Impact of low-level jets detected via remote sensing techniques on the performance of wind turbines in the German Bight

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Outline

- Motivation for low-level jet research
- Methodology
  - Offshore Measurement Campaign
  - Lidar measurements and wind profile generation
  - LLJ detection
- Results
  - Characterisation of LLJ occurrence
  - Influence of LLJs on wind turbine performance
- Conclusion & Outlook

Motivation for low-level jet (LLJ) research

- Anomaly from logarithmic wind profile
- LLJs are observed quite frequently in offshore regions
- Observed at heights of offshore wind turbine rotor area
- Effects on wind turbine power production and loads are largely unexplored
- Increasing importance for larger turbines

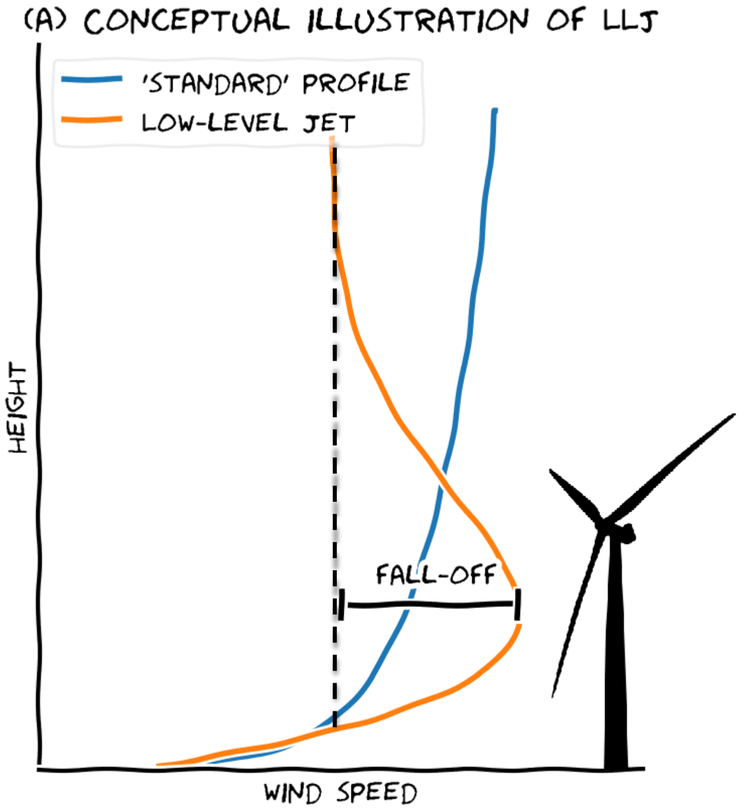


Figure: Adapted from Kalverla et al., 2019

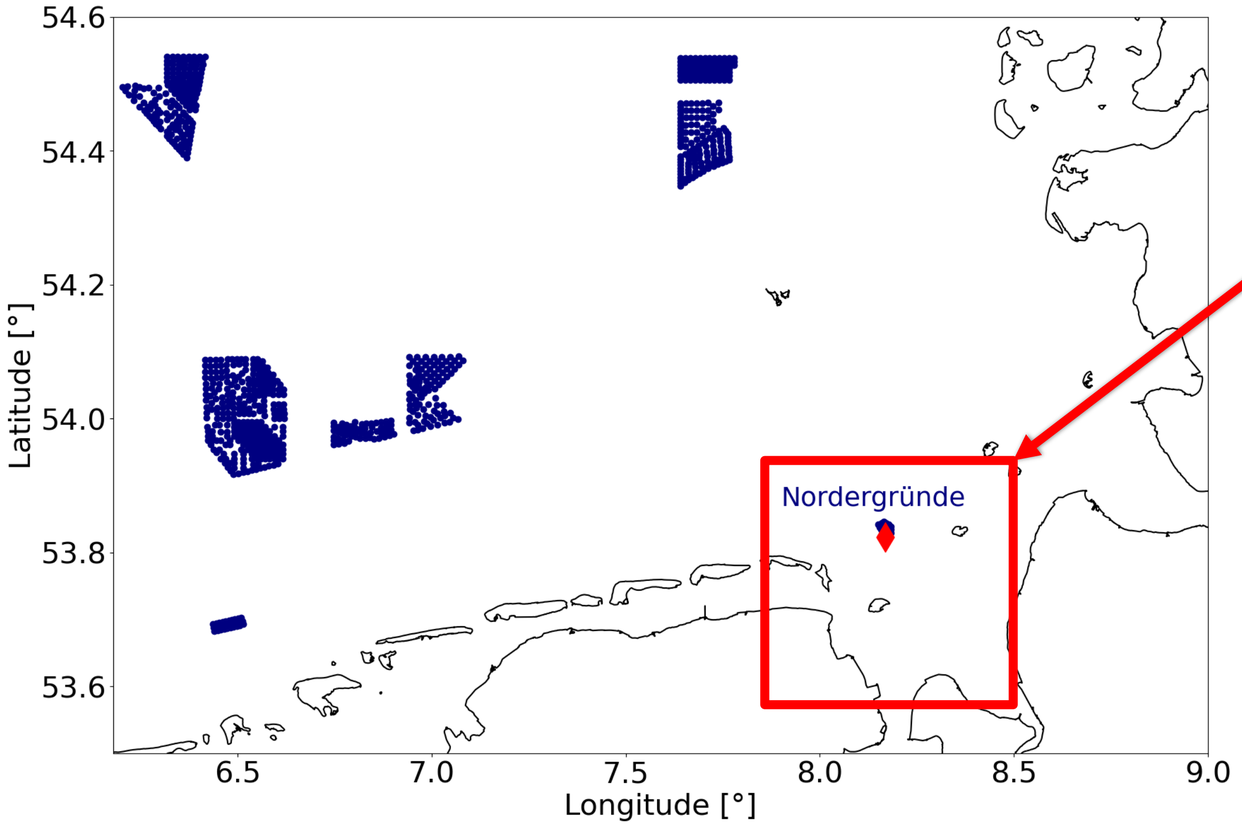
Research objectives

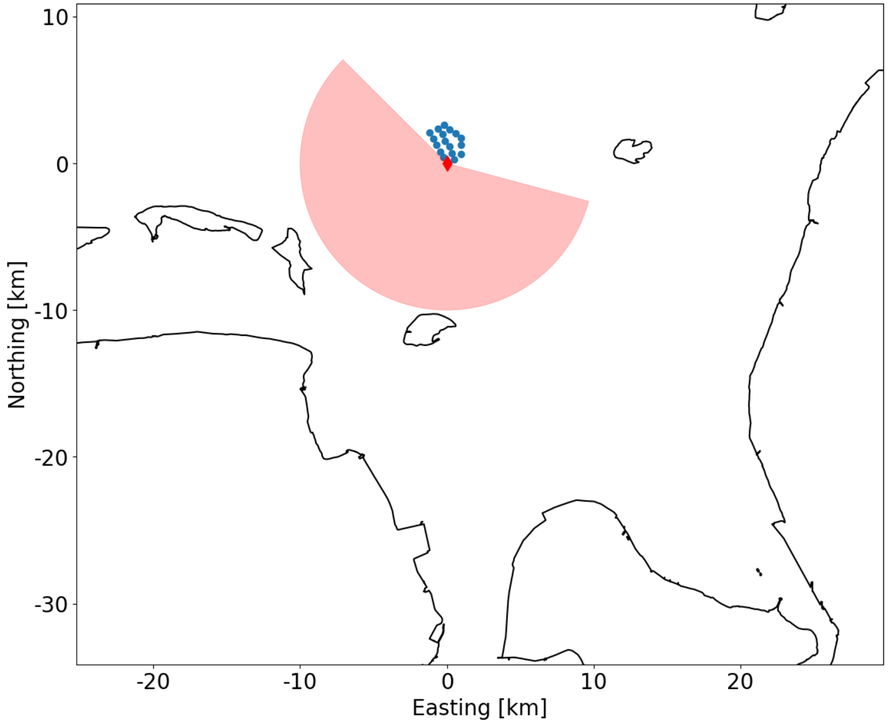
