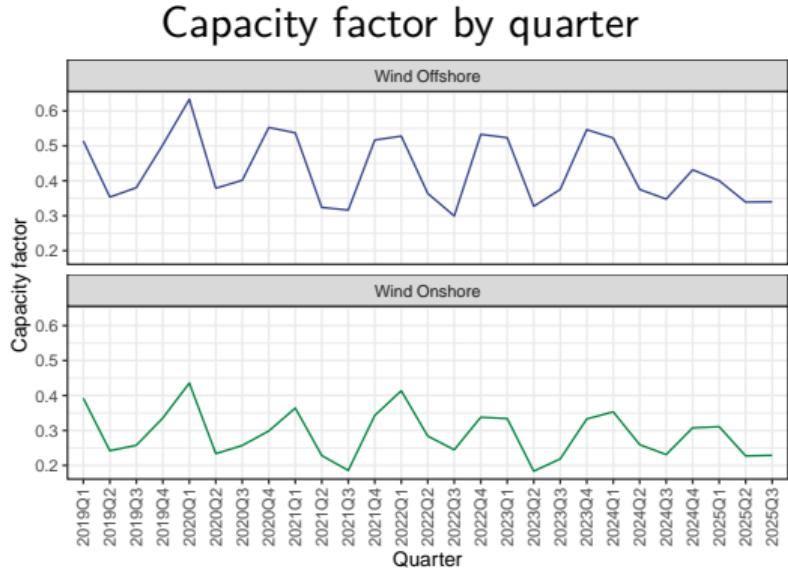
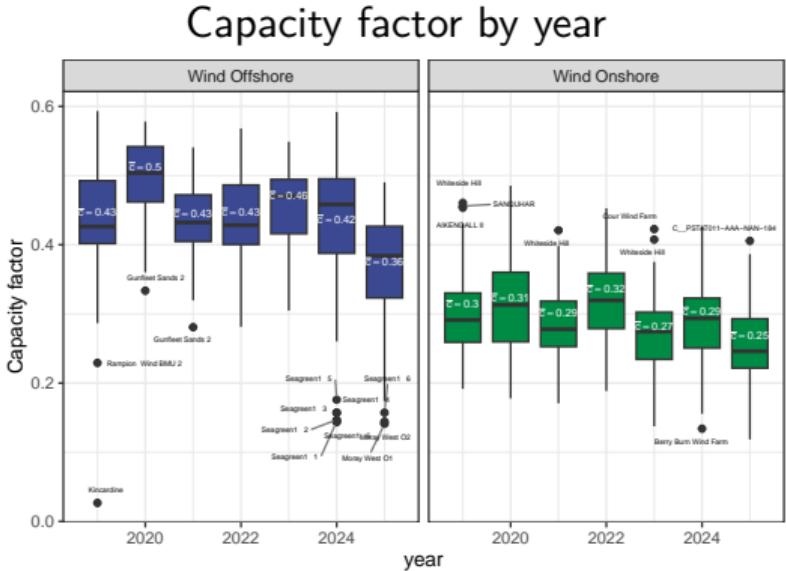


BMU wind data

BMU wind generation (2024)

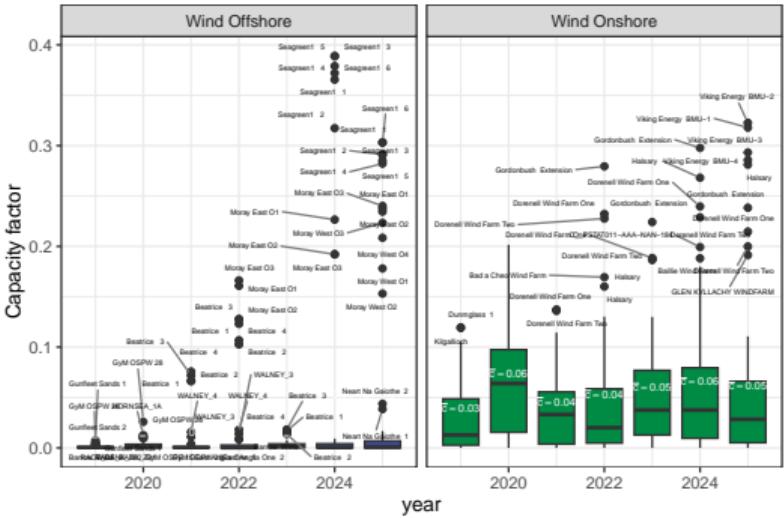
Type	Generation (GWh)	Curtailment	Potential	Capacity (MW)	Number of BMUs	CF	PF
Wind Offshore	46,907	4,902	51,810	15,563	80	0.42	0.47
Wind Onshore	16,254	3,363	19,617	7,860	123	0.29	0.34
Total	63,162	8,266	71,427	23,423	203	0.37	0.42

