Wind Energy Institute
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EERA DeepWind CONFERENCE 2025

An initial study on the environmental value of wind farm control

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Introduction

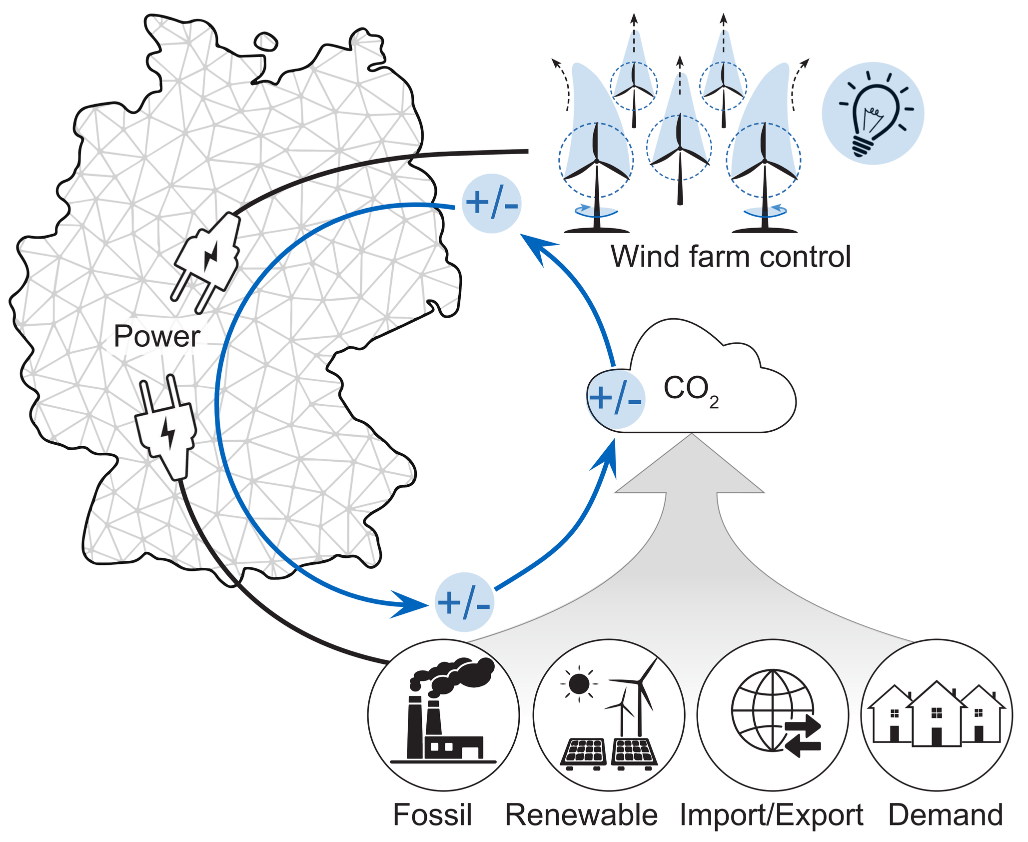


Figure 1: Visualization of the research question

Research question

"How does wind energy integration affect the grid emissions by displacing other powerplants, and which environmental benefits can be achieved through wind farm control?"

- **Environmental value** of wind energy = **displaced emissions** in connected grid
- Expressed as **marginal displacement factor (MDF)** of wind with unit *$kgCO_2$-equivalent / MWh*
- Grid emissions depend on generation mix and are therefore **time-varying**. Generation mix, in turn, depends on demand & supply (inland generation, exports and imports) in power and imbalance markets.

➔ Environmental value (MDF) of wind can be **modeled via demand & supply** in the connect energy system

➔ Wind farm control may boost the environmental performance of wind farms, but the potential is dependent on time

➔ Future research: Wind farm control optimization and control-layout co-design for concurrent consideration of climate change impacts, energy yield, fatigue loads, reliability, economic revenue, etc.