Detect LLJs from multi-elevation PPI lidar scans

Characterise LLJ occurrence at the near-coastal OWF Nordergründe

Analyse the influence of LLJs on wind turbine performance

Offshore measurement campaign at Nordergründe





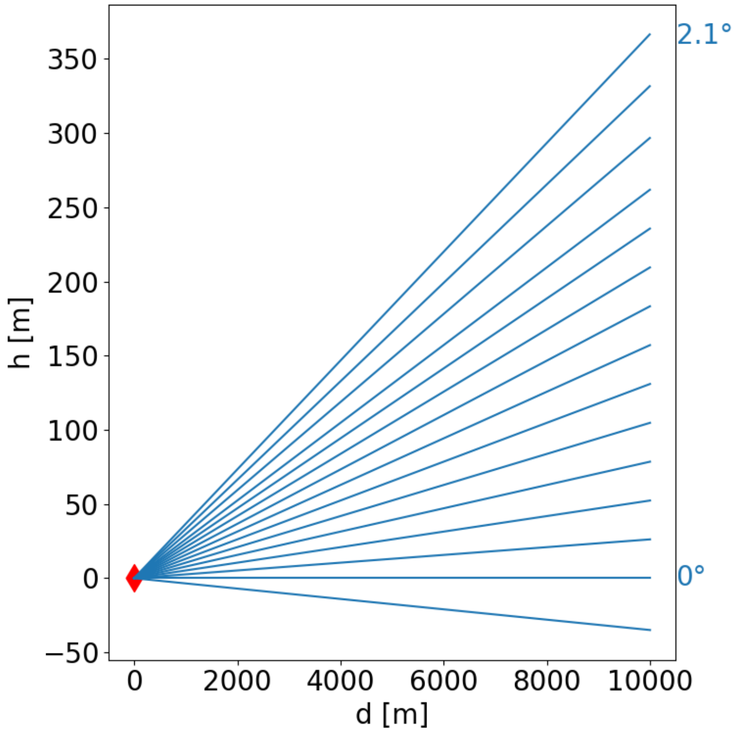
OWF Nordergründe (NG):

- 18 turbines (Senvion 6M)
- Complex coastline
- Wadden Sea

Offshore lidar measurement campaign

Available sensors:

- Long-range Doppler lidar Windcube 400S
  - Multi-elevation plan position indicator scans (from -0.2 to 2.1° in steps of 0.15°)
  - Mounted on transition piece (~16 m amsl)
- Air temperature, humidity, and pressure sensors at lidar height
- IR sensor for sea surface temperature measurements
- Data available from 10/2021 to 01/2023



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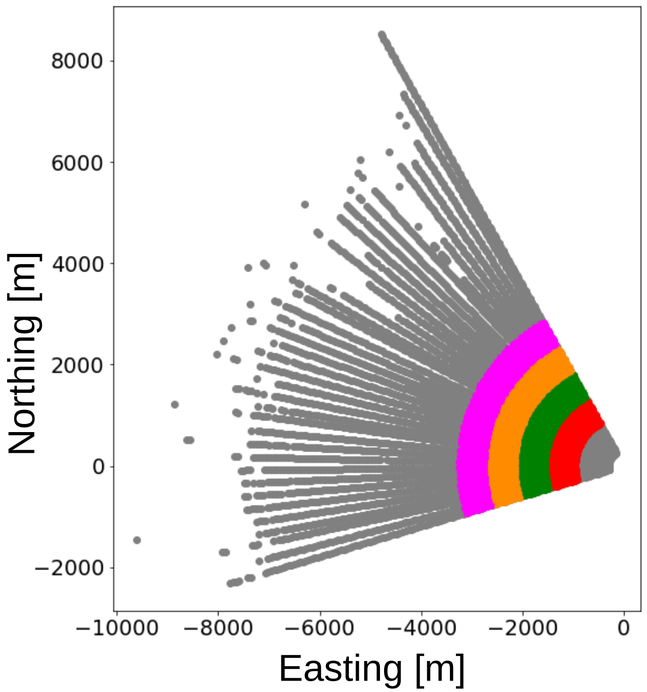
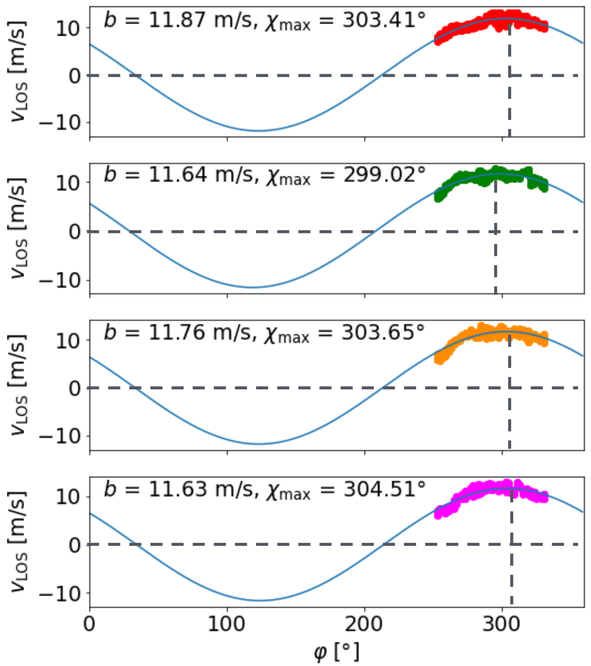
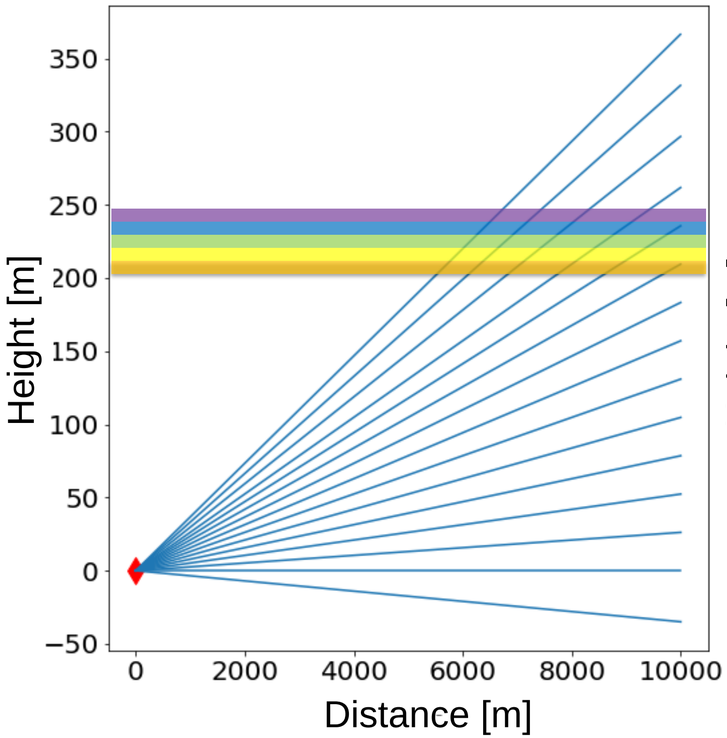
Lidar measurements and wind profile generation