Capacity factor through time

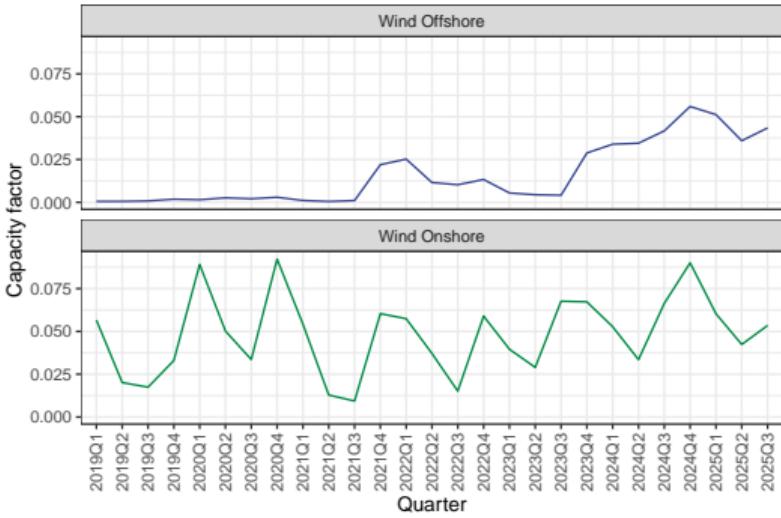


Curtailment through time

Curtailment by year

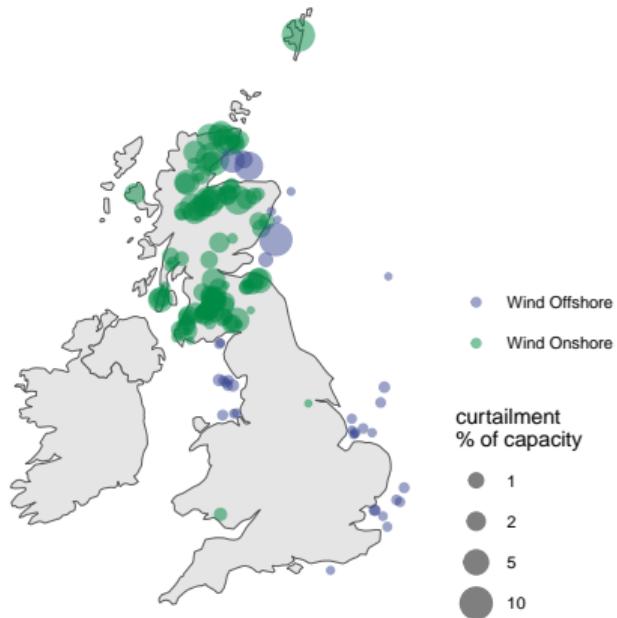


Curtailment seasonality

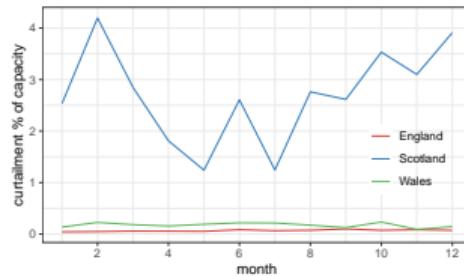


Curtailment

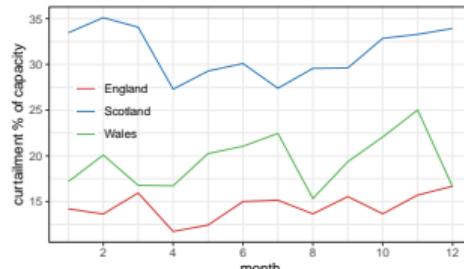
Curtailment map



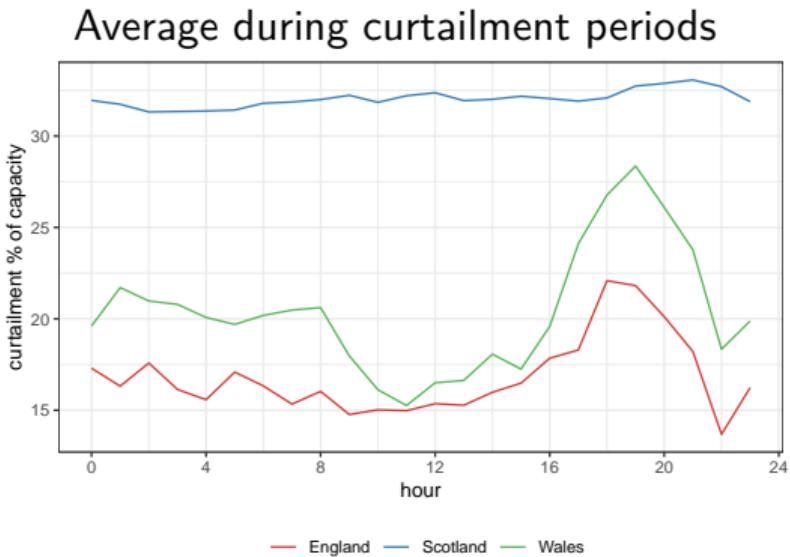
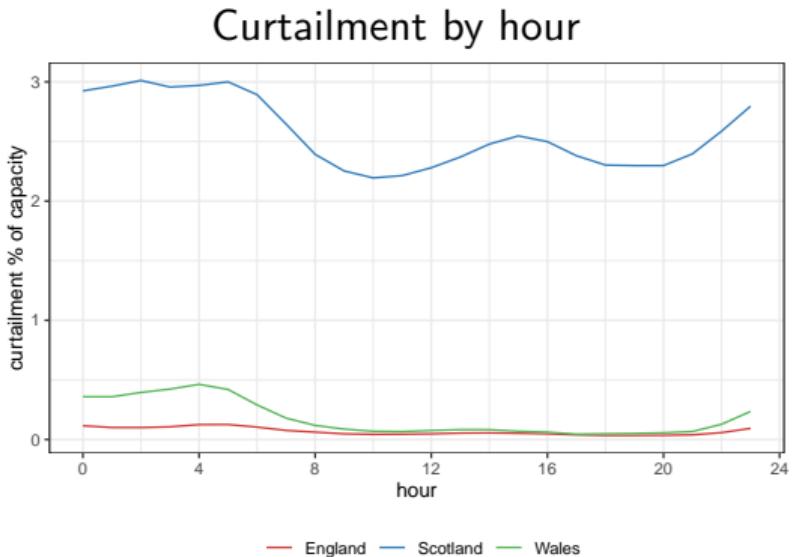
Curtailment by region



