Analysis and Verification of the Frandsen Turbulence Model for Wind Turbine Site Suitability Assessment

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hybr2d Theory of Hybrid Systems Informatik 2 | RWTH AACHEN UNIVERSITY

Motivation

- Suitable space for wind energy is limited and therefore should be used efficiently.
- Too closely spaced wind turbines can create stronger wake effects, which increase turbulence and structural loads on downstream turbines.
- **Problem:** Closely spaced wind turbines must withstand both site-specific wind and turbulence conditions and the additional wake effects from nearby turbines over their expected lifespan.

Site suitability assessment, including turbulence analysis

- Verify that the planned turbine type is designed to withstand the wind and turbulence conditions present at the considered location.

Goal

- Develop a simple tool to automatically assess a given site based on freely available datasets in accordance with all relevant national and international guidelines.

Turbulence

Turbulence Intensity

ratio of the standard deviation of the turbulent wind speed to the average wind speed:

$$I = \frac{\sigma}{v_{ave}}$$

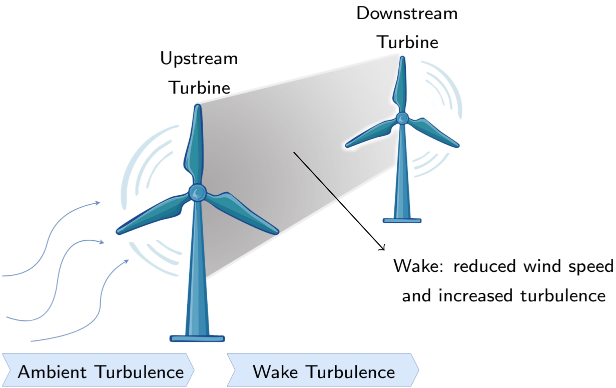


Figure: Schematic illustration of the wake effect

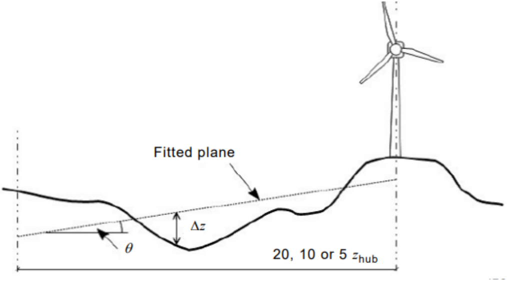
Legal Guidelines and Regulations

Multiple international and national regulations

- IEC 61400-1 2019:
  - Topographical complexity
  - Turbine design limits which may not be exceeded
  - Procedure to assess site suitability
- DIN EN 1991-1-4 National Appendix
  - Wind Zones, Terrain Roughness Categories
- DIBt Guideline
  - Verify structural stability of buildings in Germany
  - Simplifications for non-complex terrain

Topographical Complexity

- Topographical complexity can significantly affect the structure of turbulence, which could lead to more severe aerodynamic loads.
- It is defined based on the slope and variations of the terrain present at a considered site.

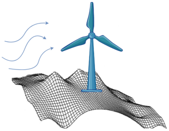
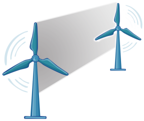
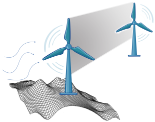


- For non-complex sites, a simplified procedure can be applied to assess the site suitability.

Determine Site Suitability for non-complex sites

Each turbine type has limits which may not be exceeded by the conditions at a specific site

- The site's average wind speed needs to be lower than the turbine's design average wind speed v_{ave}.
- The site's extreme wind speed needs to be lower than the turbine's design extreme wind speed v_{m50}.
- Effective turbulence intensity needs to be lower than turbine's design turbulence intensity for all wind speeds between $0.2v_{m50}$ and $0.4v_{m50}$.

Ambient Turbulence	Added Turbulence	Combined Turbulence	Effective Turbulence
$I_{rep}(v)$	$I_{add}(v)$	$I_{combined}(v)$	$I_{eff}(v)$
influenced by site's topography and land cover 	created by upstream turbines 	includes both ambient and wake-added turbulence 	includes all turbulence contributions from all wind directions weighted by how often the wind comes from each direction

Ambient Turbulence Intensity

Ambient turbulence intensity is heavily influenced by the wind conditions, topography, and **land cover** around a site.

