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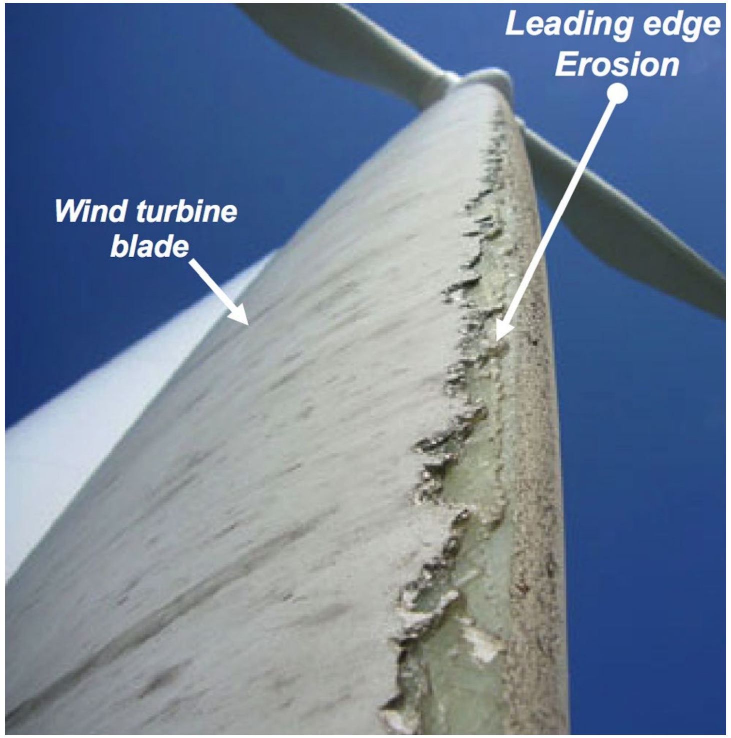
Modelling of rain-induced erosion of wind turbine blades Within an offshore wind cluster