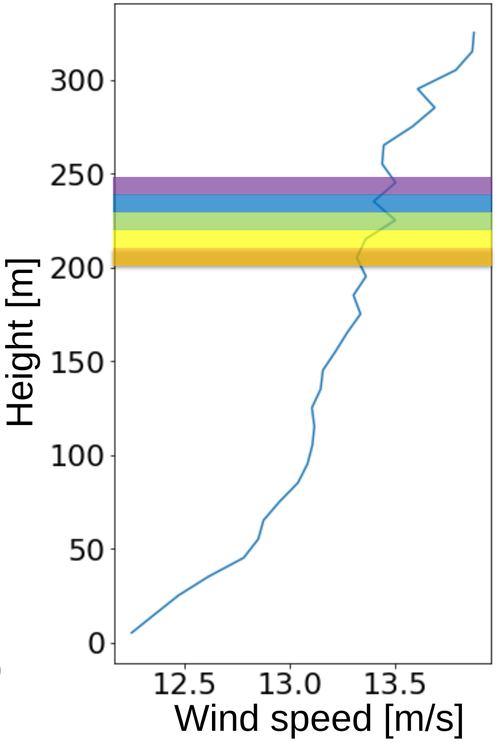
1.) PPI scan



2.) Cosine-fit to detect wind direction and speed at different ranges



3.) Combine multi-elevation PPIs and average within height bands

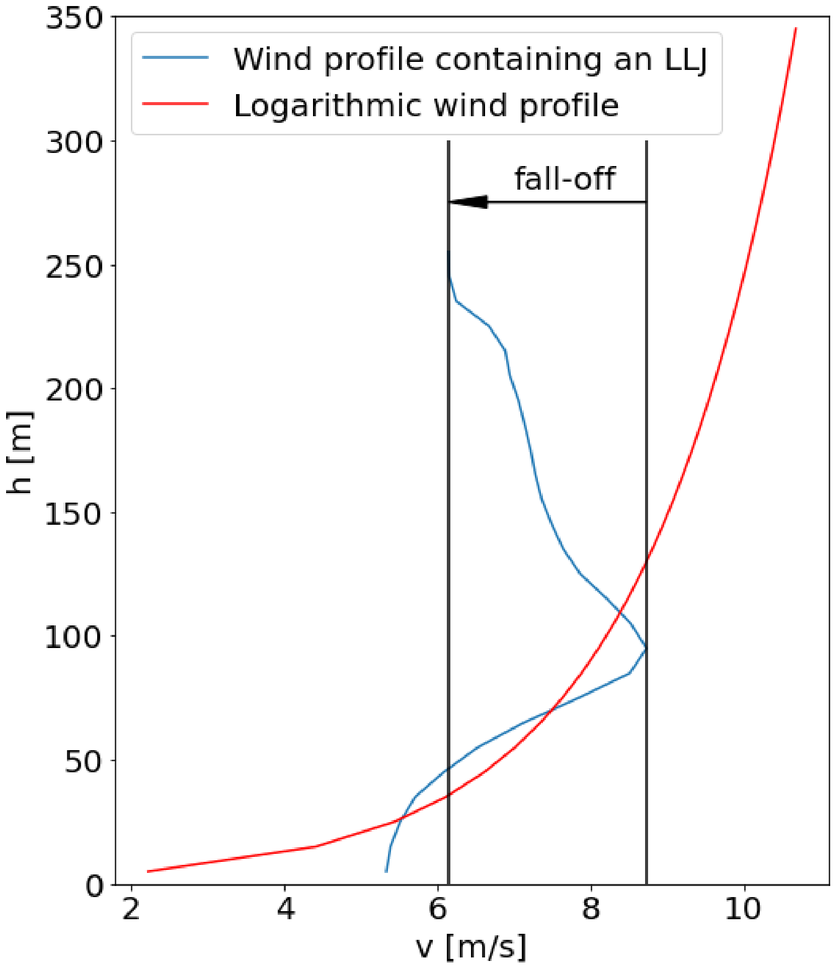


4.) Vertical wind profile

LLJ detection

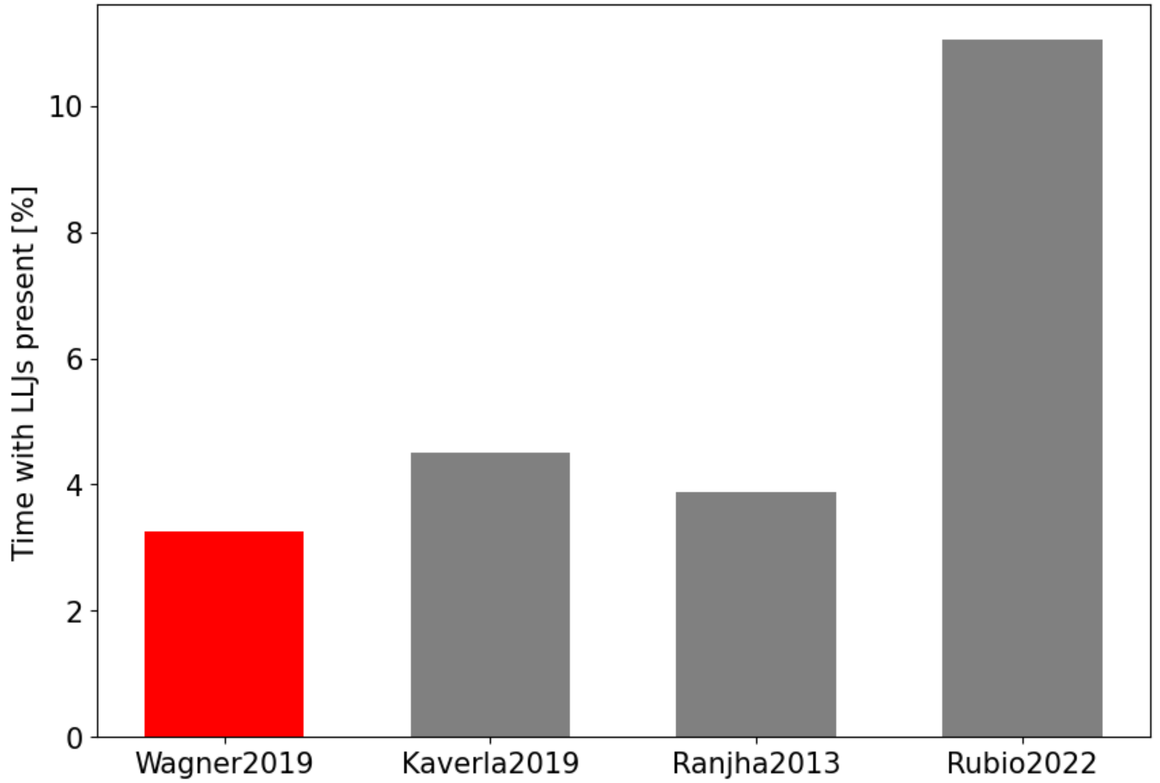
- Wind profiles averaged over 10-minute intervals
- Detection via different LLJ definitions