Average during curtailment periods

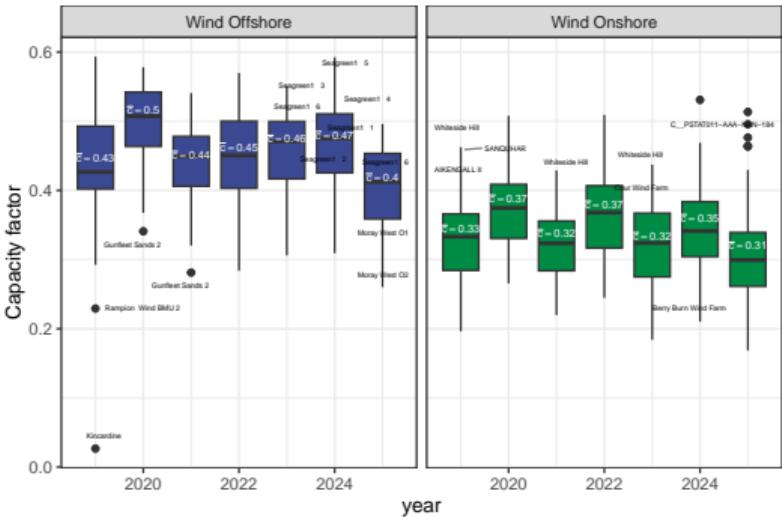


Curtailment through the day

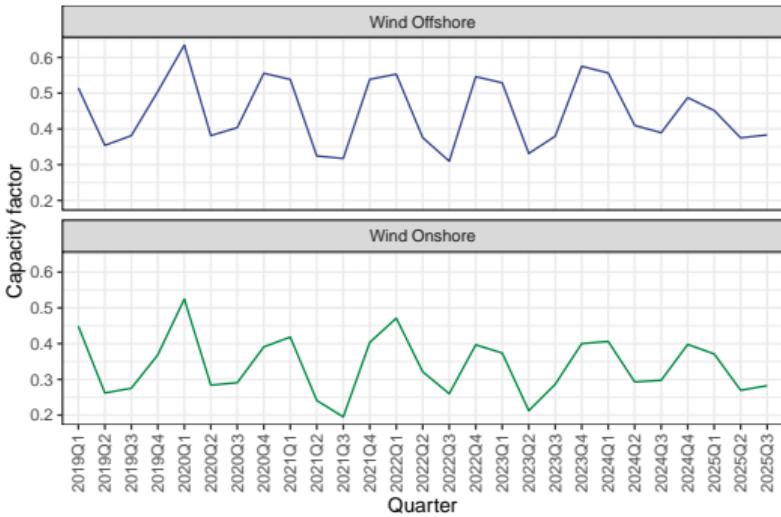


Potential generation

Potential by year



Potential seasonality



Renewable energy planning database (REPD)

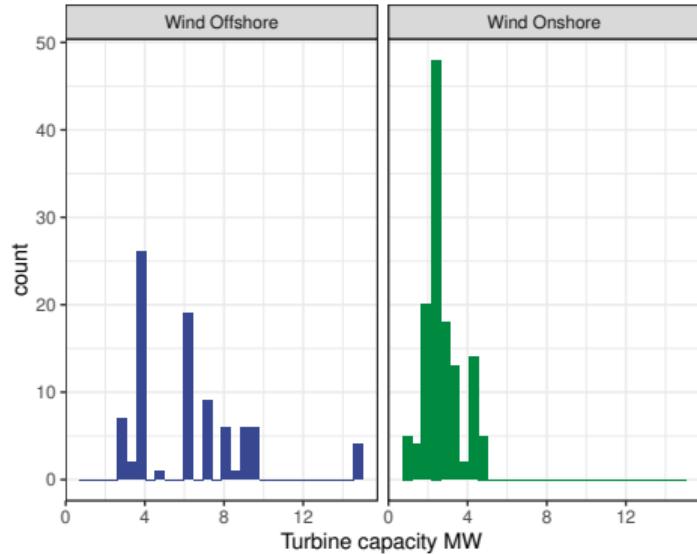
- Official UK government renewable data
- Over 800 wind farms listed as operational
- Coordinates available
- Also available:
 - Development status
 - Number of turbines
 - Turbine capacity
 - Turbine height (for some only)

REPD wind farms

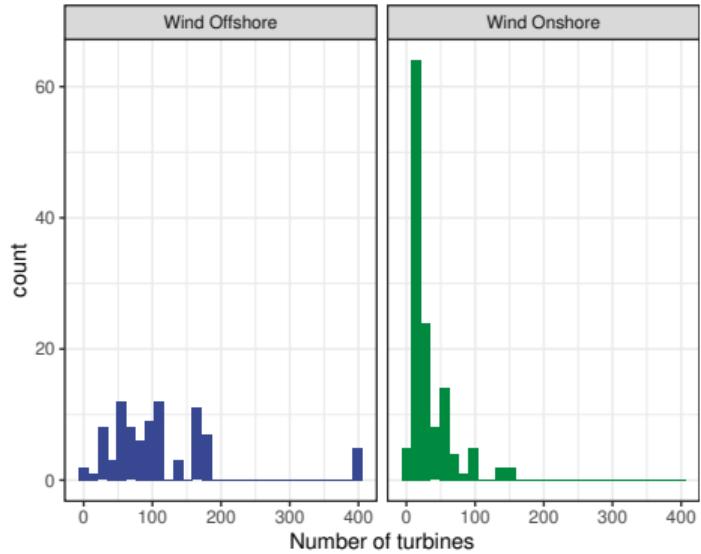
Type	Development Status	Count	Capacity MW
Wind Offshore	Operational	47	14,679
Wind Offshore	Under Construction	7	7,742
Wind Onshore	Operational	770	14,738
Wind Onshore	Under Construction	37	1,779
Total	-	861	38,938