Diederik van Binsbergen

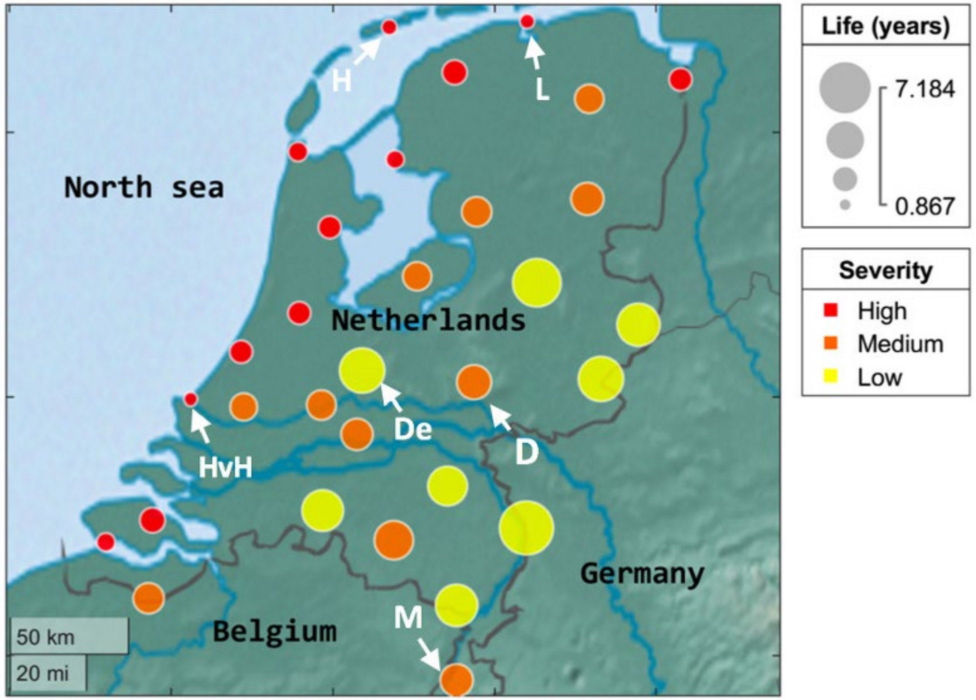
Amrit Verma, Amir Nejad, Jan Helsen

Shifting to wind farm wide erosion predictions

Going from a site-specific expected incubation time, towards …



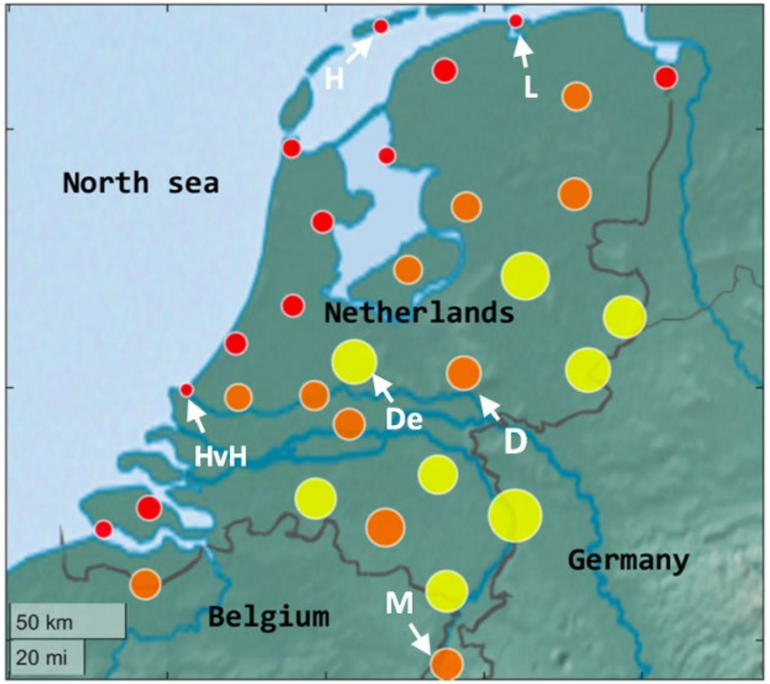
[1]Example of leading-edge erosion



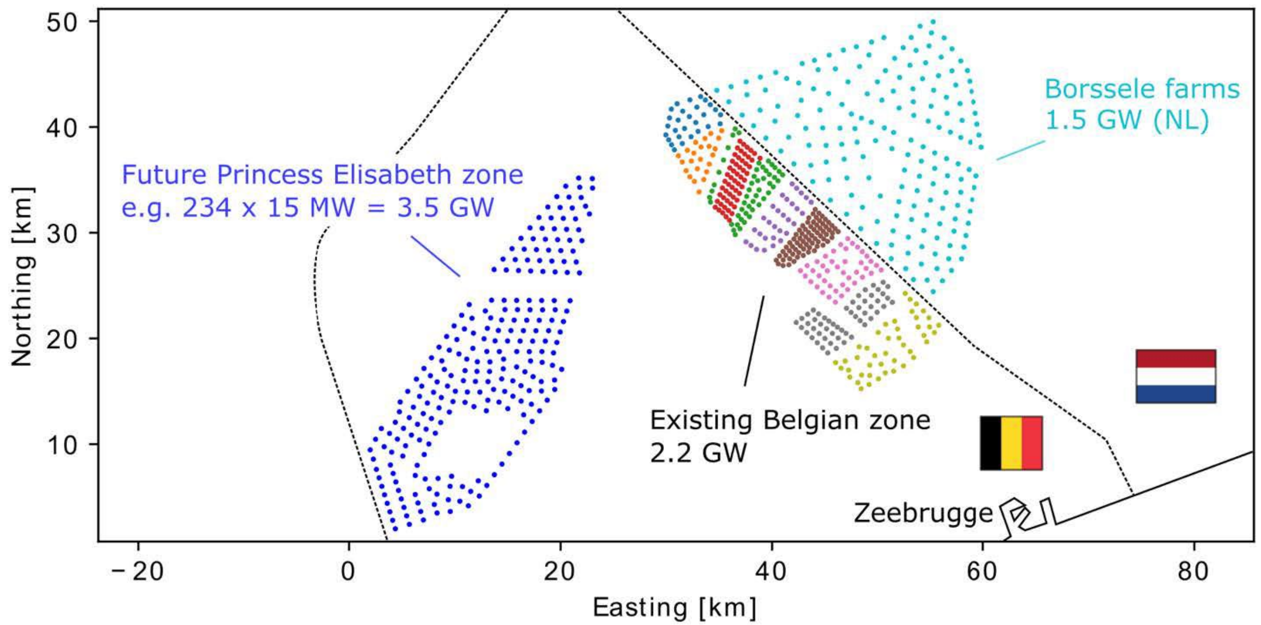
[1]Expected lifetime for the wind turbine coating system applied on the DTU 10MW wind turbine

Shifting to wind farm wide erosion predictions

Going from a site-specific expected incubation time, towards farm-wide leading-edge erosion predictions.



[1] Expected lifetime for the wind turbine coating system applied on the DTU 10MW wind turbine



Visualization of the Belgian-Dutch offshore cluster with a combined rated capacity of 3.7 GW and the future Princess Elisabeth zone with a planned rated capacity of 3.5 GW.

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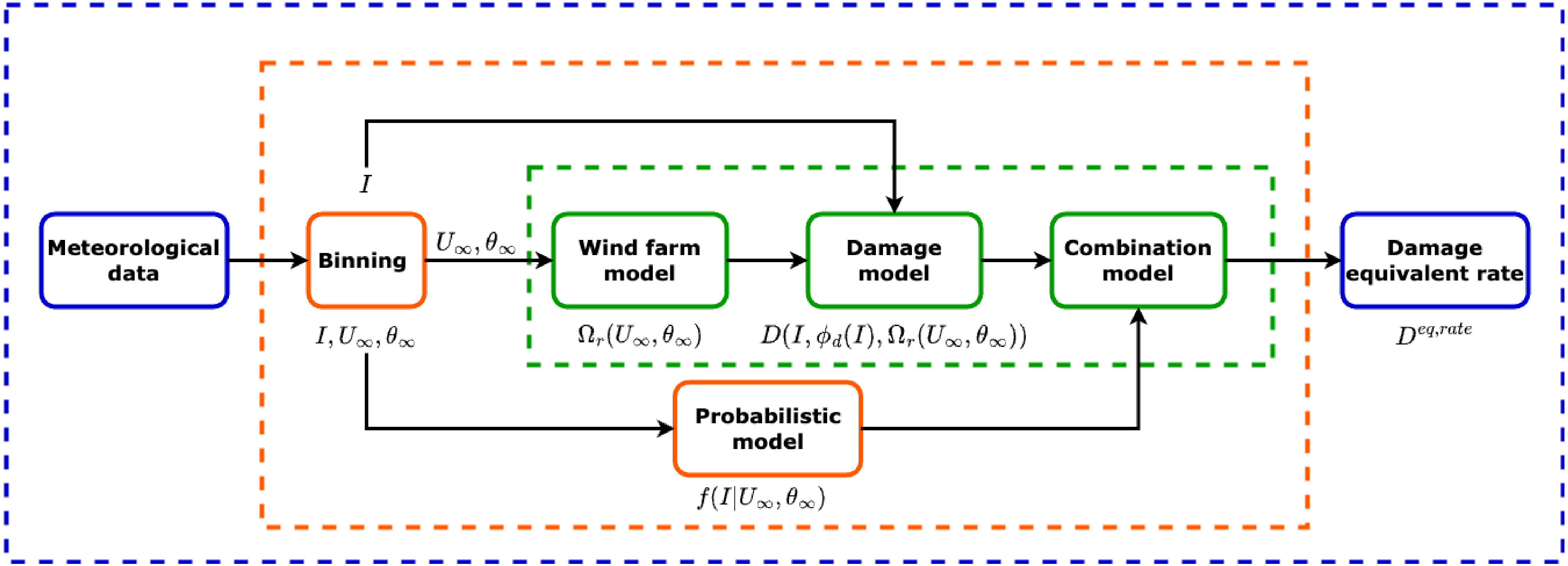
Aim

- To provide insights into leading-edge erosion across large, clustered, wind farms.
- To investigate the impact of wind turbine wakes on the incubation period of leading-edge erosion in offshore environments.
- To equip operators with physics-based models for the planning and execution of maintenance and inspections for offshore wind turbines.

Overview of the methodology



Meteorological data

Binning

Wind farm model

Damage model

Combination model

Damage equivalent rate

Probabilistic model

I

U_∞, θ_∞

$I, U_\infty, \theta_\infty$

$\Omega_r(U_\infty, \theta_\infty)$

$D(I, \phi_d(I), \Omega_r(U_\infty, \theta_\infty))$

$D^{eq,rate}$

$f(I|U_\infty, \theta_\infty)$

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Probabilistic model

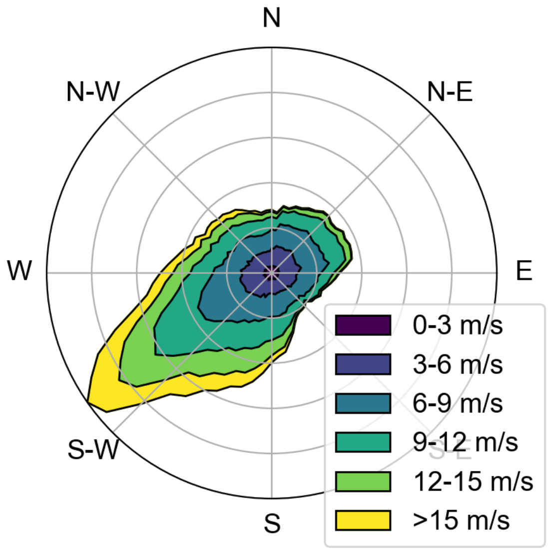
$$D^{eq,rate} = \int\int\int\int \dot{D}^{st}(U_\infty, \theta_\infty, I, \phi) f(U_\infty, \theta_\infty, I, \phi) dI d\phi dU_\infty d\theta_\infty$$

$$D^{eq,rate} = \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{P}\sum_{l=1}^{Q} \dot{D}^{st}\left(U_{\infty,i}, \theta_{\infty,j}, I_k, \phi_l\right) f\left(U_{\infty,i}, \theta_{\infty,j}, I_k, \phi_l\right) \Delta I \Delta\phi \Delta U_\infty \Delta\theta_\infty$$