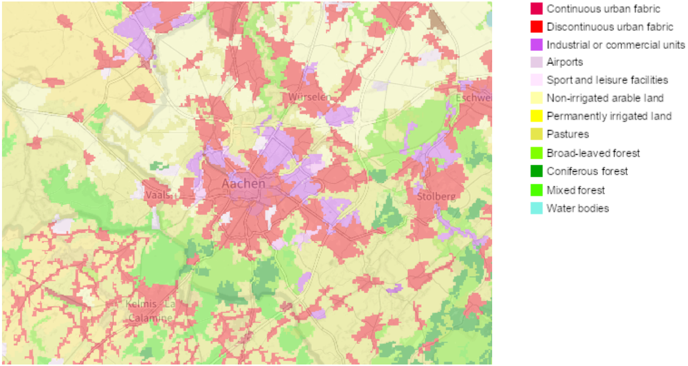


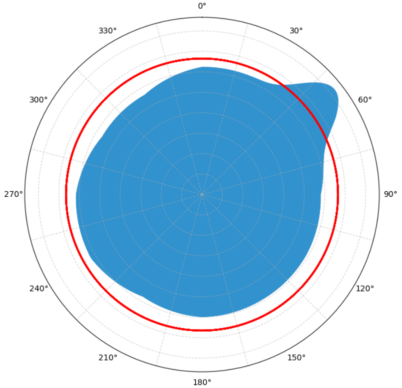
Figure: CORINE raster data for Aachen and suburbs. Legend is reduced.

Frandsen Turbulence Model

Effective turbulence intensity:

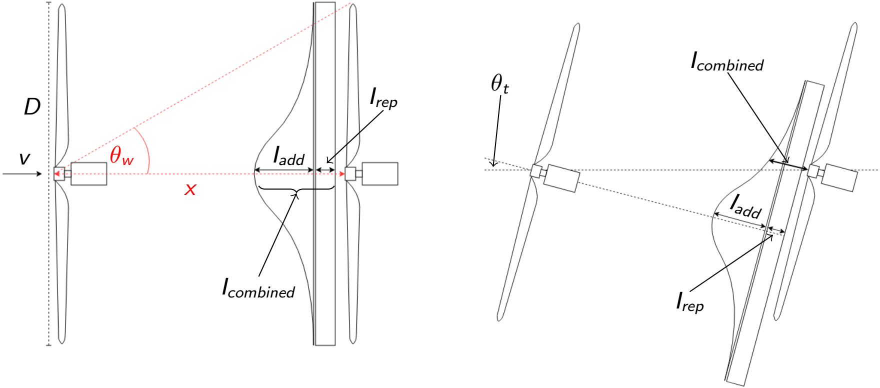
$$I_{eff}(v) = \left(\int_0^{2\pi} p(\theta|v) \cdot I_{combined}(\theta|v)^{m^T} d\theta \right)^{1/m^T}$$

where θ denotes the wind direction, $p(\theta|v)$ represents the probability of wind coming from θ given wind speed v, and m^T is the Wöhler exponent, which characterizes the material's fatigue behavior.



Frandsen Turbulence Model

Modelling the combination of ambient and wake-added turbulence of multiple turbines.



D is the rotor diameter, x the distance, θ_t the angle between the wind direction and the line connecting the two turbines, and θ_w is an estimate of the wake's angular opening.

Frandsen Turbulence Model

$I_{combined}$ according to Frandsen:

$$I_{combined}(\theta) = I_{rep}\left(1 + \alpha \exp\left(-\left[\frac{\theta_t}{\theta_w}\right]^2\right)\right)$$

with θ_t being the angle between wind direction θ and the line connecting both turbines, the wake's angular opening θ_w and

$$\alpha = \sqrt{\left(\frac{I_{add}}{I_{rep}}\right)^2 + 1} - 1$$

and maximal wake-added turbulence intensity

$$I_{add} = \frac{1}{1.5 + 0.8\frac{x/D}{\sqrt{C_T}}}$$

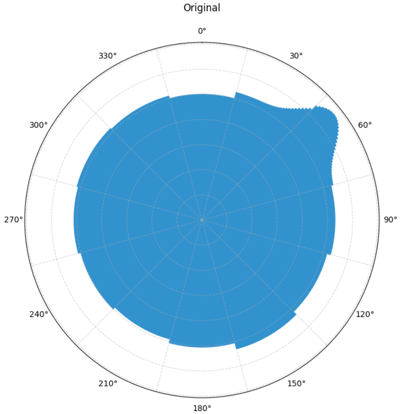
where C_T is the thrust coefficient of the upstream turbine. Intuitively, it describes how much momentum the turbine extracts from the incoming wind flow.