Defined by	Criteria
Wagner et al. (2019)	• Absolute fall-off: $2\,\mathrm{ms}^{-1}$ • Relative fall-off: 25%
Kalverla et al. (2019)	• Absolute fall-off: $2\,\mathrm{ms}^{-1}$
Ranjha et al. (2013)	• Relative fall-off: 20% • Core speed at least 20% higher than ground level wind speed • Core height below 2 km
Rubio et al. (2022)	• Absolute fall-off: $1\,\mathrm{ms}^{-1}$



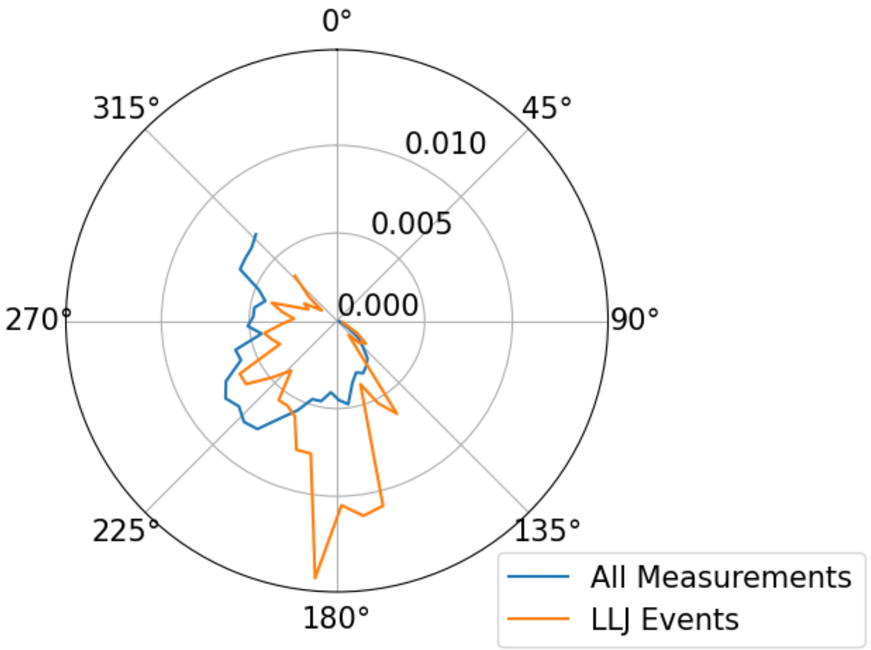
Statistical characterisation of LLJs

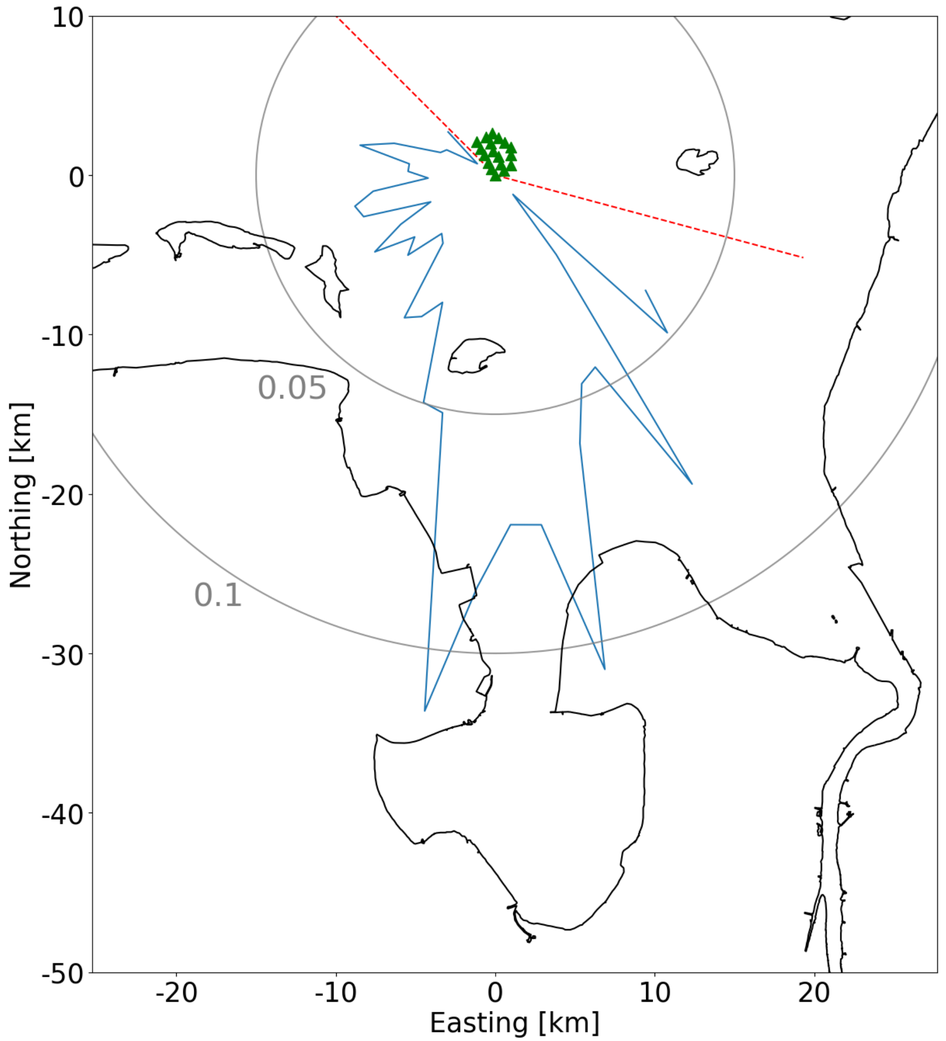
- LLJs are observed between 3% and 11% of the available measurement time inside lidar sector, depending on the used criterion