Turbine data available

Turbine capacity histogram



Number of turbines histogram

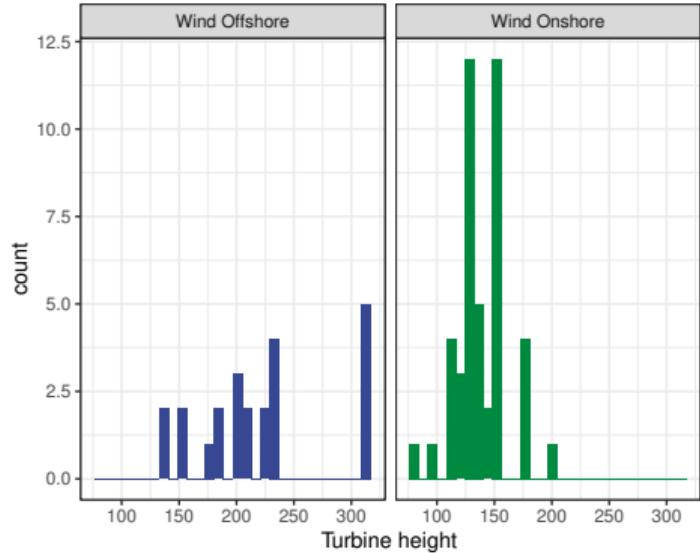


Turbine data available

Turbine Height availability

Type	Height available	Average height (m)	count
Wind Offshore	FALSE	222.0	23
Wind Offshore	TRUE	NaN	64
Wind Onshore	FALSE	137.7	45
Wind Onshore	TRUE	NaN	84

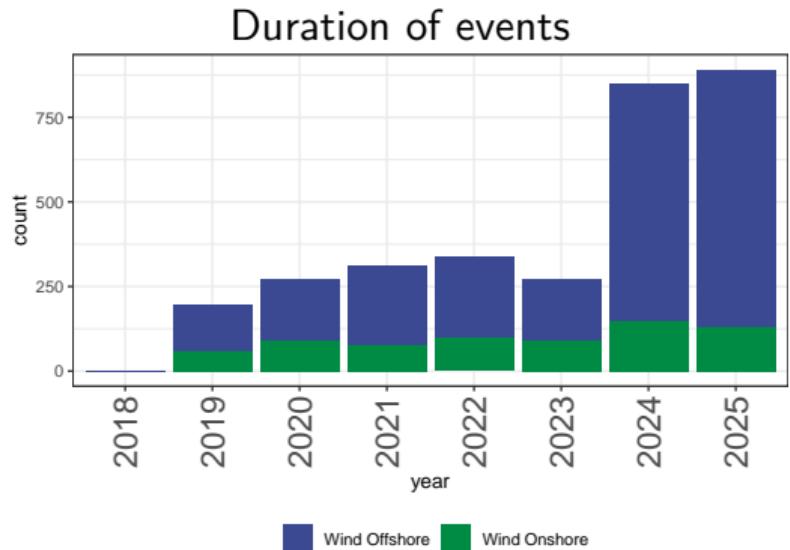
Turbine height histogram



Outages

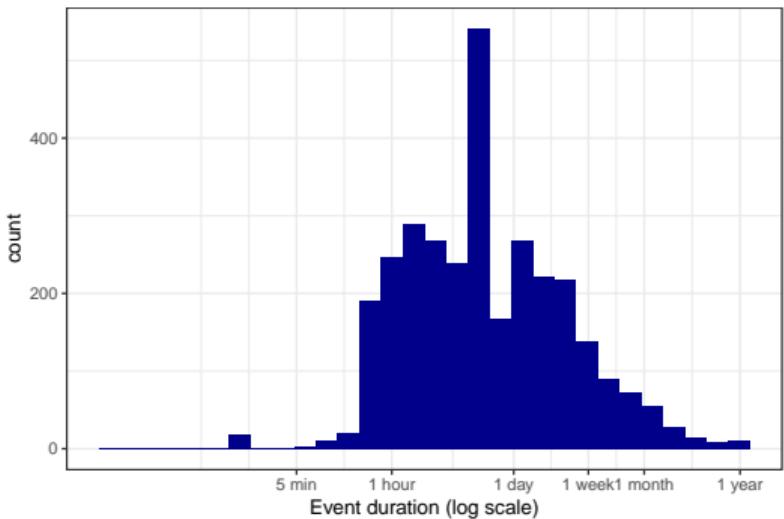
Outage data

- REMIT messages announce plan or unplanned outages
- event start / end times
- affected BMUs and capacity reduction