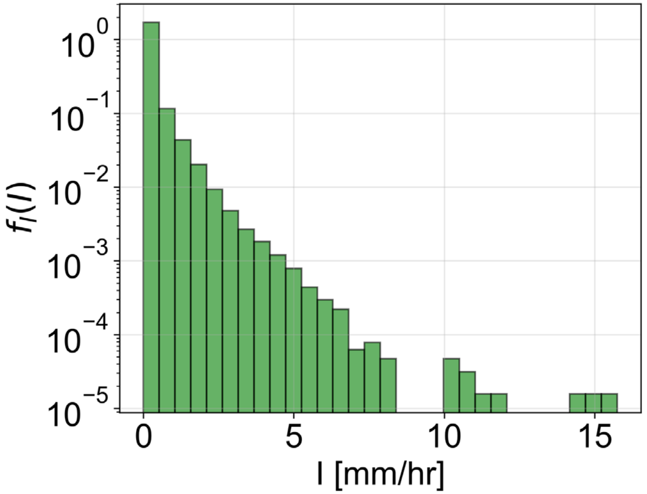
$$D^{eq,rate} = \sum_{i=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{P} \dot{D}^{st}\left(U_{\infty,i}, \theta_{\infty,j}, I_k, \phi(I_k)\right) f(I_k | U_{\infty,i}, \theta_{\infty,j}) \Delta I \Delta U_\infty \theta_\infty$$

- U_∞: freestream wind speed
- θ_∞: freestream wind direction
- I : rain intensity
- ϕ : droplet size

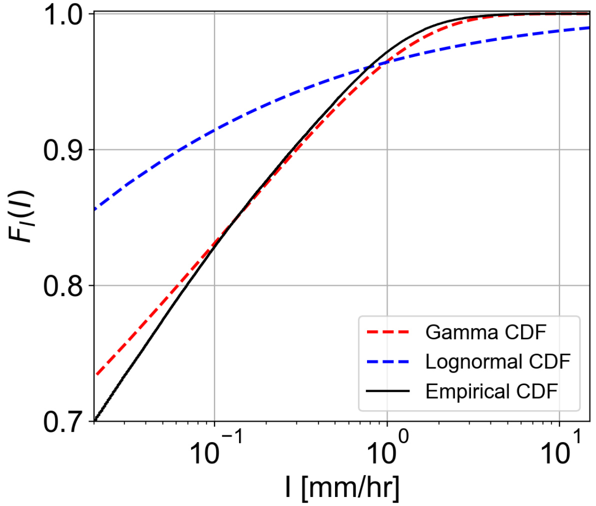
Site conditions



Wind rose from ERA5 reanalysis data[2] (1997-2022) at the specific site.

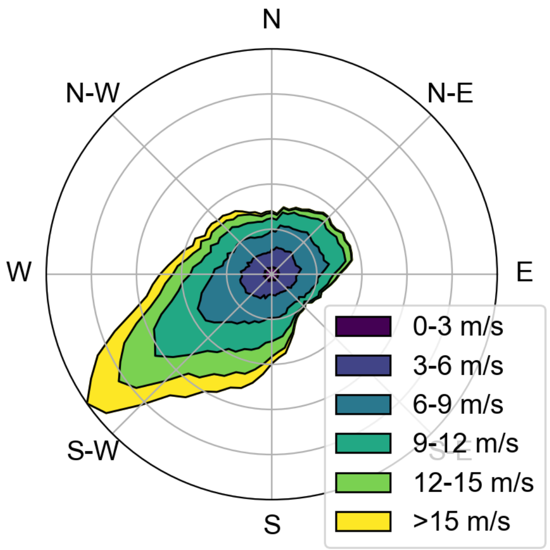


Marginal distribution of rain intensity from ERA5 reanalysis data[2].



Empirical cumulative density function (CDF) of rain intensity from ERA5 reanalysis data[2], Together with a fitted Gamma and Lognormal CDF.