Frandsen Variations

Problem: I_{eff} requires $p(\theta|v)$ for each direction but it is only available per 30° sector. Which angle should be chosen for $I_{combined}$?

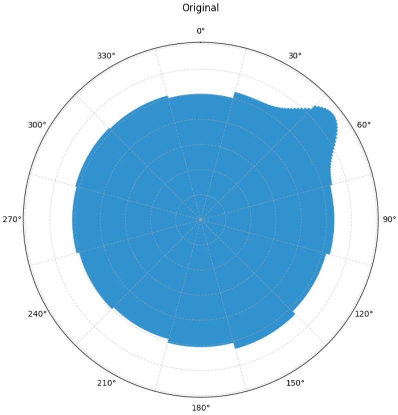
$$I_{eff}(v) = \left(\int_0^{2\pi} p(\theta|v) \cdot I_{combined}(\theta|v)^{m^T} d\theta \right)^{1/m^T}$$

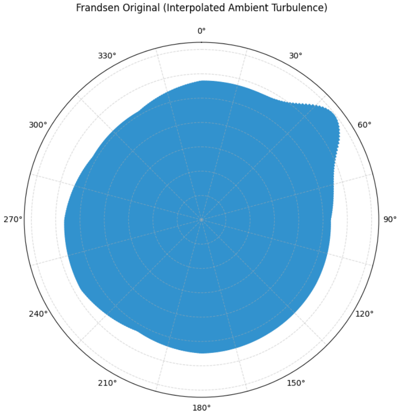
Approach: Subdivide each 30° sector i into n subsectors with each of them having a probability of $\frac{p(i|v)}{n}$.



Frandsen Variations

As the ambient turbulence I_{rep} is also only available per 30° sector, abrupt jumps at the transition of two sectors occur. To smooth it, we introduce a variant with linearly interpolated values for I_{rep}.

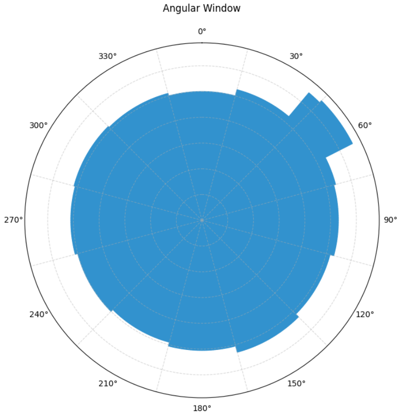




Frandsen Variations

More variations are possible:

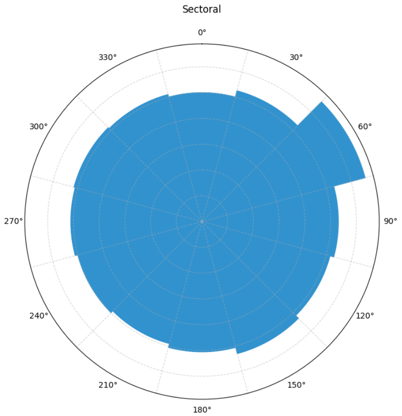
- Frandsen states that using the maximum wake at the wake center over the wake's angular opening angle θ_w produces approximately the same effective turbulence intensity **(Angular Window)**.



Frandsen Variations

More variations are possible:

- Using the maximum wake at the wake center over the whole sector, if the sector contains an upwind turbine **(Sectoral)**.



Average Wind Speed

Average wind speed v_{ave} is directly determined from measurements.

- The simulation has access to data from roughly 275 Deutscher Wetterdienst (DWD) weather stations across Germany.
- Dataset contains 10-minute average wind speeds (with corresponding wind sector).