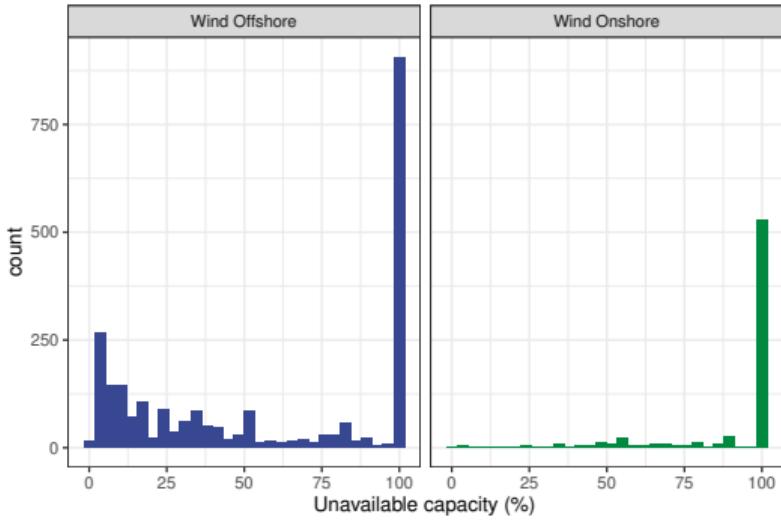


Outage characteristics

Number of events by year



Duration of events

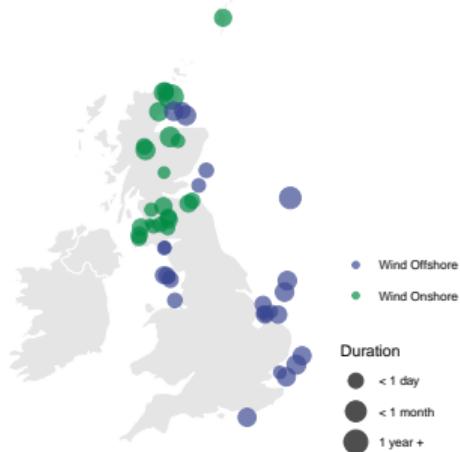


Outages characteristics by location

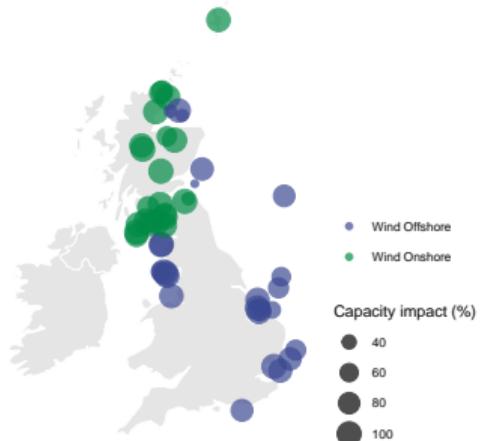
No. of events



Mean duration



Unavailable capacity



Power conversion

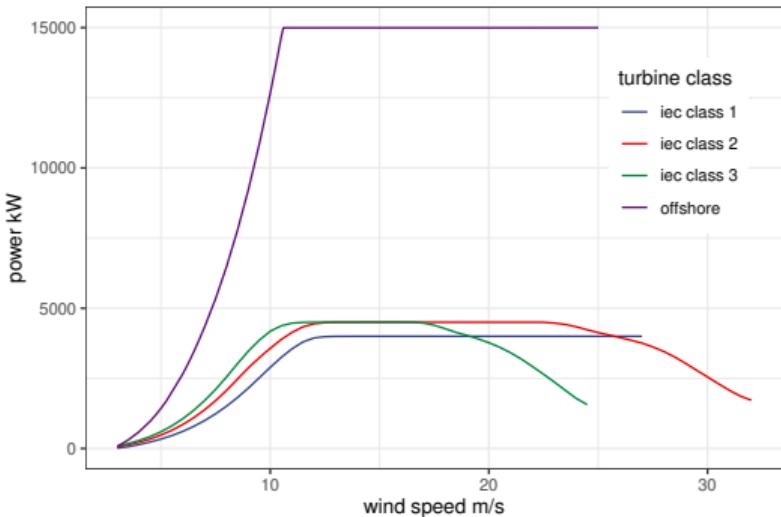
Generic power curves

- Using 3 generic power curves
- Offshore plus the IEC 3 classes
- Assigning class based on GWA mean wind speed at location
- Rescaling rated power to turbine capacity

IEC classification

Class	Mean wind speed at hub height (m/s)	Extreme 10-min gust (m/s)	Typical sites
I	10	70	Very windy / exposed sites
II	8.5	59.5	Moderate wind sites
III	7.5	52.5	Low-wind / inland sites

Generic power curves (PC_k)



Power estimate based on generic power curves

For each location i we have:

- observed raw power \tilde{p}_{it}
- curtailment amount a_{it}
- potential output $p_{it} = \tilde{p}_{it} + a_{it}$
- wind farm capacity c_i
- turbine height v_i
- ERA5 wind speed w_{it} .

Power estimate based on generic power curves

An initial estimate will require:

- Mapping location to a rescaled power curve \widetilde{PC}_k
- Estimate wind farm power in GWh

$$\hat{p}_{it} = \widetilde{PC}_k(w_{it})$$

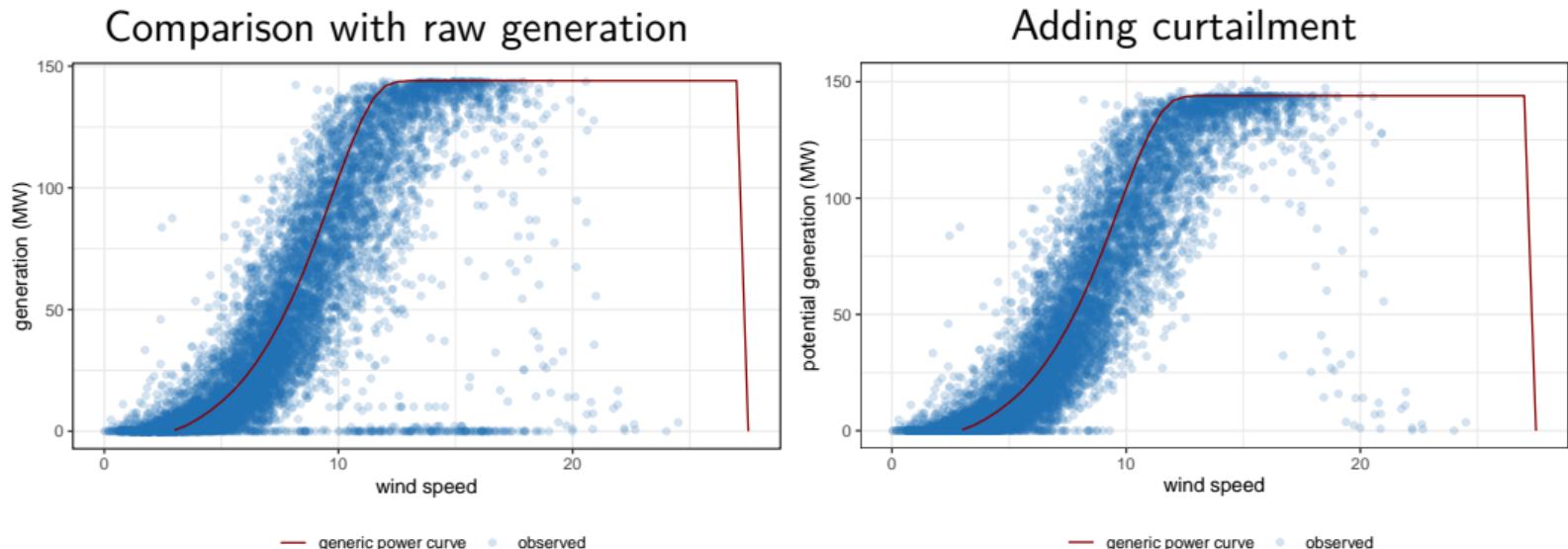
ERA5 based estimates vs Elexon 2024

- 1 Remove periods with outages
 - Modelling loss due to expected outages could be future work
- 2 Vertical interpolation of ERA5 wind speed to turbine height
- 3 Apply generic power curve to get estimated power
 - Modelling power curve from data could be future work