Wind direction dependency of LLJ occurrence

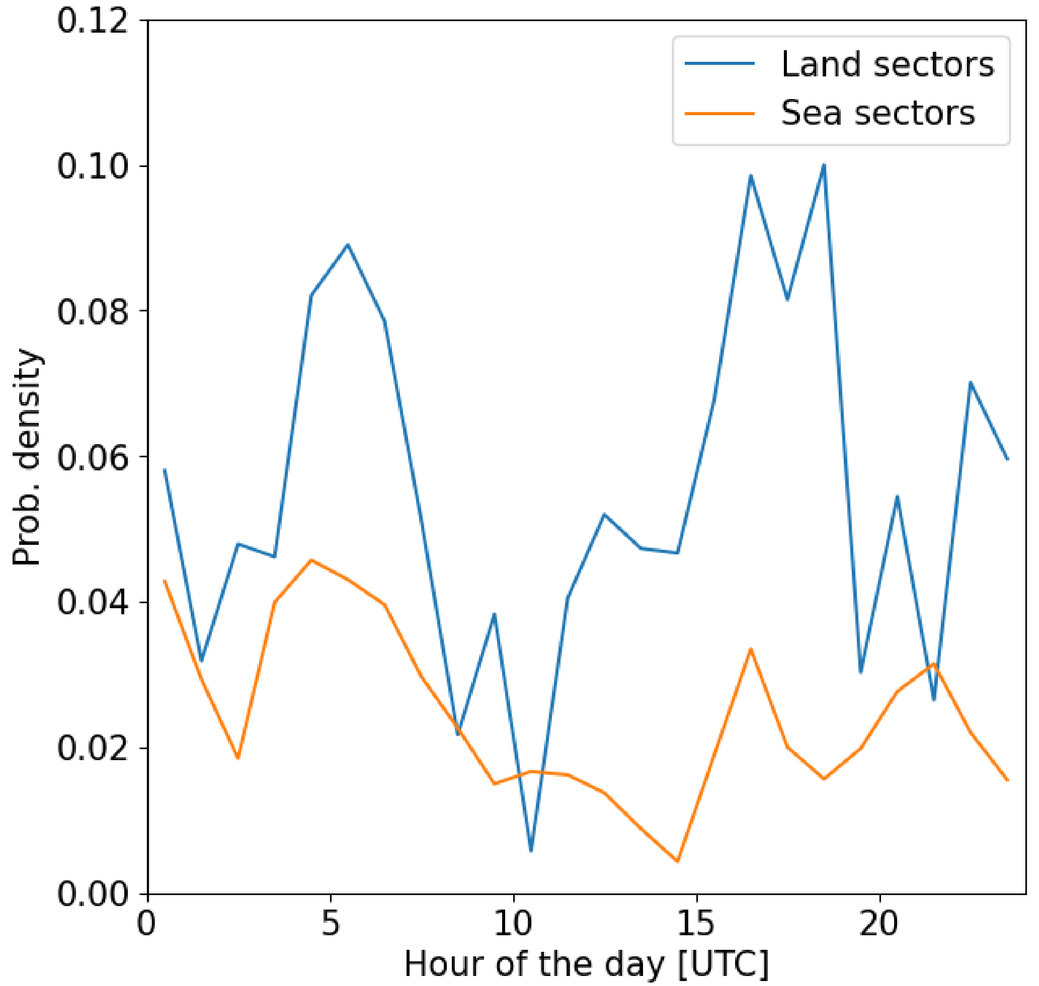
- Strong directional dependence on LLJ occurrence
- Higher LLJ occurrence for coastal wind directions





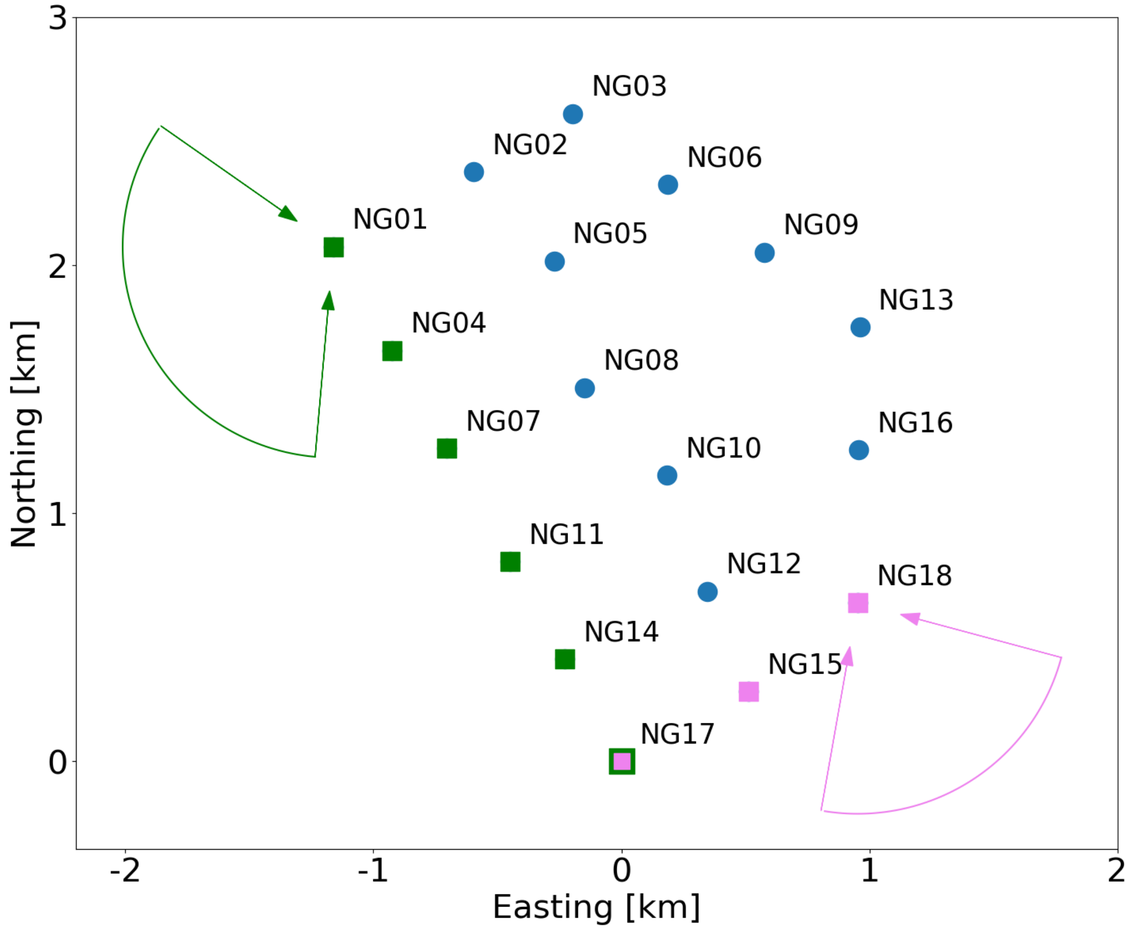
Diurnal Cycle of LLJ occurrence

- Clearly distinguishable diurnal cycle
- LLJs occur more often during early morning hours or late afternoon
- LLJ occurrence characteristics depending on land/sea directions