Method: Marginal displacement factor

Grid emission prediction

- MDF determined by **generators operating at the margin** (dependent on market, regulations and policies)
- **Data-driven approach**: all relevant driving phenomena of markets and grid implicitly considered through data
- Timeseries of total system emissions (E_{sys}) calculated via power (P) timeseries of generation mix, imports and exports with technology-specific (t) emission factors (e):

$$E_{sys} = \underbrace{\sum_t e_t \cdot P_t^{in}}_{\text{internal (in)}} + \underbrace{\sum_{nc} \frac{\sum_t e_t \cdot P_t^{nc}}{\sum_t P_t^{nc}} P_{nc}^{im}}_{\text{imports (im) from neighboring countries (nc)}} - \underbrace{\frac{\sum_t e_t \cdot P_t^{in}}{\sum_t P_t^{in}} \sum_{nc} P_{nc}^{ex}}_{\text{exports (ex) to neighboring countries (nc)}}$$

- **Artificial neural network** (ANN) to predict total system emissions dep. on generation mix, imports and exports
- One layer, 105 neurons, hyperbolic tangent activation function, Levenberg-Marquardt optimization, 500 epochs
- R^2 = 0.995 (training), R^2 = 0.994 (validation)
- **Open-source data** from ENTSOE transparency platform → applicable to any EU country, market or control zone

MDF calculation

The p features $\underline{p} = [D, P_w, P_S, P_c, \ldots]$ are decomposed into their **principal components** $\underline{\theta}$ via transformation matrix $\boldsymbol{T}$

$$\underline{p} = \boldsymbol{T}\underline{\theta}$$

The ANN maps principal components to system emissions

$$E_{sys} = Y(\underline{\theta})$$

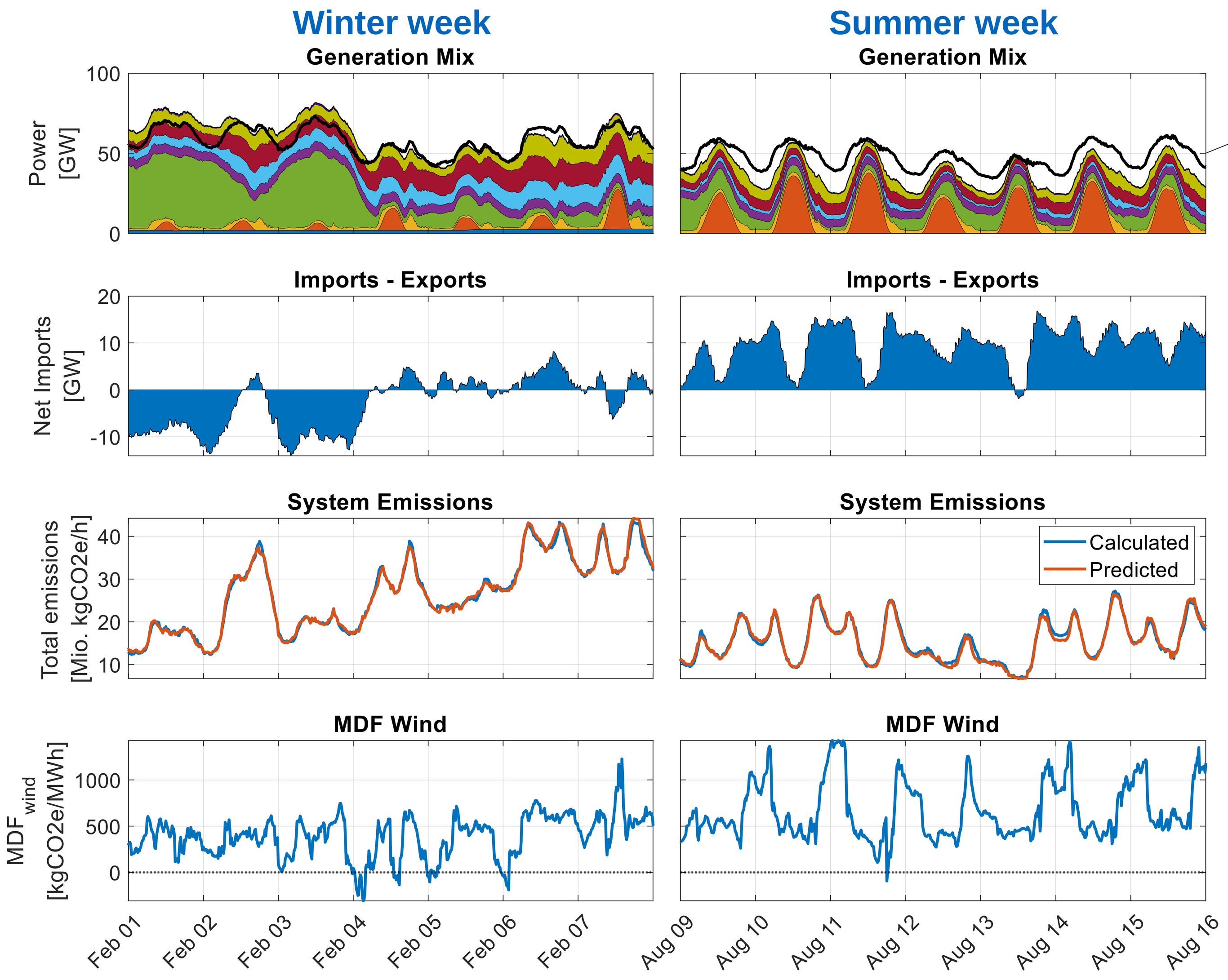
The **constraint** ensuring that **demand meets supply** reads