Curtailment and outages in select wind farms

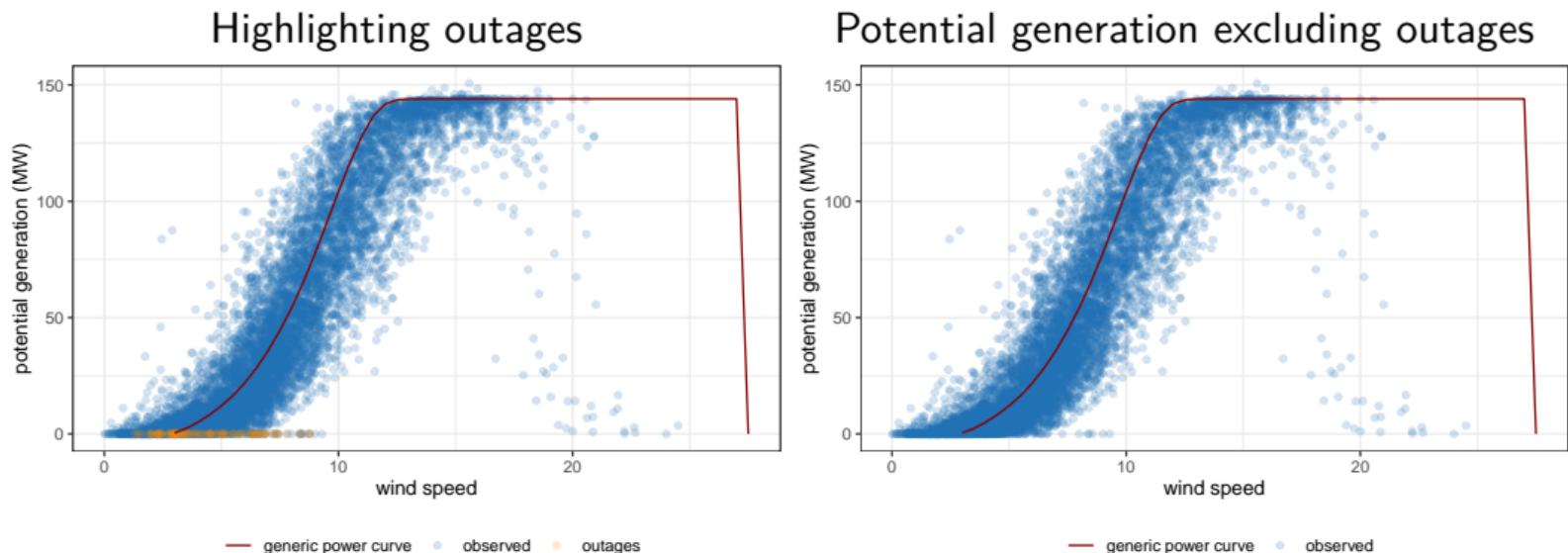
Generic power curves vs observed data - Fallago Rig

Onshore wind farm with moderate curtailment



Generic power curves vs observed data - Fallago Rig

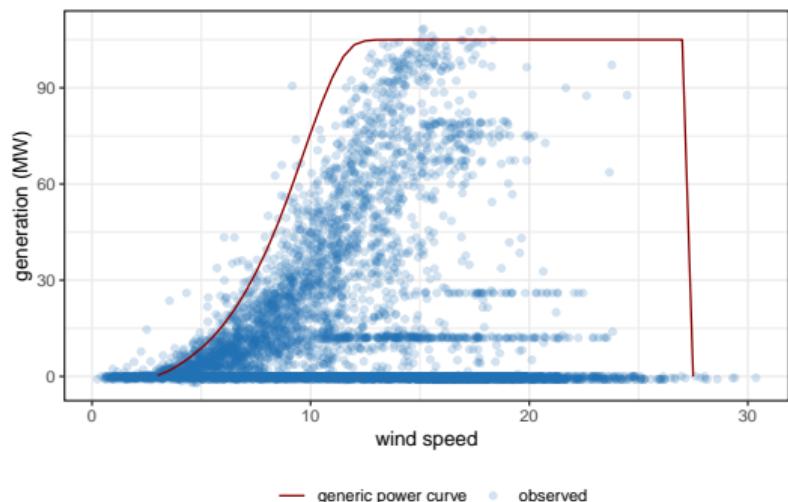
Onshore wind farm with moderate curtailment



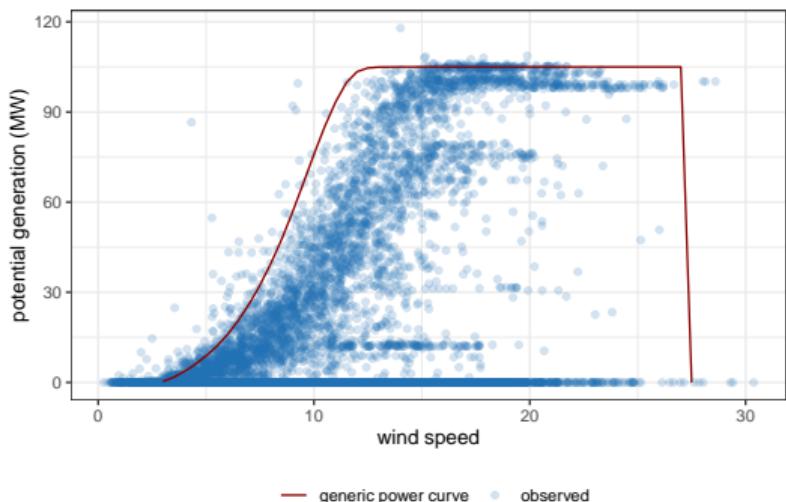
Generic power curves vs observed data - Viking