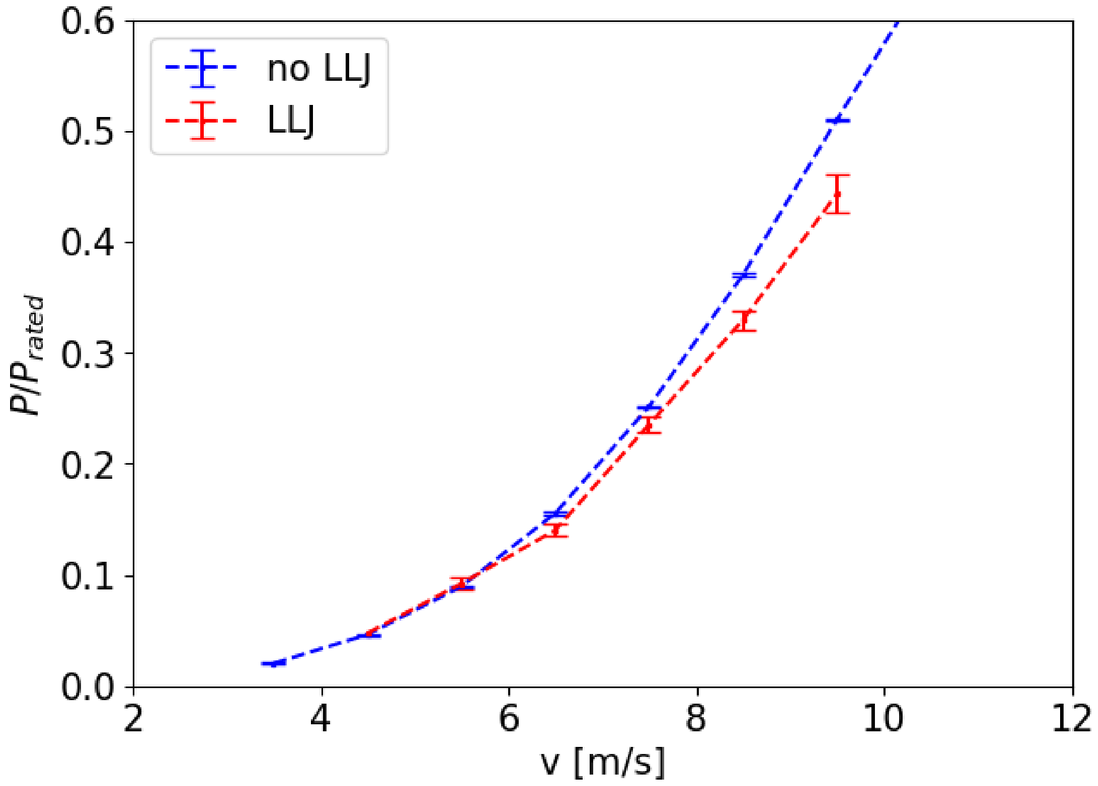
Influence of LLJs on wind turbine performance: preprocessing

- LLJs in the height of the rotor area are considered
- 1Hz SCADA data, averaged to 10-minute intervals
- Wind turbines with free inflow sectors considered
- Filtered for operating conditions



Influence of LLJs on wind turbine performance: Nacelle anemometer

- Nacelle anemometer: hub height wind speed
- Comparison of power production with and without LLJs present for same hub height wind speed
- Slightly lower power reading is observed
- How to represent inhomogeneously changing wind speed across rotor area?
- No power curve according to IEC standards!

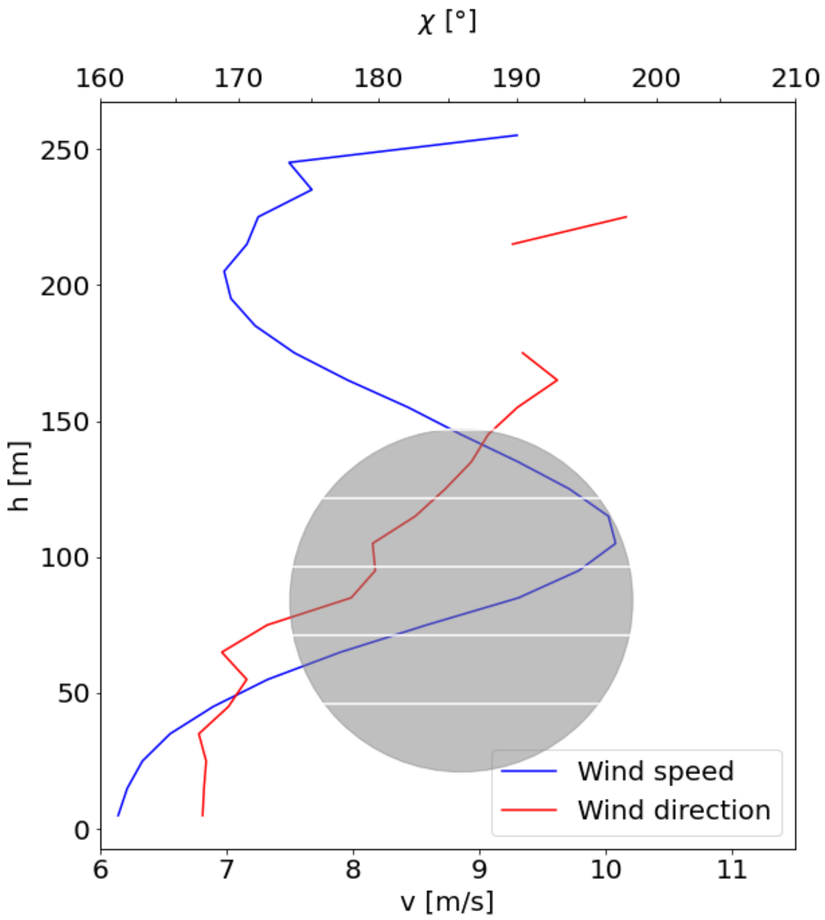


Influence of LLJs on wind turbine performance: REWS methodology

- Rotor equivalent wind speed (REWS) provides better representation of energy contained in the wind
- Adapted from Wagner (2010)
- Cubic average of wind speed weighted with partial area of a rotor segment
- Additional correction due to the wind veer incorporated