$$\underline{n}^T \partial \underline{p} = 0, \text{ with } \underline{n} = \frac{1}{\sqrt{p-1}}[0,1,1,1,\ldots]$$

MDF is calculated as the **constrained partial derivative** of the system emissions with respect to $\underline{p}$

$$\underline{MDF} = \frac{\partial E_{sys}}{\partial \underline{p}} = \left(\frac{\partial Y}{\partial \underline{\theta}}\right)^T \boldsymbol{T}^T \left(\boldsymbol{I} - \underline{n}\underline{n}^T\right)$$

$\frac{\partial Y}{\partial \underline{\theta}}$ is calculated numerically using finite differences.



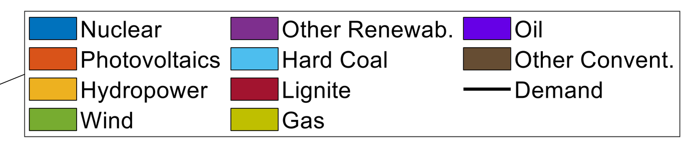


Figure 2: Timeseries of supply, demand, system emissions, and MDF_{wind} for two exemplary weeks in winter (left) and summer (right) in Germany in 2023

MDF probability distributions

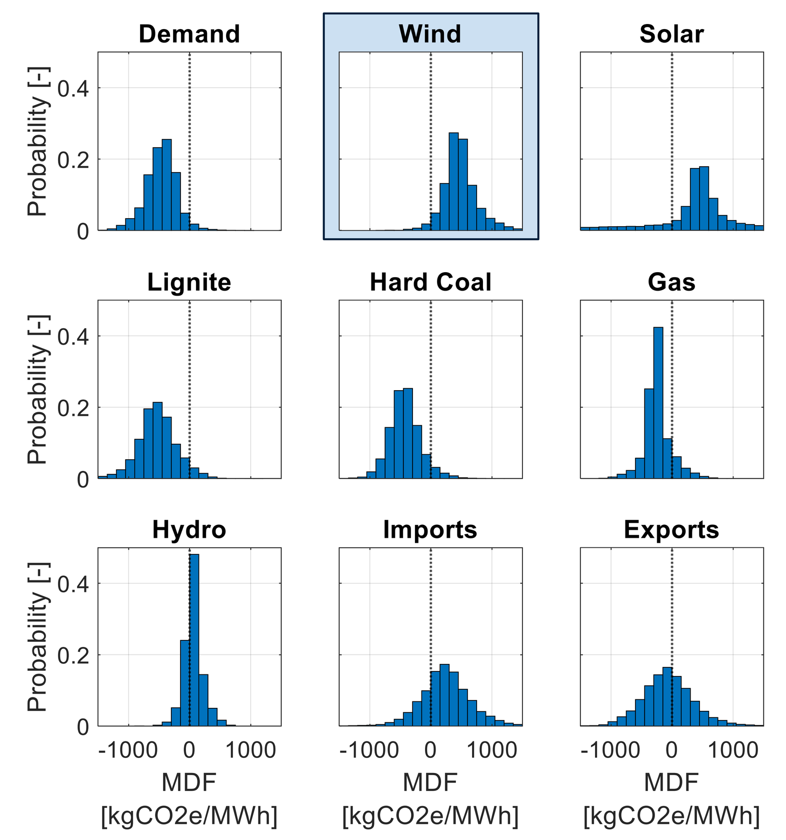


Figure 3: MDF distributions of nine features in $\underline{p}$ in Germany in 2023