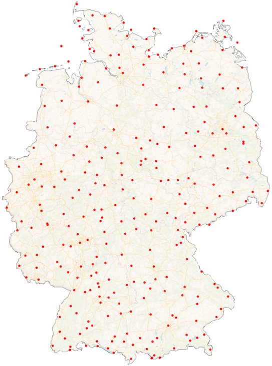
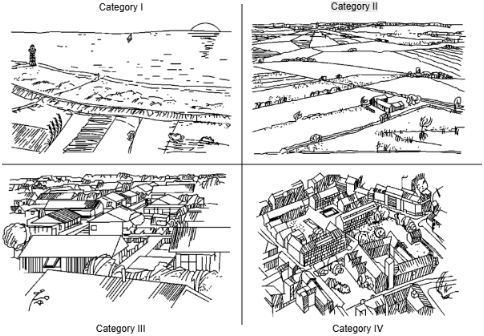


Figure: Available DWD wind stations in Germany.

Extreme Wind Speed

Extreme wind speed v_{m50} is estimated according to legal guidelines.

- v_{m50} is the value of the highest wind speed, averaged over 10 minutes, with a return period of 50 years (annual probability of exceedance of 0.02).
- It can be estimated based on the wind zone and terrain category of a site and the hub height of the turbine.

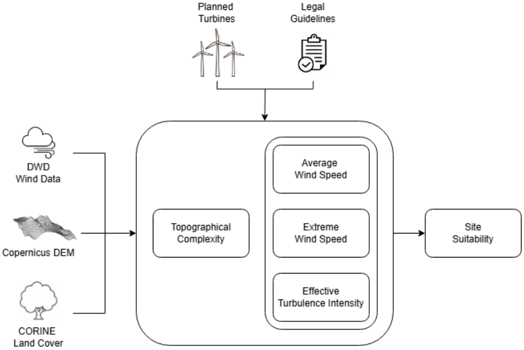


Results

Comparison of our simulation with three different wind farms with professional site reports by I17. The wind farms consist of one, two and four turbines.

The comparison includes:

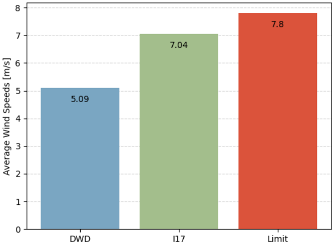
- Topographical complexity
- Average wind speed
- Extreme wind speed
- Effective turbulence intensity

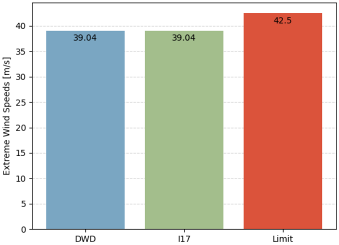


Results - Wind Farm Berge

Wind farm in Berge, Lower Saxony, consisting of one turbine. As no wake effects occur, this case is perfect for comparing the approach used to estimate the ambient turbulence intensity.

- Both assessments classify the site as non-complex
- Different average wind speed, because different wind-data sources were used (DWD station with a distance of 25 km used)
- Same extreme wind speed





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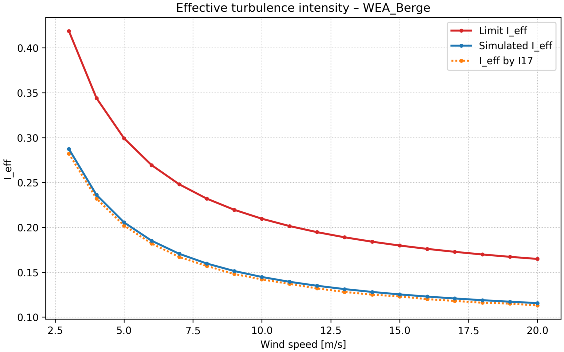
- Different average wind speed, because different wind-data sources were used (DWD station with a distance of 25 km used)
- Same extreme wind speed
- Comparable results for effective turbulence intensity (average deviation of 2.06%). Both assessments are well below the turbine's limit.



Results - Wind Farm Bever

Wind farm in Glandorf, Lower Saxony, consisting of two turbines. Good for comparing all variations of the Frandsen Turbulence Model.

Results - Impact of Subdivision

For this configuration, a reference turbulence simulation is performed for the **Frandsen Original** variant, using a subdivision of $n = 3000$.