Site conditions



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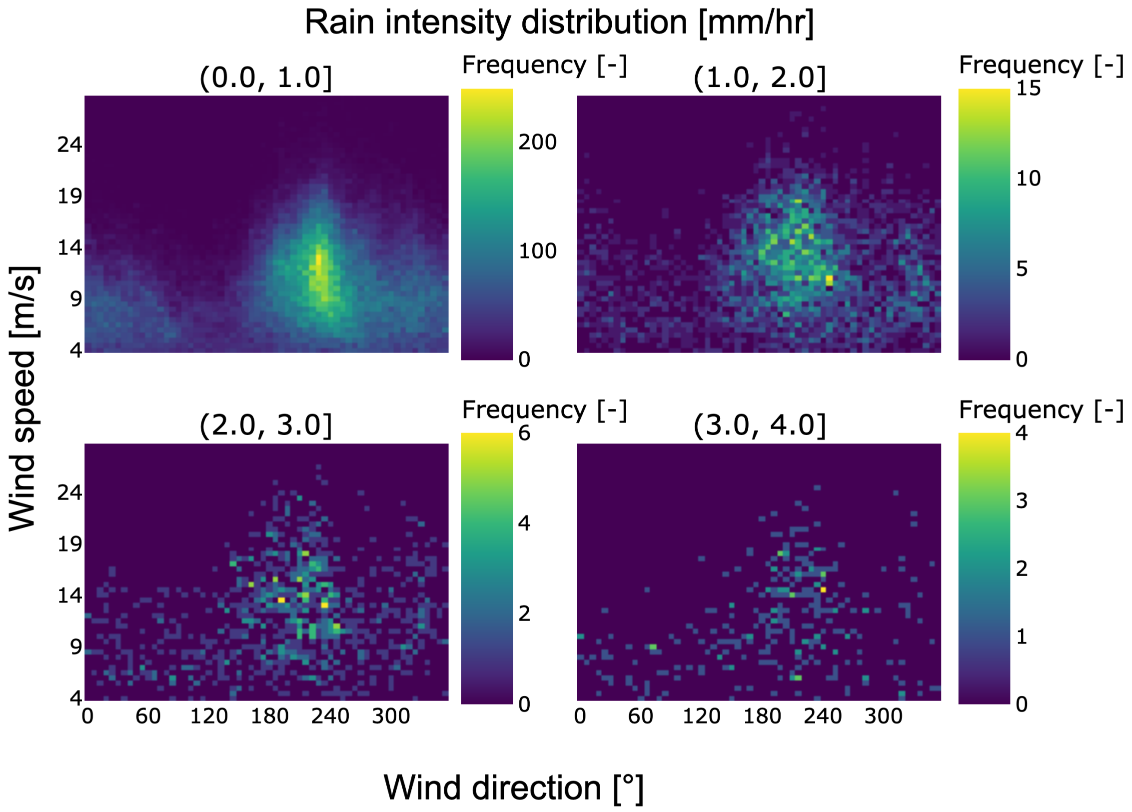
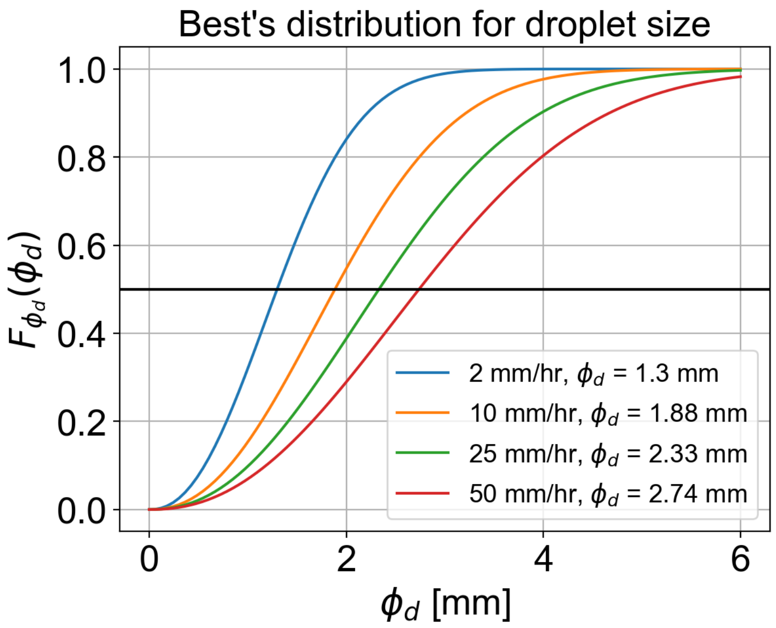
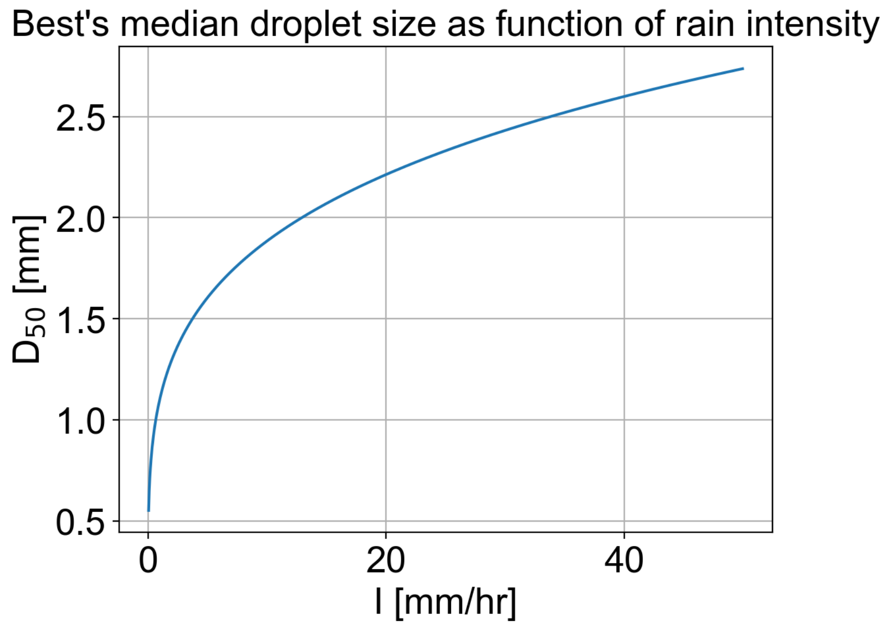


Joint distribution of rain intensity with respect to wind speed and wind direction from ERA5 reanalysis data[2].

Site conditions

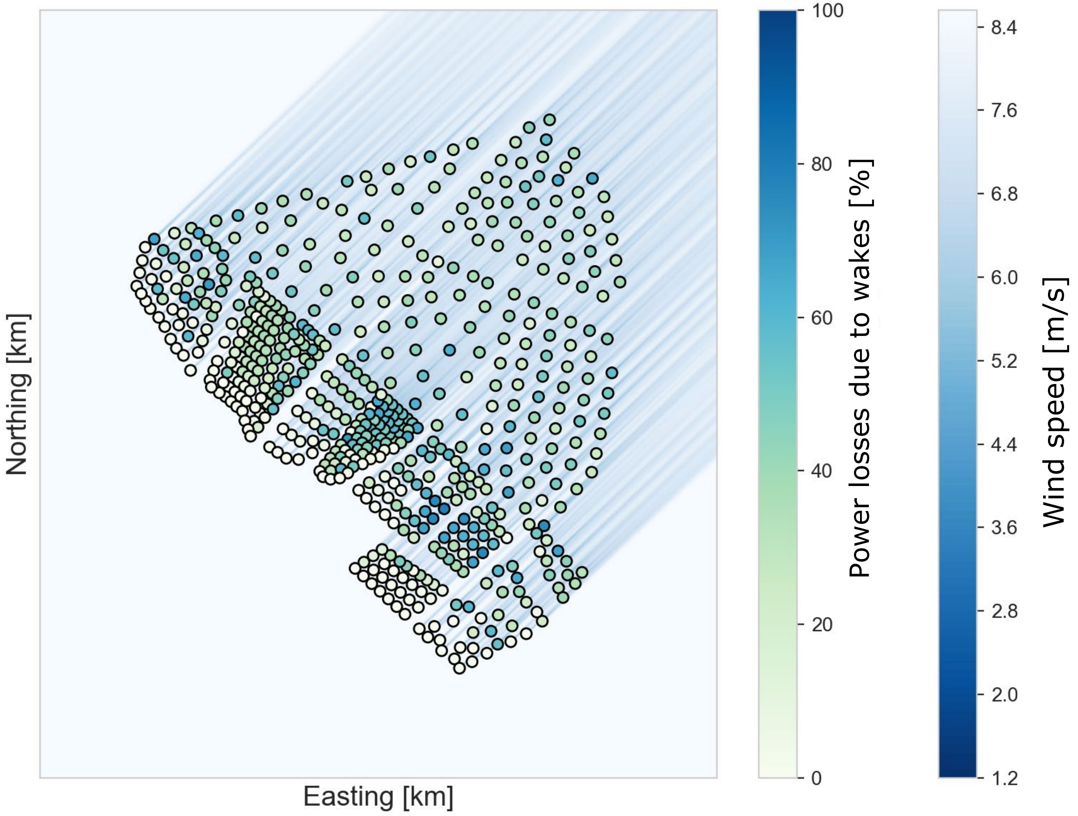


Best’s droplet size distribution[3]
for different rain intensities.