Onshore wind farm with high curtailment

Comparison with raw generation

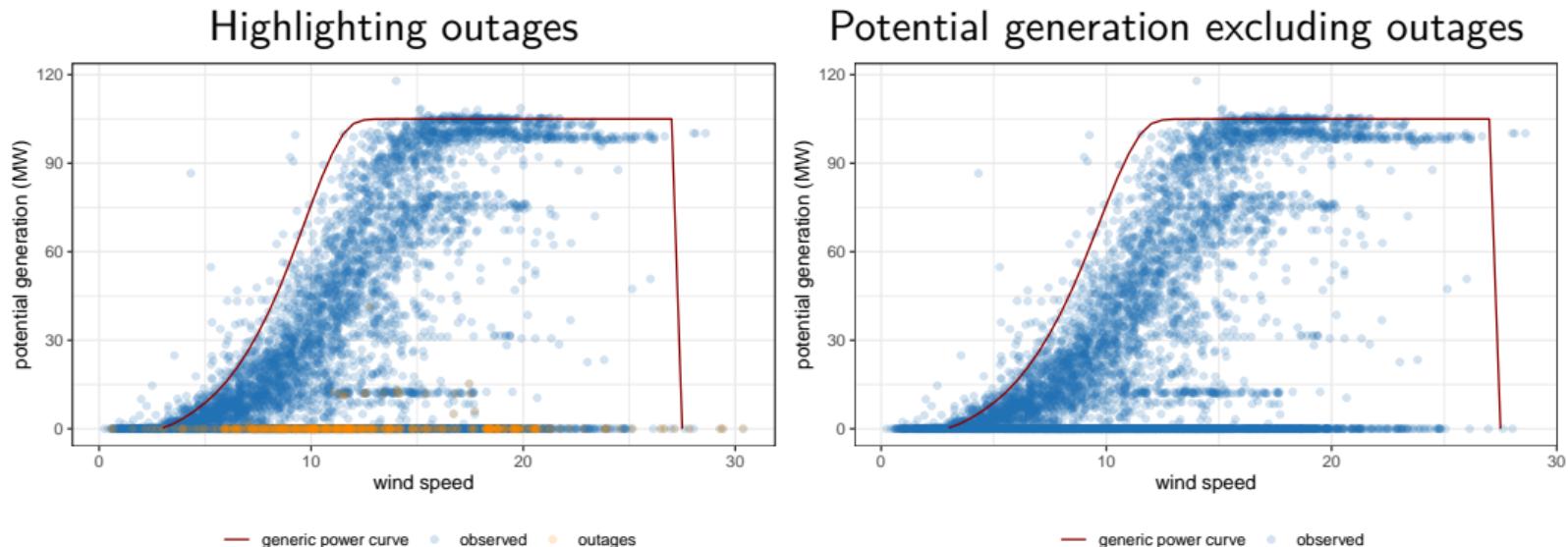


Adding curtailment



Generic power curves vs observed data - Viking

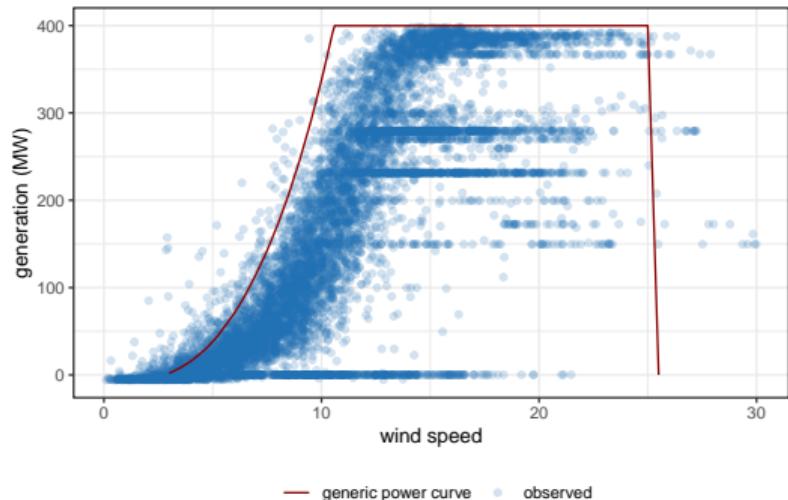
Onshore wind farm with high curtailment



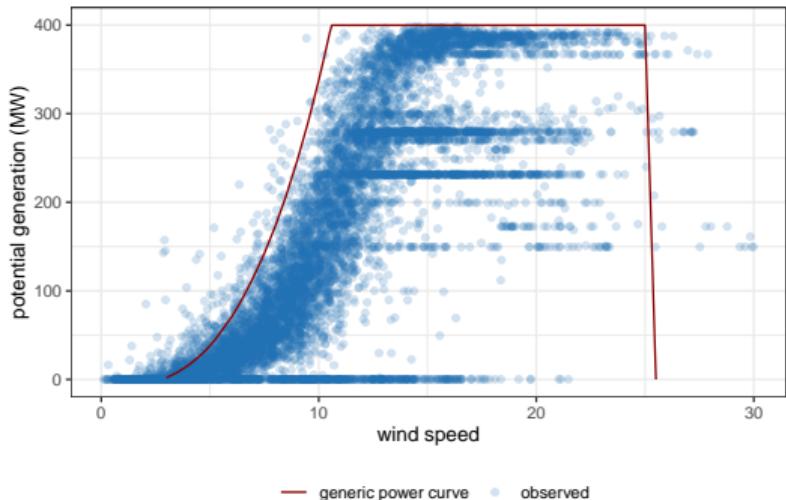
Generic power curves vs observed data - Hornsea 1