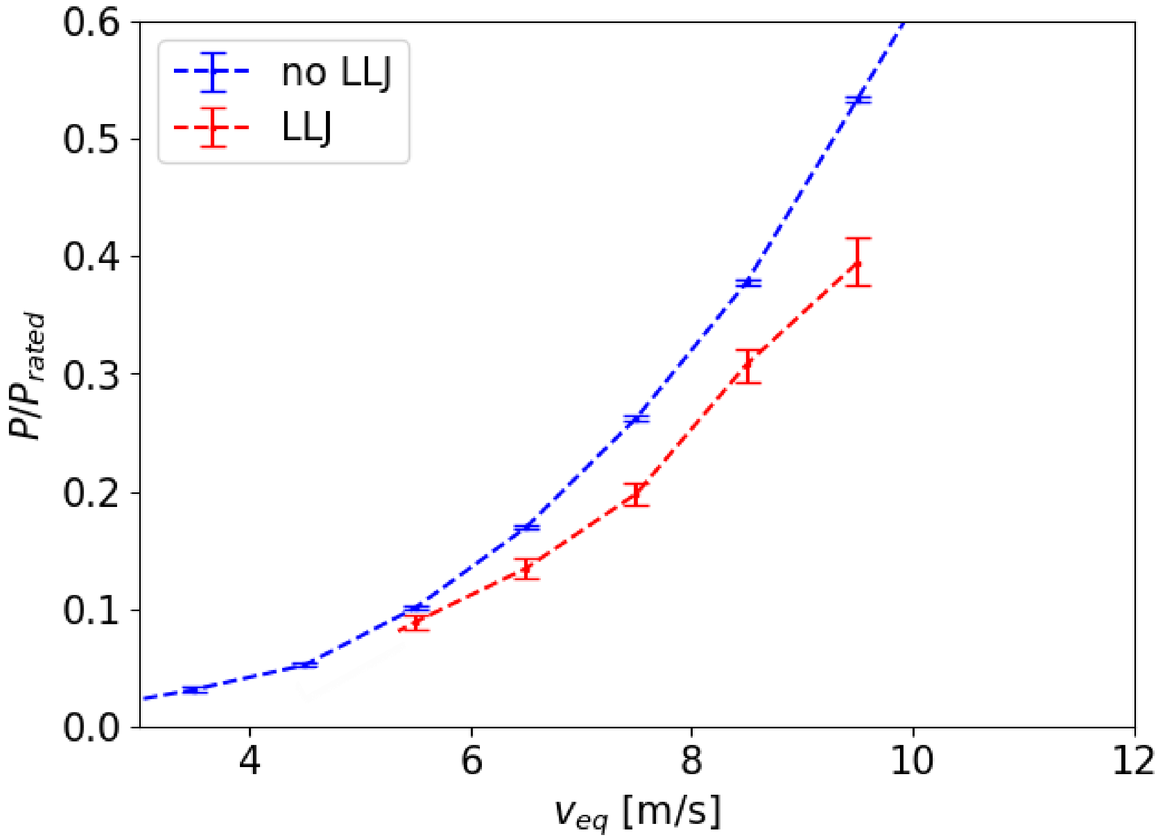
$$v_{i,\mathrm{corr}} = v_i \cdot \cos\left(|\chi_i - \chi_{hh}|\right)$$

$$v_{eq} = \left(\sum_{i=1}^{n_h} v_{i,\mathrm{corr}}^3 \frac{A_i}{A}\right)^{\frac{1}{3}}$$



Influence of LLJs on wind turbine performance: REWS

- No power curve according to IEC standards!
- Energy contained in the wind increased by LLJ
- Increased energy availability can not be completely converted to increased power
- No yaw misalignment considered



Conclusion

- Multi-elevation lidar PPI scans enable vertical wind profile estimation
- LLJs are a frequent phenomenon in the offshore environment
- Strong differences in occurrence between LLJs emerging over land and over sea
- Influences on wind turbine performance
  - Possibly increased energy availability in LLJ situations
  - Wind turbines only use increased energy availability to a limited extent
  - Caution, small sample size! ⟶ Further research required

Outlook

- Further research within EU project FLOW
- Larger data-set can allow for separation of LLJ events into
    - Different core height situations
    - Different meteorological conditions
- Larger turbines
    - Higher occurrence of LLJs in rotor area
    - Larger shear and veer across rotor swept area
- Publication in Wind Energy Science in preparation

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Forschungszentrum Jülich

Any open questions?

