A Quantification of Power Fluctuations from Generic Offshore Wind Farms

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Minute-scale power fluctuations — A knowledge gap

Intermittency of wind power is well studied for timescales of days to weeks with hourly resolution. The sub-hour range has received less attention, yet it is becoming increasingly important:

- As the penetration of converter-based power sources increases, reducing inertia and damping in the main electrical grid
- For isolated grids incorporating energy storage systems such as energy islands and wind-powered oil&gas platforms
- For wind power to participate in balancing markets, providing flexibility to the grid

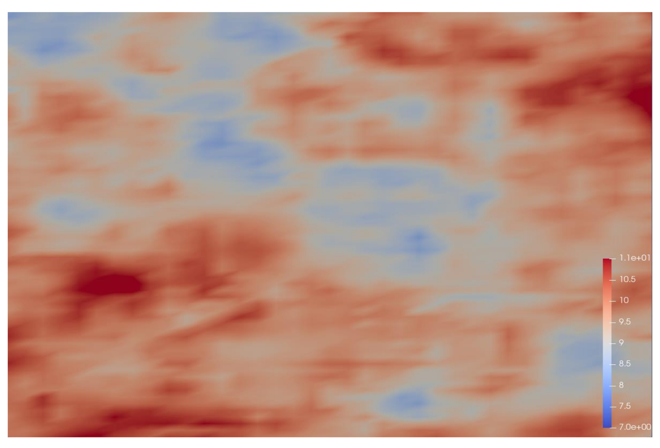
Previous studies in the literature focus on existing wind farms with defined layout, wind conditions and turbine specifications. However, DTU developed a hybrid data-driven and physics-based approach [1] that is extendable to all offshore wind farms in the North Sea. This study aims at using this modelling approach to quantify power fluctuations for generic wind farms as function of farm size, turbine size, capacity density, wind speed and wind direction. This will provide a reference database to electrical engineers with the design of energy storage systems as main application.

Methodology

- State-of-the-art model [2] for farm-wide turbulence based on turbulence aggregation, extensive measurements in Danish wind farms and complex coherence matrix lifting the frozen-turbulence assumption
- Static DWM model for wakes [3]

- 12 farm sizes (1 to 12x12 turbines), 5 turbine sizes, 2 capacity densities, 9 wind speeds, 3 wind directions, 5 stochastic realisations
- → 1880 1h-long, 1s-resolution Monte Carlo simulations

FLAggTurb (SINTEF) [2]