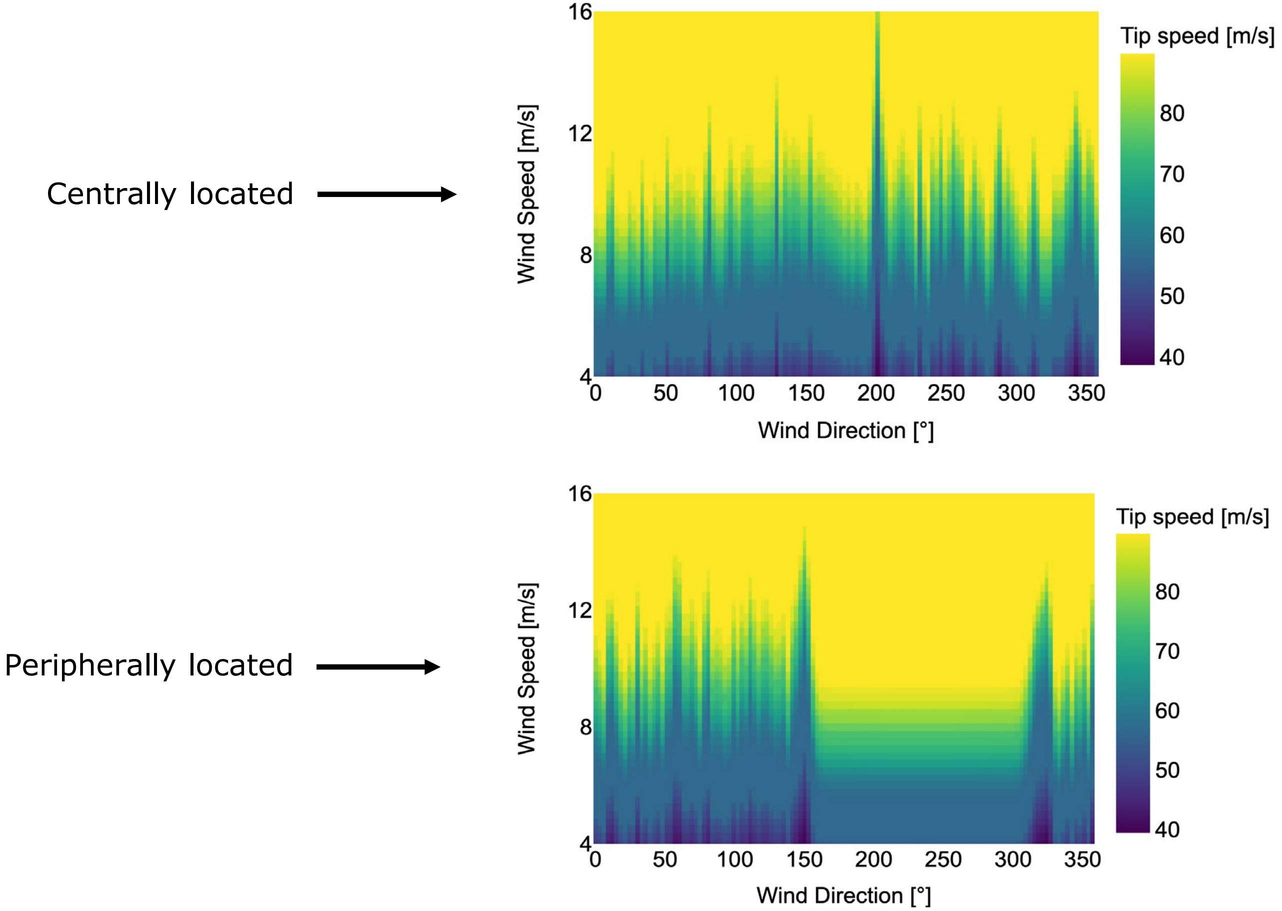


Best’s median droplet size distribution[3]
as function of rain intensity.

Wind farm model



Example of a wake calculation applied on the case study wind cluster using the TurbOPark model with Gaussian wake profile[4]. This calculation is performed for each wind speed and wind direction bin.


Centrally located

Peripherally located

Joint distribution of blade tip speed in [m/s] for wind speed bins of 0.25 m/s and wind direction bins of 3°.

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Damage model

Springer[5] model:

$$V_{tg} = 9.65 - 10.3e^{-0.6\phi_d}$$

$$\bar{q} = 530.5\frac{I}{V_{tg}\phi_d^3}$$

$$D^{st}\left(I, \phi_d, \Omega_r(U_\infty, \theta_\infty)\right) = \frac{\bar{q}V_{imp}\beta_d}{\frac{8.9}{\phi_d^2} \cdot \frac{S^{5.7}}{p_{wh}}}$$