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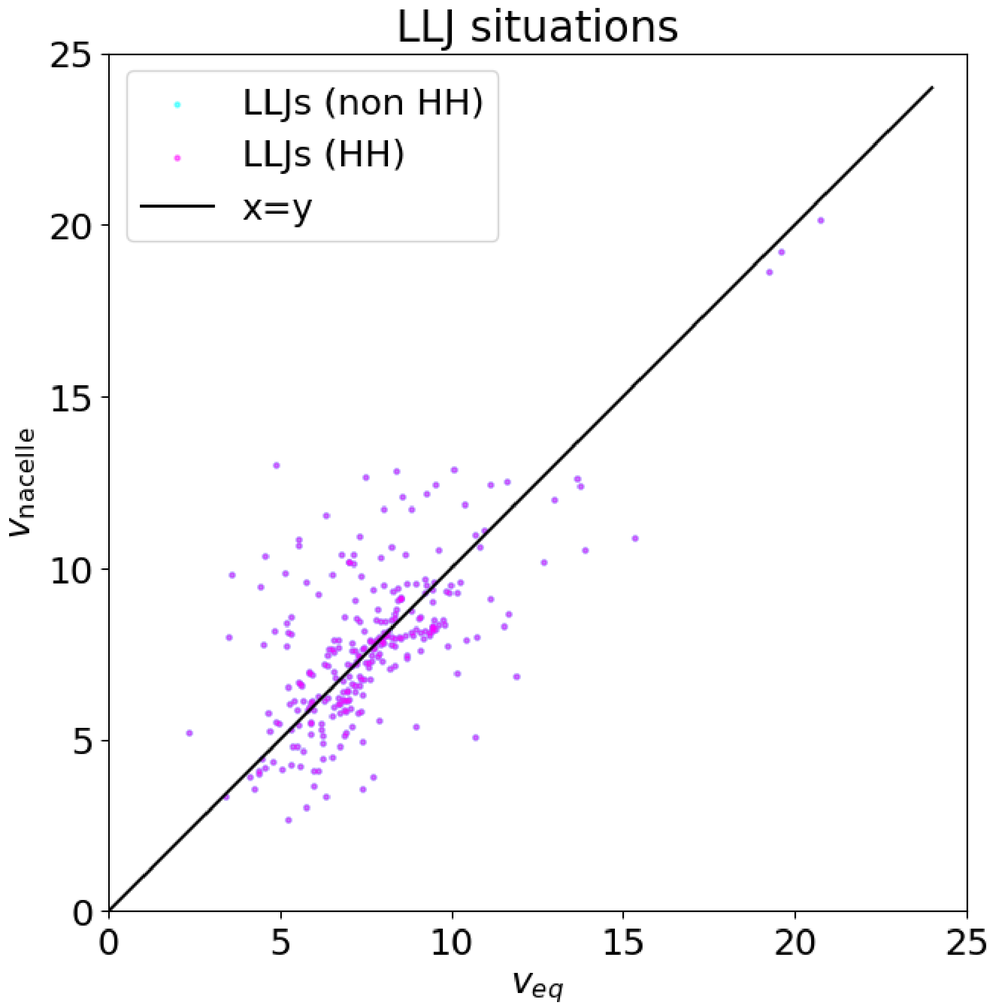
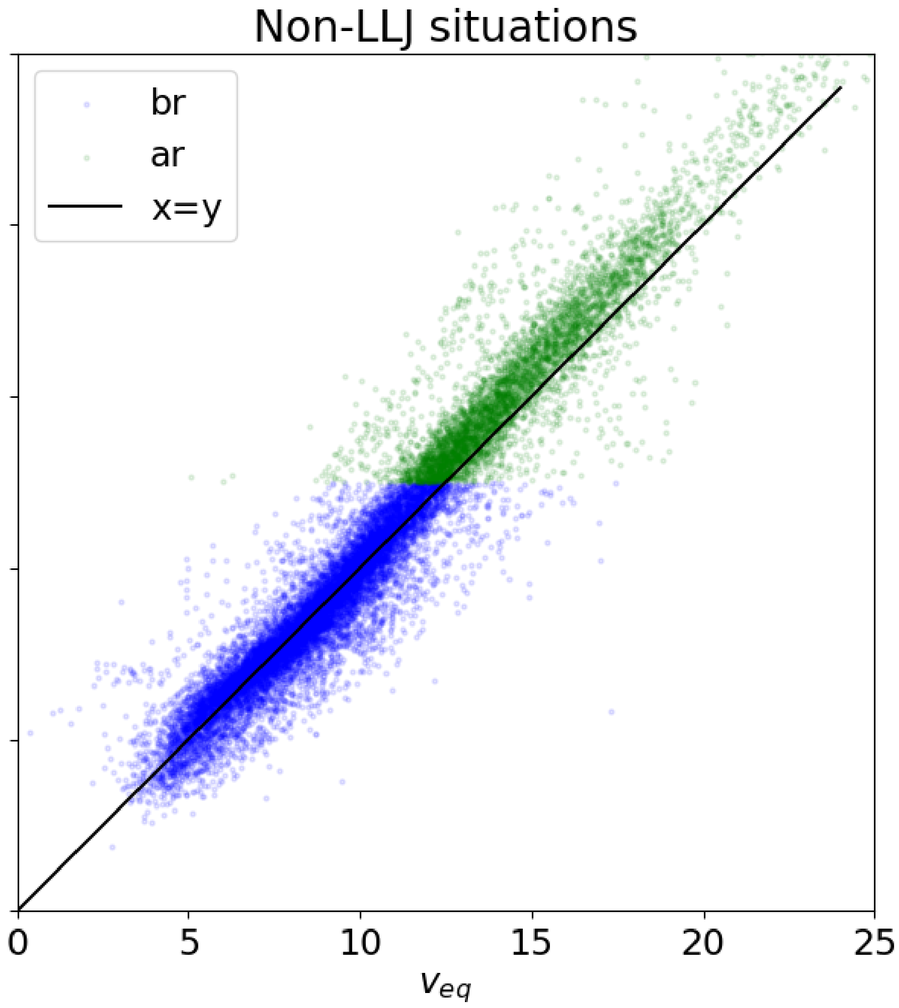
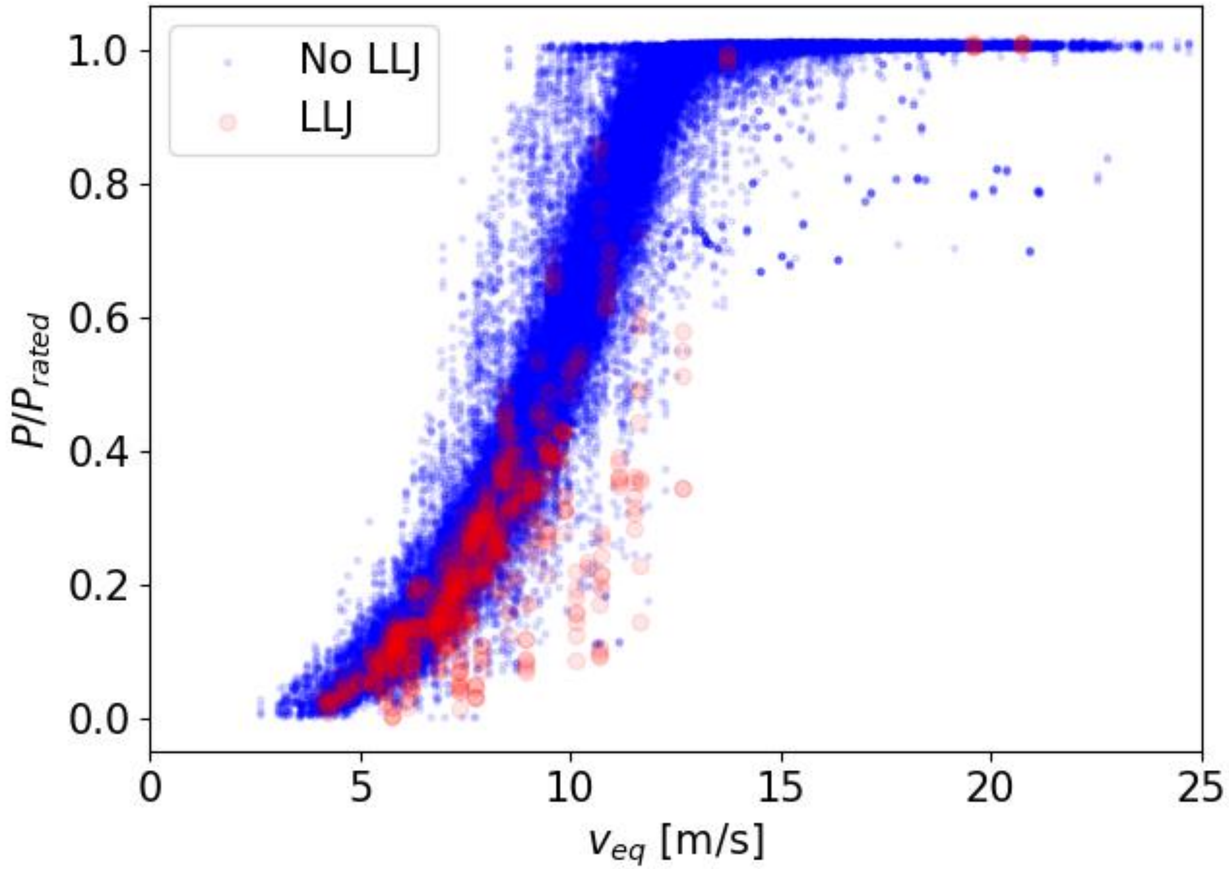
Correlation between Nacelle wind speed and REWS





Non-averaged power production over wind speed



Influence of LLJs on wind turbine performance: POTI

- Increased fluctuation of power supply
  - $P_{TI} = \frac{\sigma_P}{\mu_P}$
- Rather small sample size