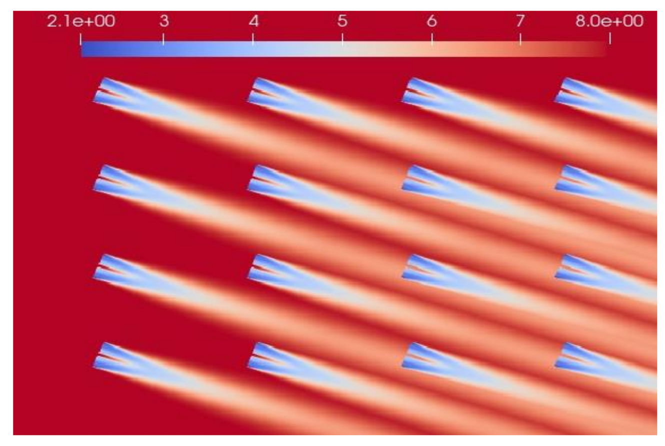


Rotor-averaged wind speed and power for each turbine

$$U = \bar{U} - \Delta_{U_{wake}} + u_{turbulence}$$

$$P = \frac{1}{2}\rho A\, C_P(U)\, U^3$$

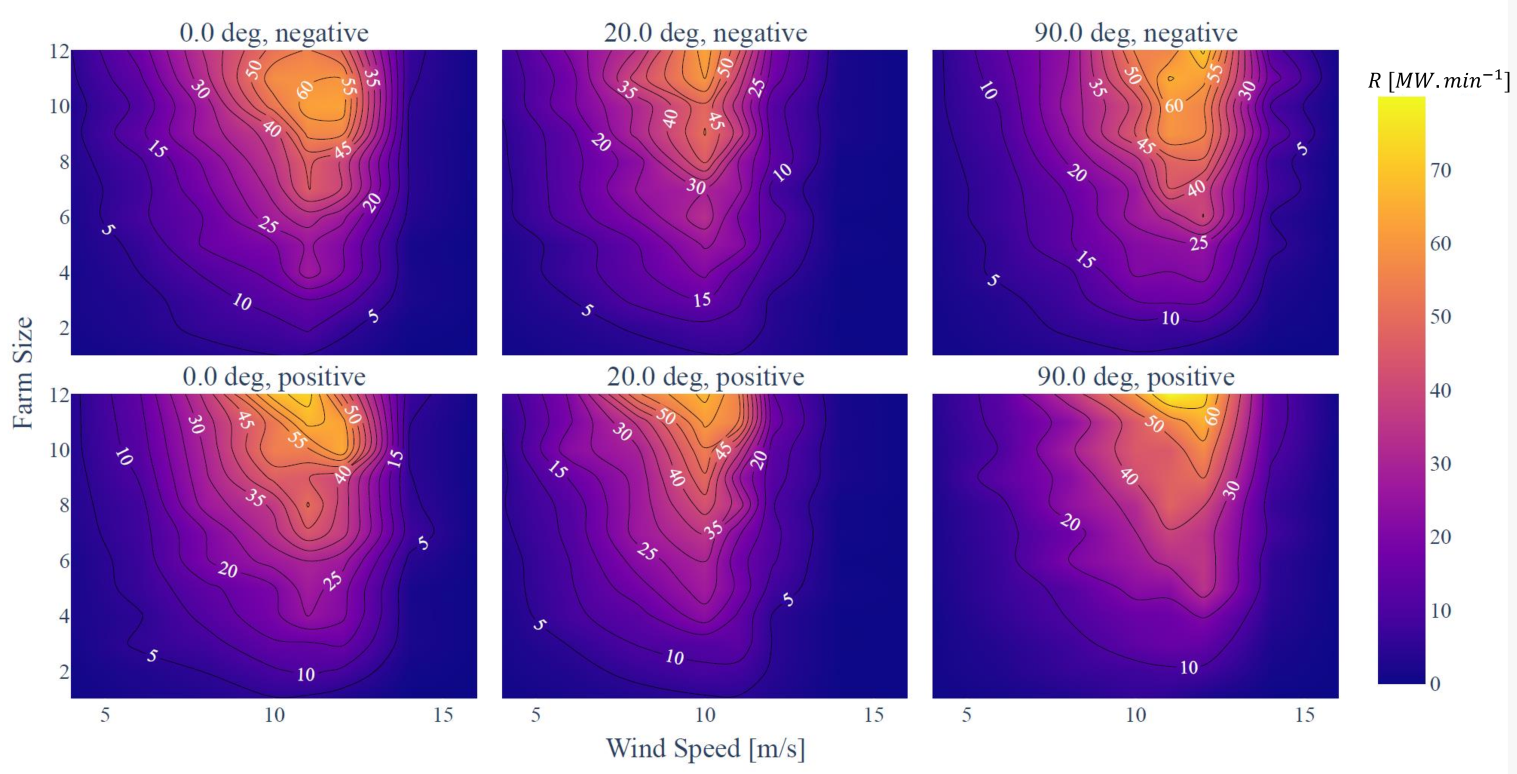
DIWA (SINTEF) [3]



$\frac{d}{dt}$ $\qquad$ $\int_0^t$

Ramp rates

- Ramp rates are power gradient maxima over a time interval. They can be positive (power surplus), or negative (power shortage). They must be compensated by other production sources or load flexibility to keep power flow in balance else risking frequency deviations.

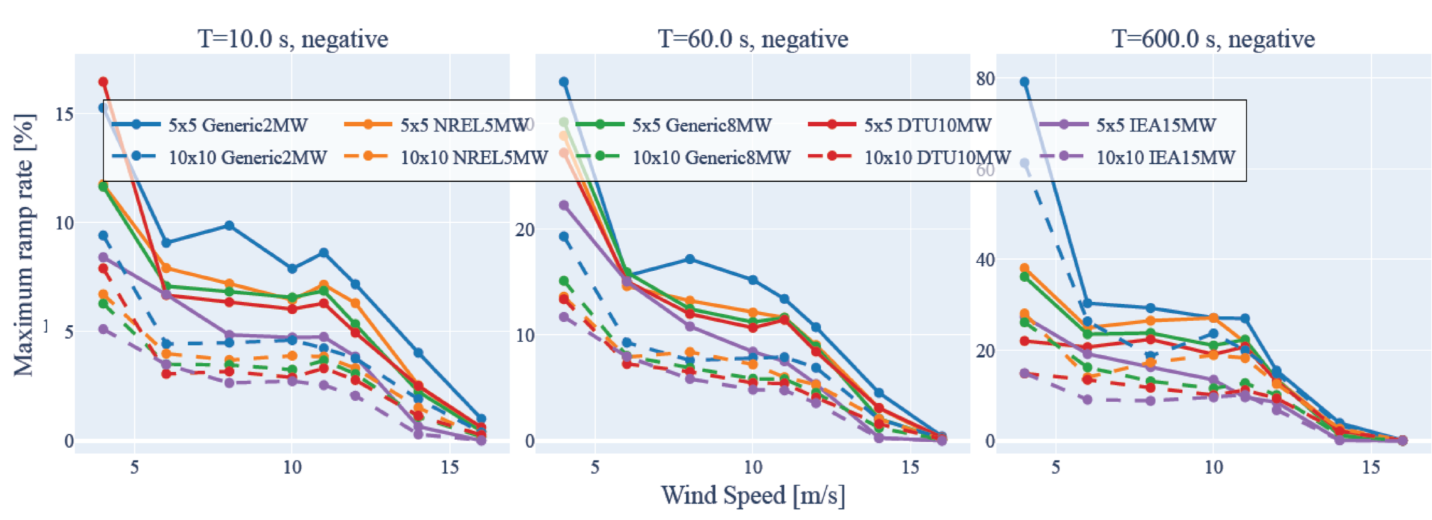


- Largest ramp rates occur around rated wind speed, where wind fluctuations are largest before turbine control stabilises power through blade pitching.
- For large wind farms (≈100 turbines), cancellation effects between turbines prevail over increasing installed capacity and ramp rates show a peak.