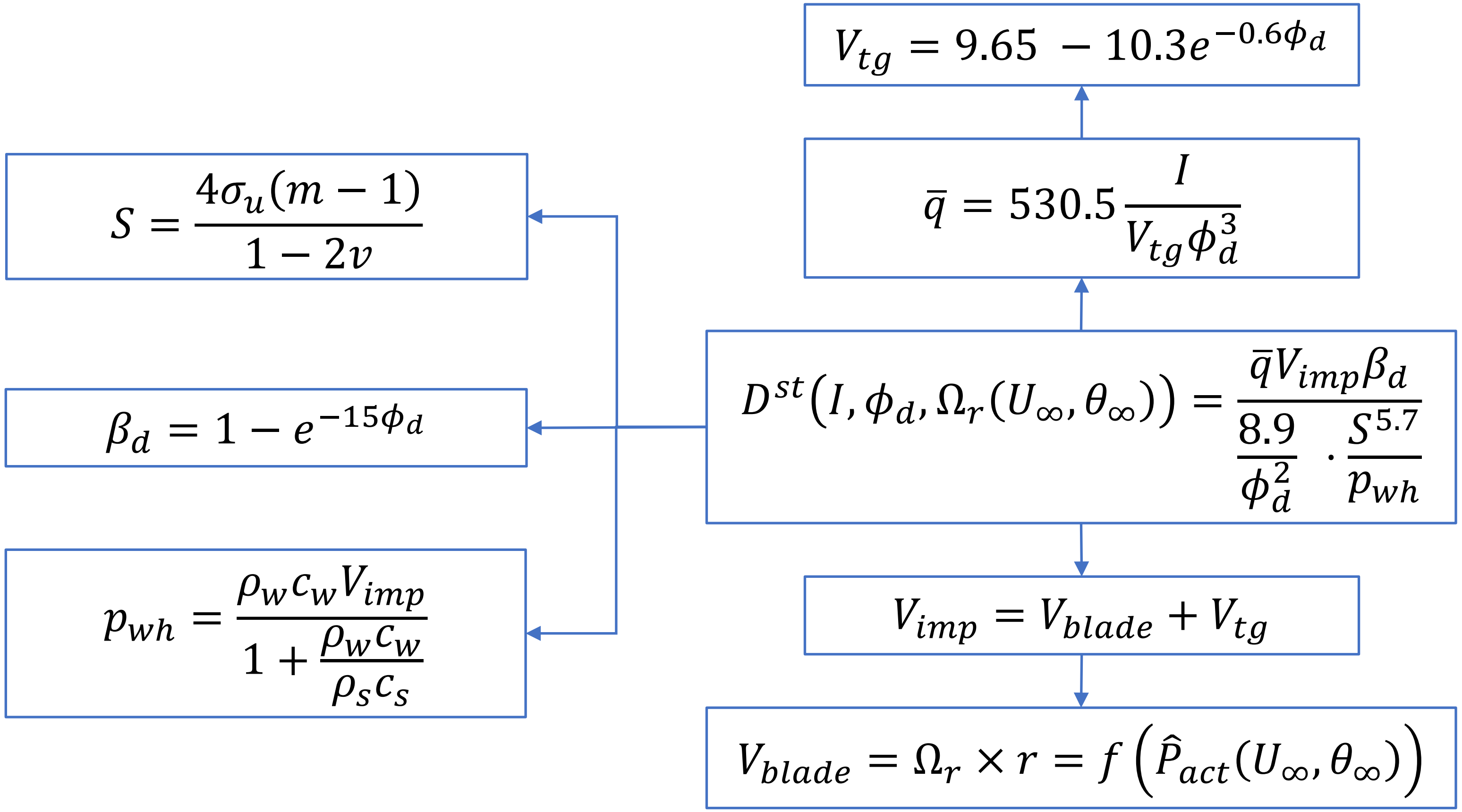
$$V_{imp} = V_{blade} + V_{tg}$$

$$V_{blade} = \Omega_r \times r = f\left(\hat{P}_{act}(U_\infty, \theta_\infty)\right)$$

- $\bar{q}$: *Number of rain droplets per unit volume*
- V_{imp}: *Impact velocity of the rain droplet [m/s]*
- β_d: *Impingement efficiency [-]*
- S: *Erosive strength of the material [MPa]*
- p_{wh}: *Waterhammer pressure [MPa]*
- V_{tg}: *Terminal velocity of the rain droplet [m/s]*
- V_{blade}: *Wind turbine blade tip speed [m/s]*
- Ω_r: *Rotor speed [rad/s]*
- r: *Blade radius [m]*
- $\hat{P}_{act}$: *Expected power from wake simulation [MW]*

Damage model

Springer[5] model:



$$V_{tg} = 9.65 - 10.3e^{-0.6\phi_d}$$

$$\bar{q} = 530.5\frac{I}{V_{tg}\phi_d^3}$$

$$D^{st}\left(I, \phi_d, \Omega_r(U_\infty, \theta_\infty)\right) = \frac{\bar{q}V_{imp}\beta_d}{\frac{8.9}{\phi_d^2} \cdot \frac{S^{5.7}}{p_{wh}}}$$

$$V_{imp} = V_{blade} + V_{tg}$$

$$V_{blade} = \Omega_r \times r = f\left(\hat{P}_{act}(U_\infty, \theta_\infty)\right)$$

$$S = \frac{4\sigma_u(m-1)}{1-2v}$$

$$\beta_d = 1 - e^{-15\phi_d}$$

$$p_{wh} = \frac{\rho_w c_w V_{imp}}{1 + \frac{\rho_w c_w}{\rho_s c_s}}$$

- $\bar{q}$: *Number of rain droplets per unit volume*
- V_{imp}: *Impact velocity of the rain droplet [m/s]*
- β_d: *Impingement efficiency [-]*
- S: *Erosive strength of the material [MPa]*
- p_{wh}: *Waterhammer pressure [MPa]*
- σ_u: *Ultimate tensile strength of material [MPa]*
- m: *Wohler's slope [-]*
- v: *Poisson's ratio of coating material [-]*
- ρ_w, ρ_s: *Density of water and coating material [kg/m³]*
- c_w, c_s: *Speed of sound of water and coating material [m/s]*