Offshore wind farm with low curtailment

Comparison with raw generation

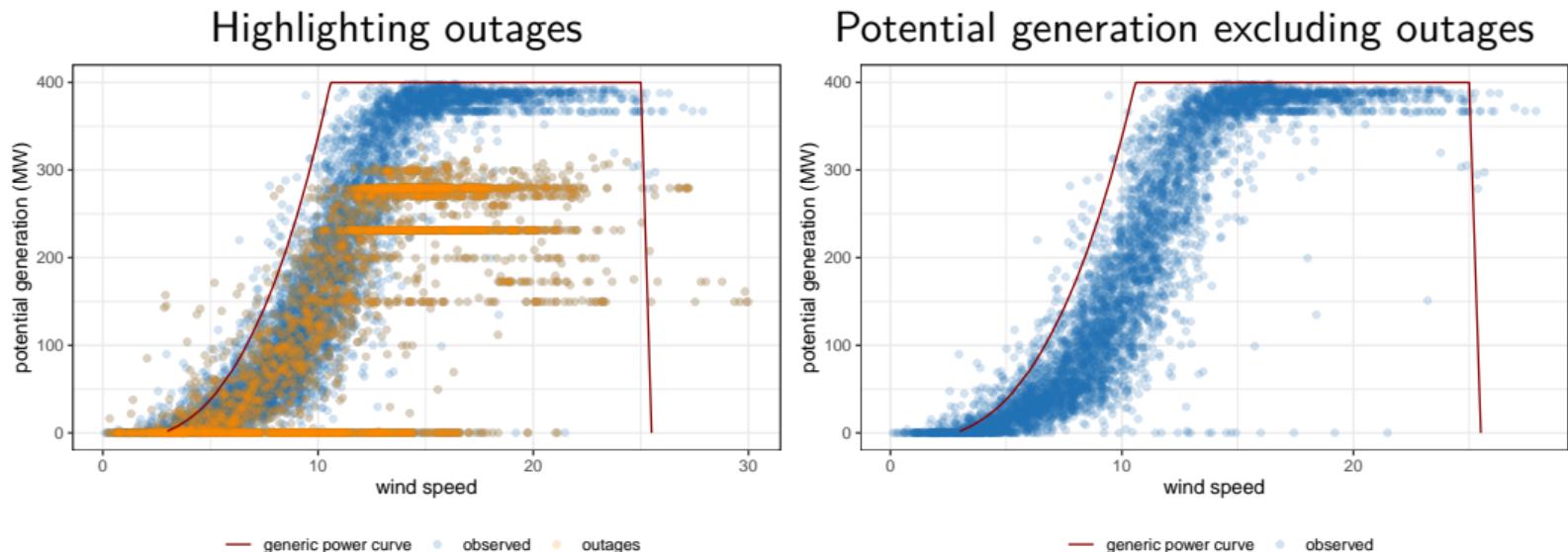


Adding curtailment



Generic power curves vs observed data - Hornsea 1

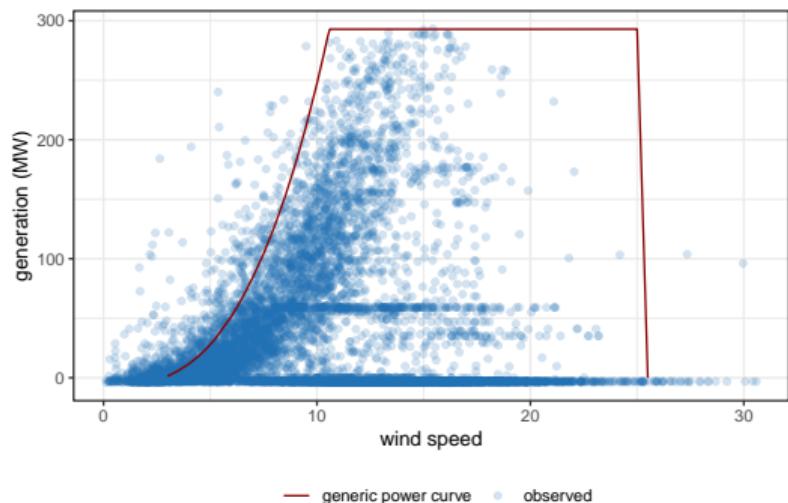
Offshore wind farm with low curtailment



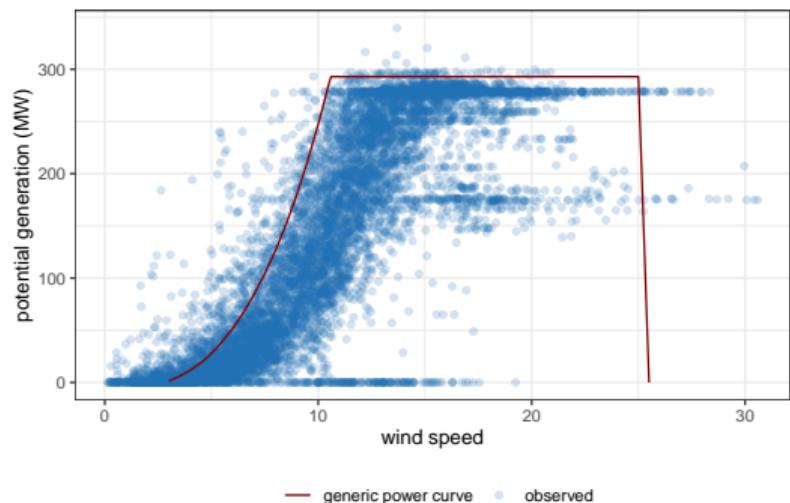
Generic power curves vs observed data - Seagreen 1

Offshore wind farm with high curtailment

Comparison with raw generation



Adding curtailment



Generic power curves vs observed data - Seagreen 1

Offshore wind farm with high curtailment