Comparison with smaller numbers of subdivisions:

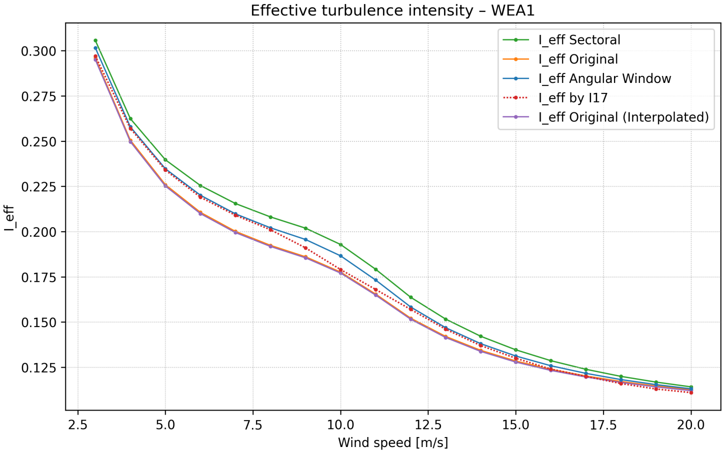
n	Avg WEA1 [%]	Max WEA1 [%]	Avg WEA2 [%]	Max WEA2 [%]
1	3.70	7.83	4.87	8.75
2	1.77	3.24	2.15	3.33
3	0.4	0.83	0.46	0.83
4	0.03	0.08	0.04	0.08
5	0.04	0.08	0.04	0.05
10	0.01	0.02	0.01	0.02
15	$<$0.01	$<$0.01	$<$0.01	$<$0.01
30	$<$0.01	$<$0.01	$<$0.01	$<$0.01

Table: Average and maximum absolute differences in effective turbulence intensity for different numbers of subdivisions n, relative to the reference case $n = 3000$.

For the Frandsen Original variant, the default number of subdivisions is set to 30 in the simulation.

Results - Comparison of all four Frandsen Variations

- While the **Original** variant consistently underestimates the I17 reference results, the **Sectoral** approach consistently overestimates them.
- **Angular Window** approach is closest to I17 reference with average deviation of 1.40% and maximum deviation of 4.22% at 10 m/s.



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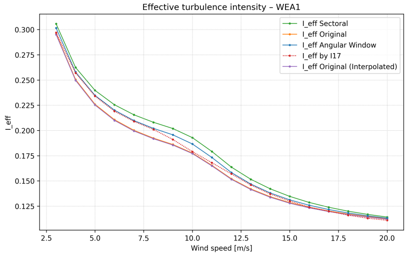


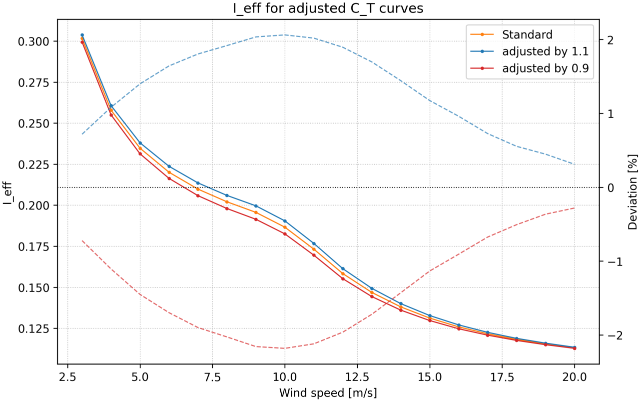
Possible Explanations:

- Different approach/formulas for ambient turbulence intensity
- Different C_T curve (non-public, usually provided by the turbine manufacturer)

Results - Sensitivity C_T curve

How does the effective turbulence intensity respond to changes in the C_T curve?

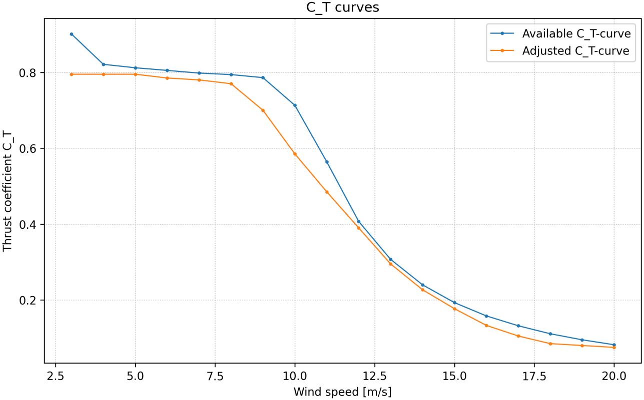
- Scaled the available C_T curve by $\pm 10\%$



- Most sensitive at a wind speed of around 10 m/s, but with a damped effect.