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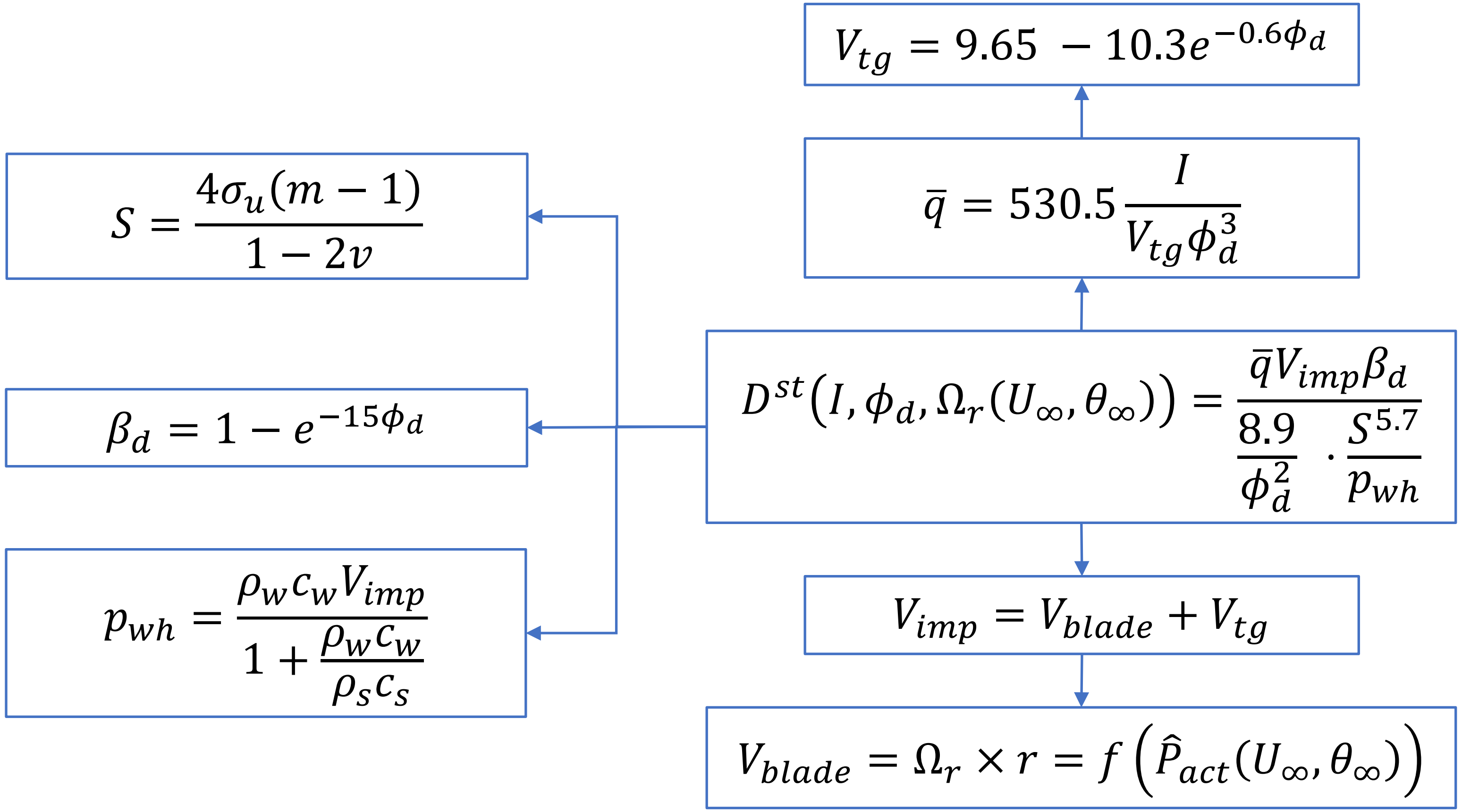
Damage model

Springer[5] model:



$$V_{tg} = 9.65 - 10.3e^{-0.6\phi_d}$$

$$\bar{q} = 530.5 \frac{I}{V_{tg}\phi_d^3}$$

$$D^{st}(I, \phi_d, \Omega_r(U_\infty, \theta_\infty)) = \frac{\bar{q} V_{imp} \beta_d}{\frac{8.9}{\phi_d^2} \cdot \frac{S^{5.7}}{p_{wh}}}$$

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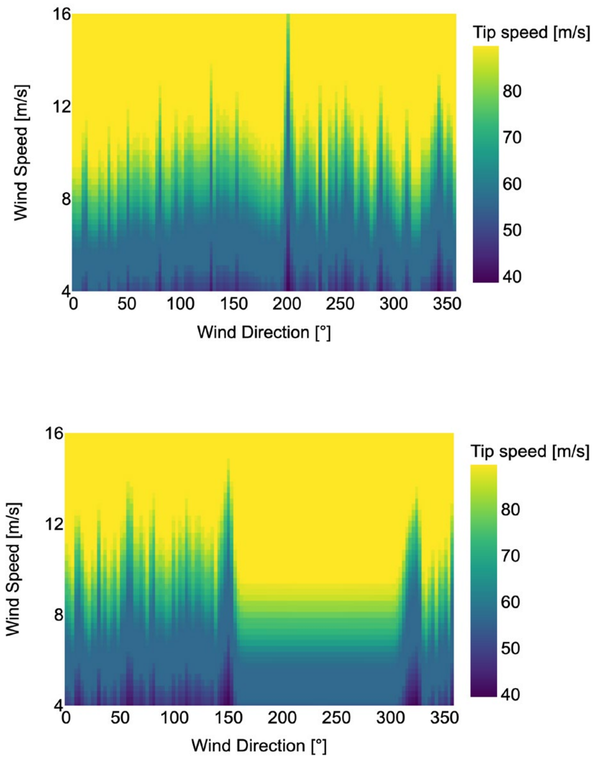
- *$\bar{q}$: Number of rain droplets per unit volume*
- *V_{imp}: Impact velocity of the rain droplet [m/s]*
- *β_d: Impingement efficiency [-]*
- *S: Erosive strength of the material [MPa]*
- *p_{wh}: Waterhammer pressure [MPa]*
- *Coating properties taken from Verma et al. (2021) [1]*