Application: Environmental value of wind farm control

- Test case offshore wind farm **Wikinger**: 70 turbines (350 MW) in Baltic Sea connected to German grid
- Time-series analysis with FLORIS and ERA5 weather data for the year 2023
- Baseline: greedy turbine control (no wind farm control)
- Wind farm control scenario: yaw-optimised **wake steering** for maximum power (lookup tables created with *Serial-Refine Method*) → 47.1 GWh/a, **+3.0% AEP**
- Postprocessing of **environmental benefit** of wake steering → +22,600 tCO_2e/a, **+3.4% displaced grid emissions** with respect to baseline

Conclusions

1. Environmental value of wind energy quantified via marginal displacement factor (MDF), representing the displaced grid emissions.
2. In 2023 in Germany, MDF_{wind} varied significantly, mostly ranging between 0-1000 $kgCO_2$/MWh → profound positive impact on grid emissions.
3. Wind farm control significantly boosts environmental value w.r.t. baseline, matching or exceeding the relative increase in energy production.

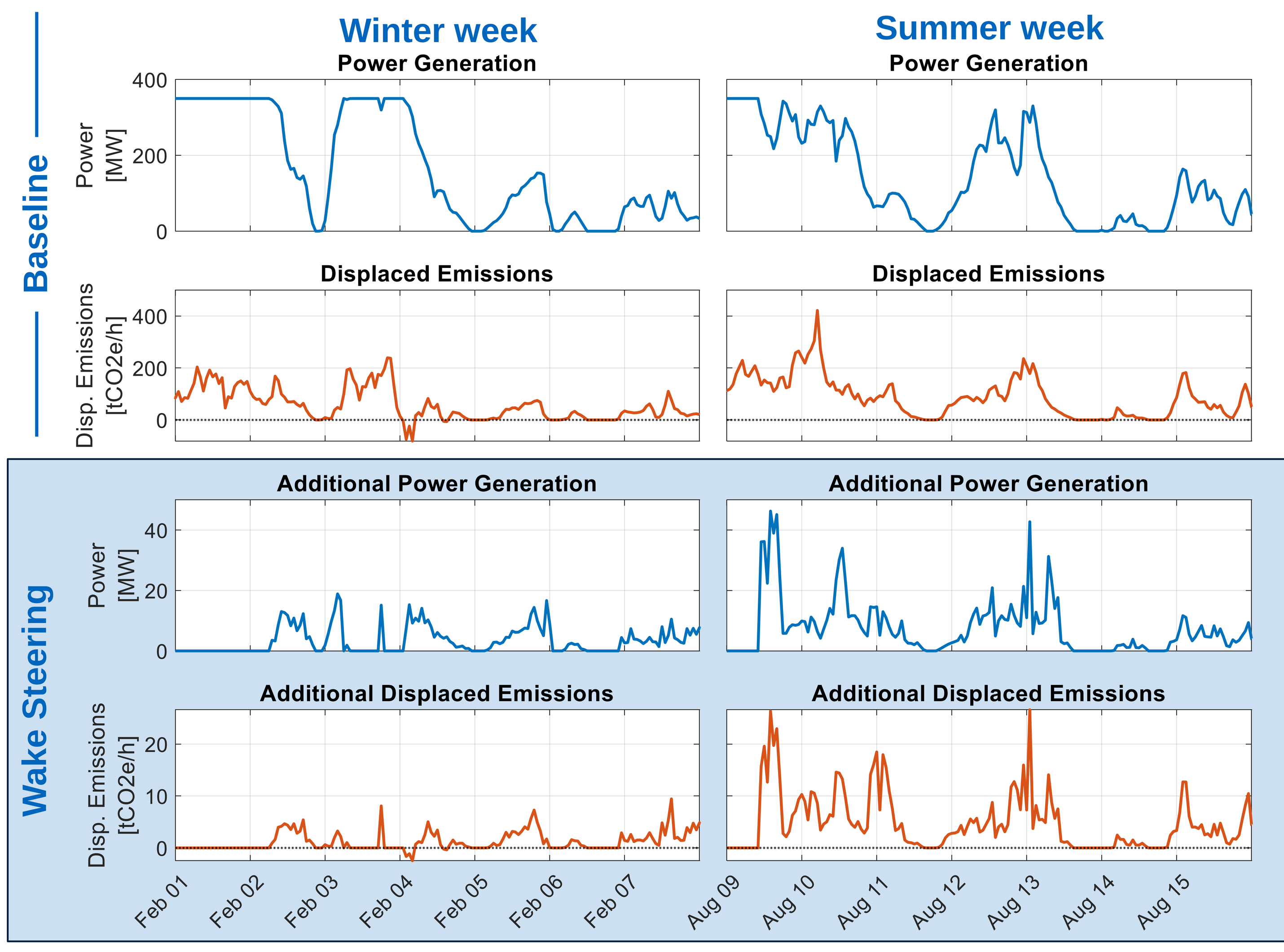


Figure 4: Timeseries of Wikinger's baseline power generation and displaced emissions (top), and additional potential benefit by wake steering (bottom) for two exemplary weeks in winter (left) and summer (right) in 2023

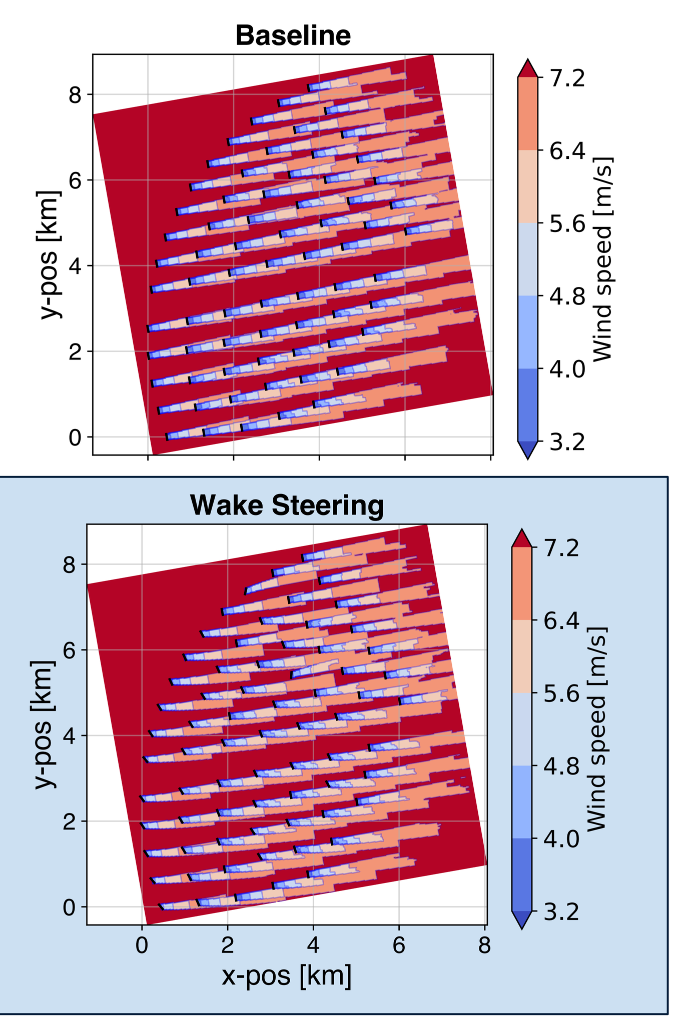


Figure 5: Flow field for main inflow direction and mean wind speed for baseline scenario (top) and with wake steering (bottom)

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This work has been partially supported by the MERIDIONAL, the SUDOCO and the TWAIN projects, which receive funding from the European Union's Horizon Europe Programme under the grant agreement No. 101084216, No. 101122256 and No. 101122194, respectively. The authors acknowledge Irène Apra for the visualization of the research question (Figure 1).

MERIDIONAL TWAIN SUDOCO