Results - Sensitivity C_T curve

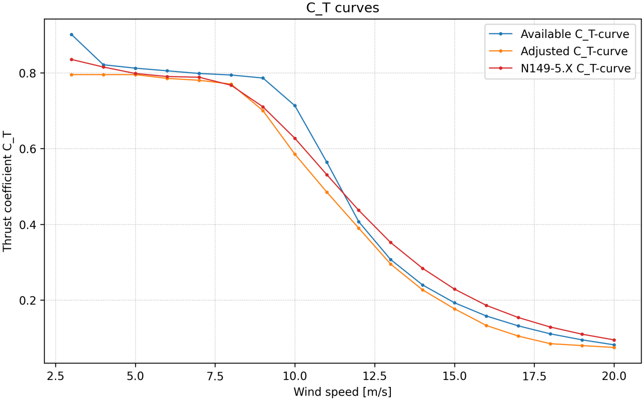
What shape would the C_T curve need to have in order to reproduce the same results as I17?



Blue: available thrust curve from an unreliable source. **Orange**: adjusted thrust curve to match I17 results.

Results - Sensitivity C_T curve

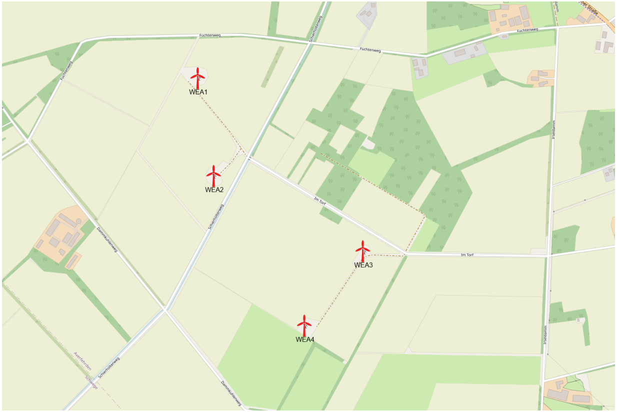
Which curve is more plausible?



Blue: available thrust curve from an unreliable source. **Orange**: adjusted thrust curve to match I17 results. **Red**: thrust coefficients of a similar turbine with a higher rated power.

Results - Wind Farm Glandorf

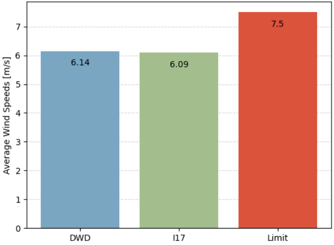
Wind farm in Glandorf, Lower Saxony, consisting of four turbines. Here, also the **Angular Window** approach provided the closest results.

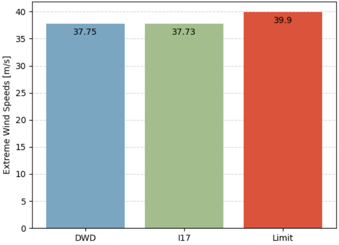


Results - Wind Farm Glandorf

Wind farm in Glandorf, Lower Saxony, consisting of four turbines. Here, also the Angular Window approach provided the closest results.

- Both assessments classify the site as non-complex
- Comparable average wind speed (DWD station with a distance of 17 km used)