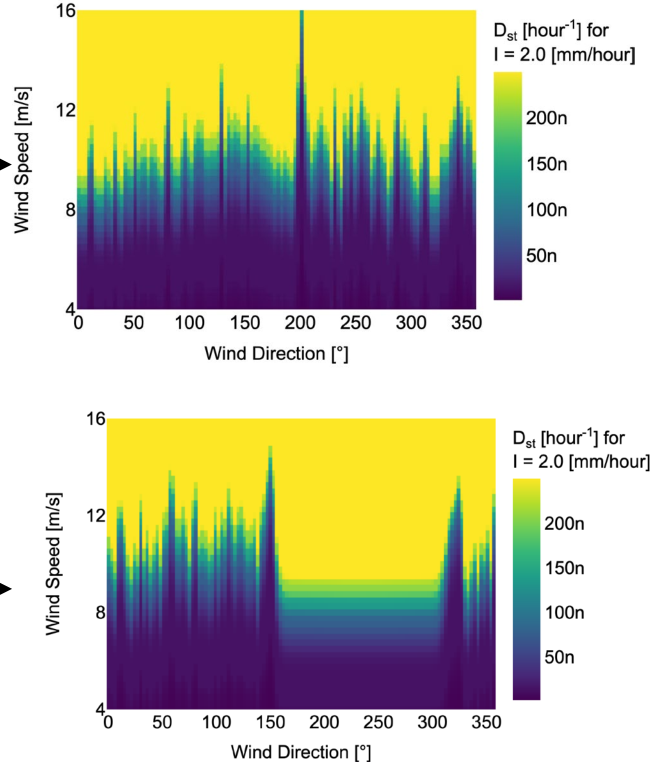
Results

Centrally located →

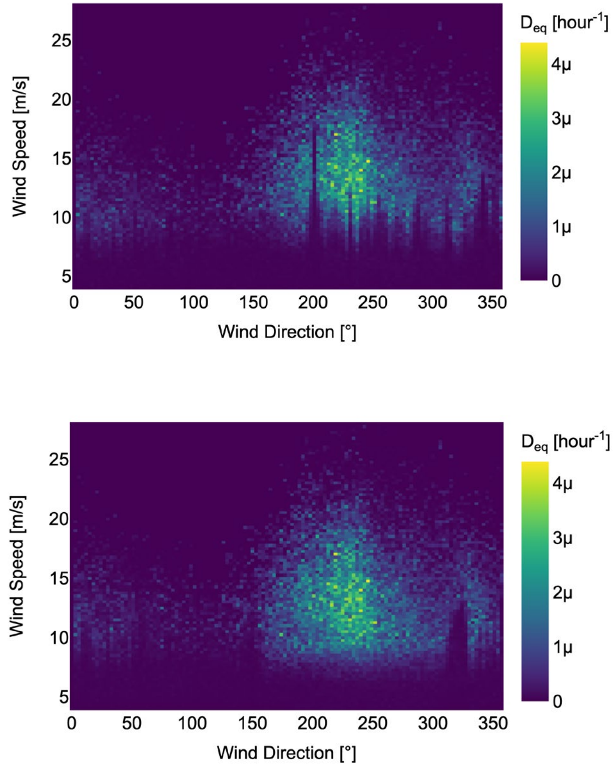
Peripherally located →



Joint distribution of blade tip speed in [m/s] for wind speed bins of 0.25 m/s and wind direction bins of 3°.



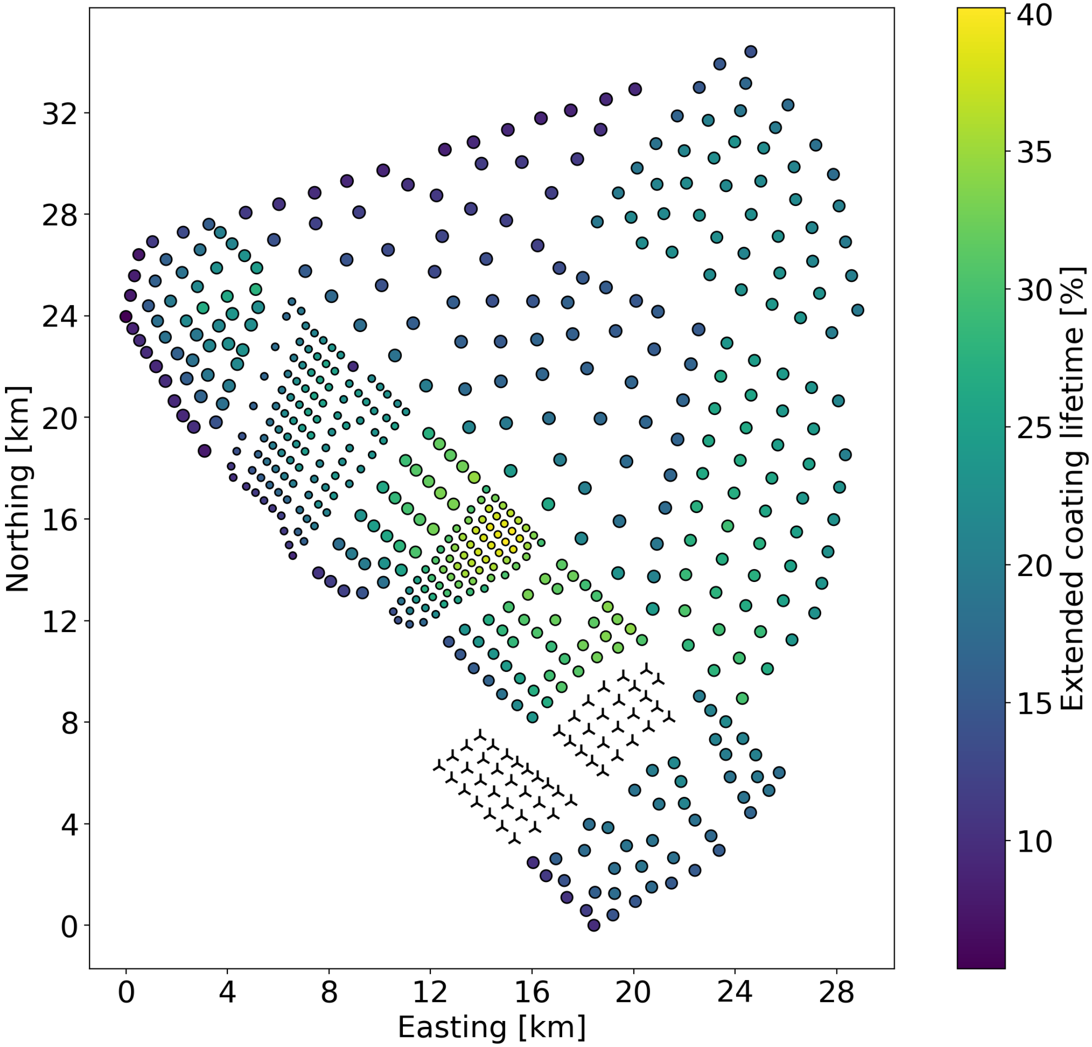
Joint distribution of short-term damage in [hour^{-1}] for wind speed bins of 0.25 m/s and wind direction bins of 3°.



Joint distribution of equivalent damage in [hour^{-1}] for wind speed bins of 0.25 m/s and wind direction bins of 3°.

Results

- Coating lifetimes can be extended ranging from 5% to 40% for densely packed wind farms.
- Turbines predominantly positioned upstream are found to have the shortest coating lifetime.
- Coating lifetime increases can vary between different turbine manufacturers due to different rotor speed curves.



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Conclusion

- The effect of rain-induced leading-edge erosion on wind turbine blades using a physic-based framework is presented.
- Wind and rain statistics are derived from ERA5 data[2].
- Wake effect are modeled through the TurbOPark model with Gaussian wake profile[4].
- Springer[5] fatigue model is applied to calculate the short-term damage.
- Results show that coating lifetime variability across the wind farms can be as high as 35%.
- Turbines predominantly positioned upstream are found to have the shortest coating lifetime.

Acknowledgements

- The Norwegian Directorate for Higher Education and Skills (HK-dir) through the NUWind project (project number UTF-2021/10157)
- The Flemish Agency for Innovation and Entrepreneurship (VLAIO) through project ICON Rainbow and project Cloud4Wake.

References

[1]Verma A, Jiang Z, Ren Z, et al. 2021 *Wind Energy* **24** 1315-1455 ISSN 0960-1481

[2]Hersbach H 2020 *Quarterly Journal of the Royal Meteorological Society* **146** 1999-2049 ISSN 1477-870X

[3]Best A C 1950 *Quarterly Journal of the Royal Meteorological Society* **76** 16-36 ISSN 1477-870X

[4]Pedersen J G, Svensson E, Poulsen L and Nygaard N G 2022 *Journal of physics: Conference Series* **2265** 022063

[5]Springer G S 1976 *Erosion by liquid impact*

Thank you for your attention

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