10 seconds	1 minute	10 minutes
40 MW	70 MW	250 MW

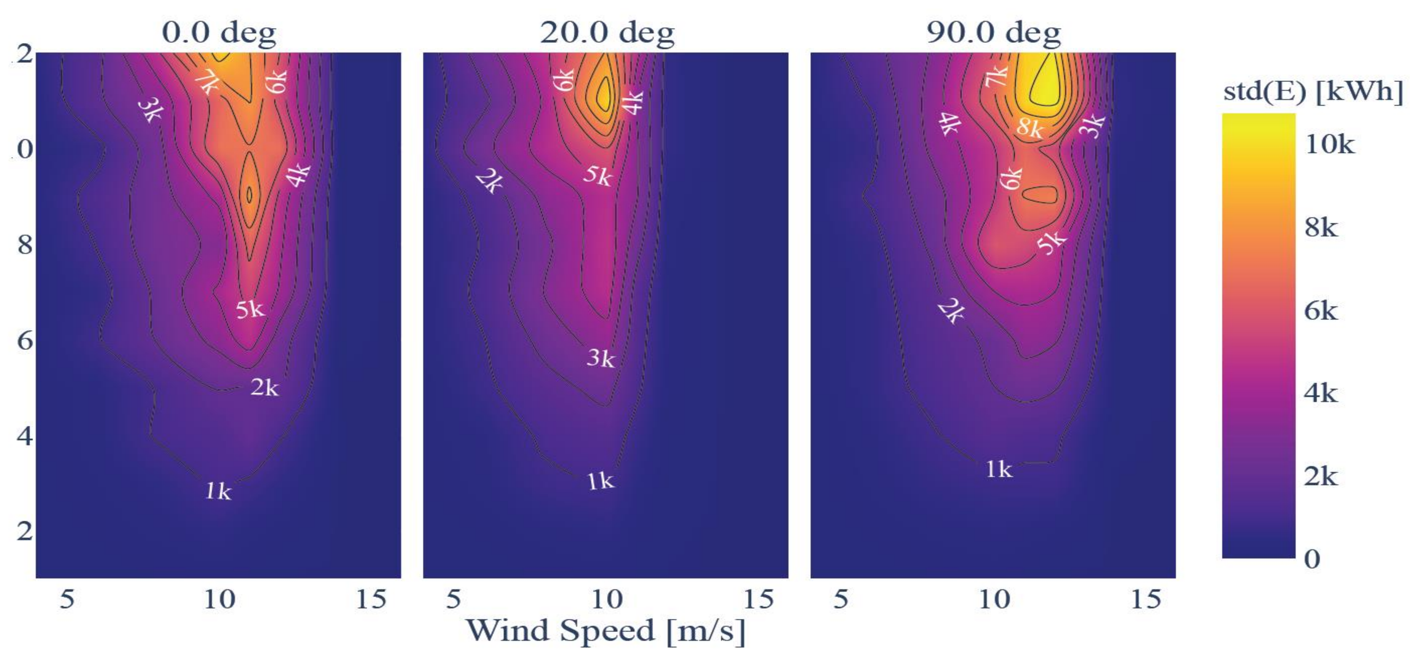
Maximum ramp rates over a time interval, 121x15MW wind farm

- Ramp rates decrease with turbine size and layout sparsity as distance between turbines increases.



Energy fluctuations

- Energy fluctuations are power integrals over a time interval, around a slowly-varying trend. They drive the capacity that an energy storage must have to smoothen out all power fluctuations occurring during this time interval. They are characterised through their standard deviation.



- Energy fluctuations show the same trends as ramp rates.

10 minutes	1 hour
2.8 MWh	10 MWh

Maximum standard deviations of energy fluctuations over a time interval, 121x15 MW wind farm

Discussion

- Further validation should be done on newer wind farms. Atmospheric stability affects power fluctuations and should be looked at more closely.
- Can be linked to weather hindcast and forecast for multiscale timeseries generation and predictions.

References

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2. V. Chabaud, "Synthetic turbulence modelling for offshore wind farm engineering models using coherence aggregation" Wind Energy, vol. 27, no. 2, 2024.
3. B. Panjwani, M. Kvittem, L. Eliassen, H. Ormberg, and M. Godvik, "Effect of Wake Meandering on Aeroelastic Response of a Wind Turbine Placed in a Park," Journal of Physics: Conference Series vol. 1356, p. 012039, Oct. 2019.

Acknowledgments

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