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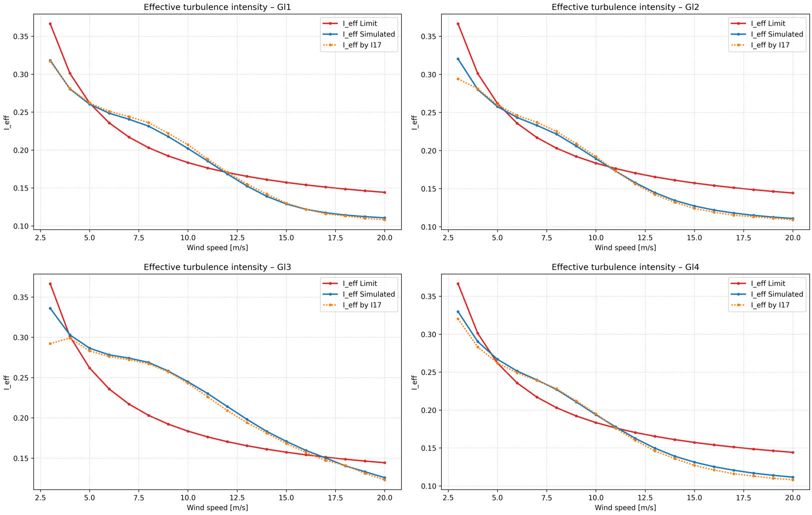

Conclusion and Future Work

Current state

- Professional-grade results are achievable using free, publicly available data sources.

But further validation needed

- Benchmarking our tool in the 2025 round-robin comparison on ambient turbulence conducted by the Bundesverband WindEnergie.
  - A study with 24 certified consultants analyzing the same site for ambient turbulence using identical input data.
- Test cases and comparisons with other providers of site suitability assessments (TÜV Nord, TÜV Süd, ...)

Additional Material

Extreme Wind Speed

- Instead of the log wind profile, the wind profile power law should be used in Germany

$$v(z) = v(z_{ref}) \cdot \left(\frac{z}{z_{hub}}\right)^{\alpha}$$

- DIN 1991-1 NA provides required profile exponents and coefficients for each wind zone and terrain category

Example for wind zone 2 and terrain category III:

$$v_{m50}(z) = 0.77 \cdot 25.0 \left(\frac{z}{10}\right)^{0.22}$$

Wind Zone	$v_{b,0}$ [m/s]
WZ 1	22.5
WZ 2	25.0
WZ 3	27.5
WZ 4	30.0

Figure: Basic wind speeds $v_{b,0}$ for the four German wind zones

Ambient Turbulence Intensity

Ambient turbulence intensity is heavily influenced by the wind conditions, topography and **land cover** around a site.

Approach:

- The area surrounding each turbine is divided into 30° sectors, and raster land-cover data in each sector is analysed.
- Each land-cover class is assigned a suggested roughness length z_0 according to the European Wind Atlas.
- For each sector, a representative roughness length is calculated by weighting the roughness values of the land-cover tiles based on their distance from the turbine.
- Using these sector-specific roughness lengths, the ambient turbulence intensity can be estimated.

Ambient Turbulence

The ambient turbulence intensity can then be estimated according to the "Guidelines for Design of Wind Turbines" using the sector-specific roughness lengths:

$$I_{amb} = A_x k \frac{1}{ln(\frac{z_{hub}}{z_0})}$$

with A_x being an empirical parameter ranging from 1.8 for rough terrain to 2.5 for smooth terrain, von Karman's constant $k \approx 0.4$ and roughness length z_0.

Turbine Design Limits

Each turbine type comes with

- A wind speed class, providing design v_{ave} and v_{m50} at hub height.
- A turbulence category, providing a reference turbulence value I_{ref}.
- The normal turbulence model (NTM) describes the expected turbulence during normal wind turbine operation:

$$I_{NTM}(v) = I_{ref}\left(0.75 + \frac{5.6\,\frac{m}{s}}{v}\right)$$

Wind Speed Class	$v_{ave}(z_{hub})$ [m/s]	$v_{m50}(z_{hub})$ [m/s]
I	10	50
II	8.5	42.5
III	7.5	37.5
S	-	-

Turbulence Category	I_{ref}
A+	0.18
A	0.16
B	0.14
C	0.12
S	-

Site Suitability for Complex Sites

The procedure for assessing site suitability for complex sites extends the method used for non-complex sites by including:

- Requirements for the wind speed distribution.
- The wind energy-weighted mean of the site flow inclination from all directions shall be between -8° and $+8^\circ$.
- The energy-weighted average of the site's vertical wind shear exponent α across all wind sectors must be in the range of 0.05 to 0.25.
- Requirements for air density.
- Requirements for extreme ambient turbulence and extreme wake turbulence (ETM).