TURBULENCE OF WIND TURBINES

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RWTH Aachen University

Overview

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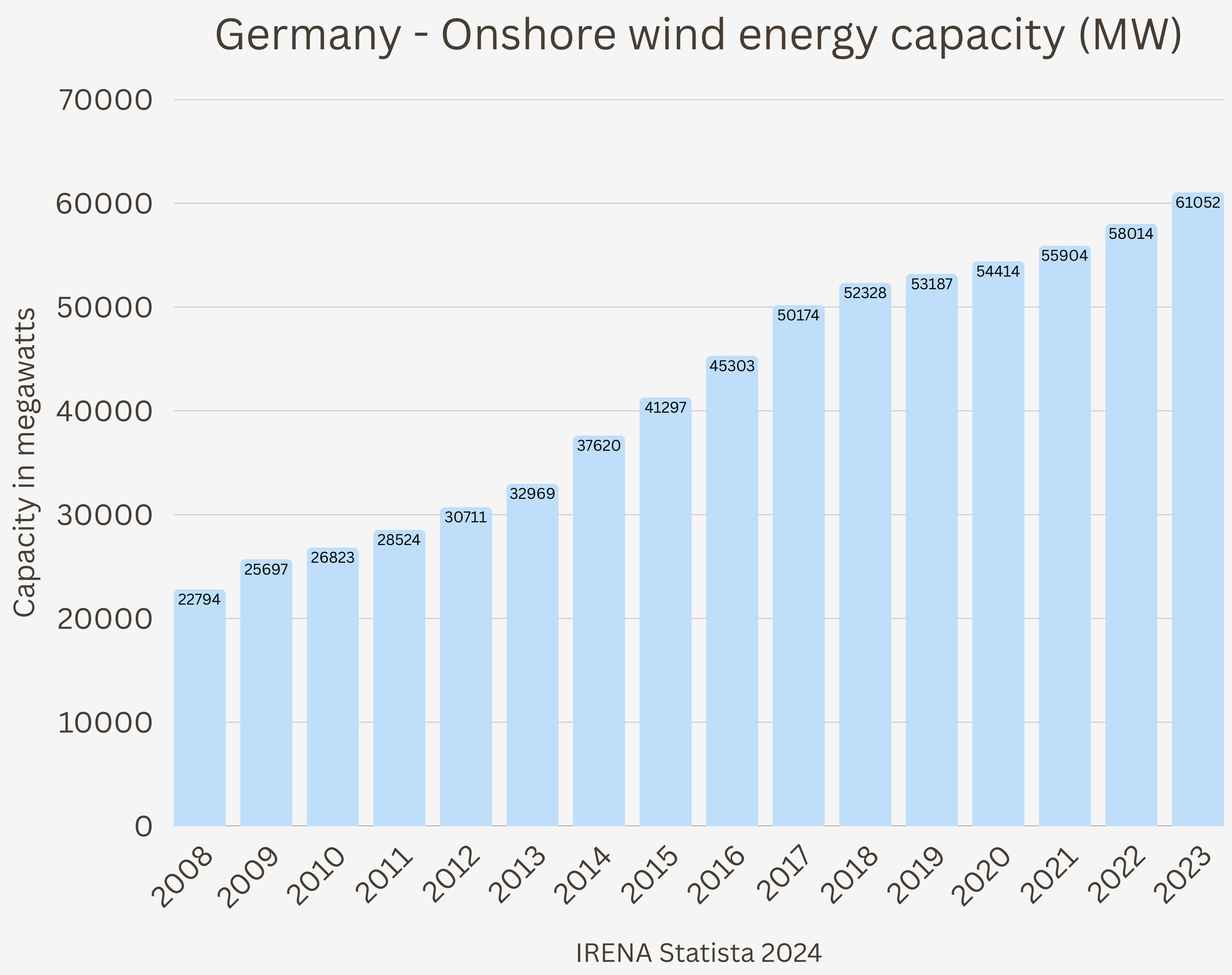
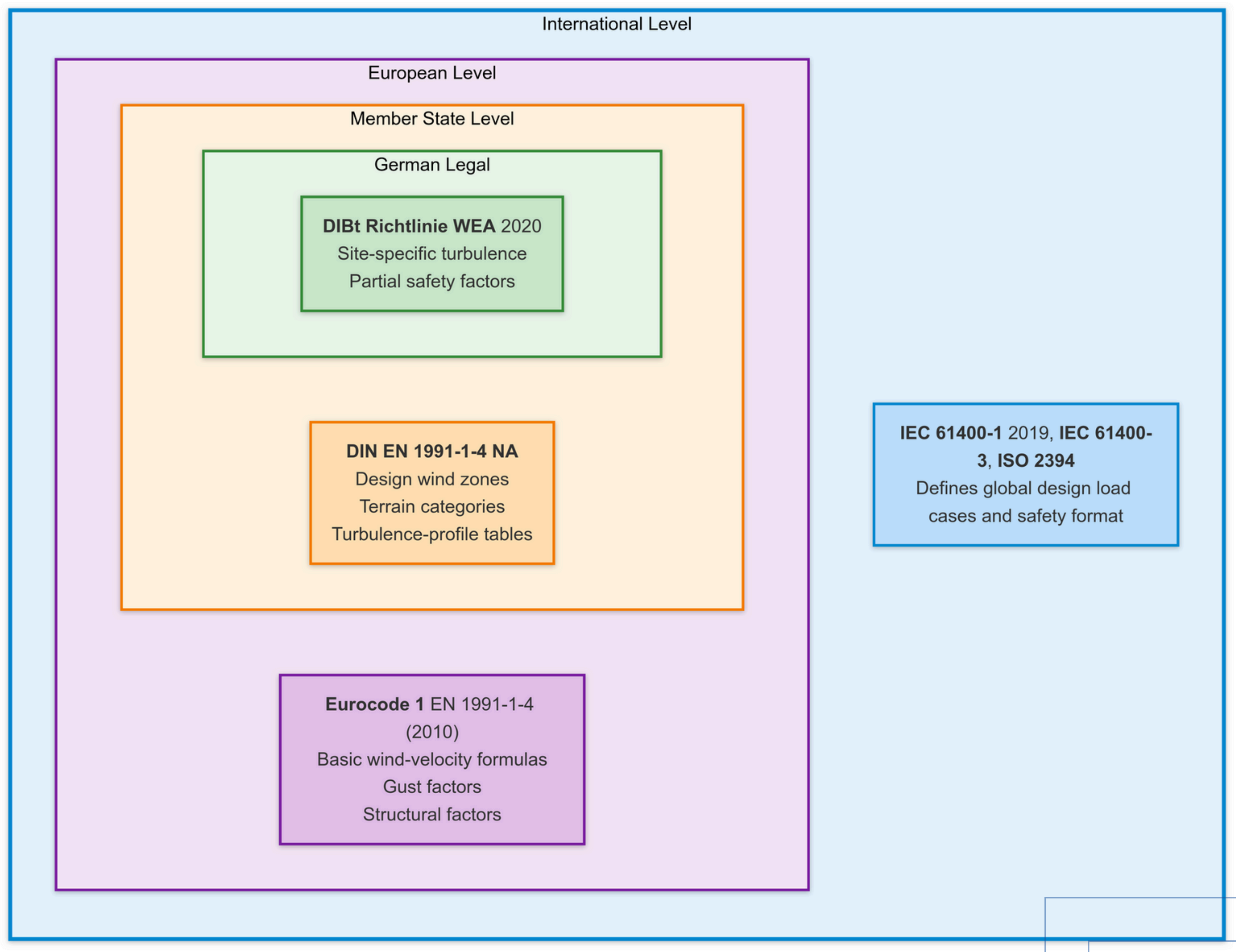
Motivation

- **Energy Transition Goal**: Massive expansion of wind energy is critical
- **Bottleneck:** Slow approval processes in Germany
- **Core Problem: Turbulence**
  - Reduces energy output by 10-15% due to wake effects.
  - Increases mechanical stress, shortening turbine lifespan.
  - Incorrect assessment leads to financial and safety risks.
- **Goal:** Develop a precise, accessible, and open-source tool to accelerate regulatory-compliant turbulence analysis.



Regulations and Norms

- **IEC 61400-1 2019:**
  - International Norm with minimum requirements for wind turbines (NTM, ETM, Complexity).
- **DIN EN 1991-1-4 NA:**
  - German national appendix of European norm.
  - Wind Zones, Terrain Roughness Categories.
- **DIBT Richtlinie:**
  - Guideline to verify structural stability of buildings in Germany.
  - Simplifications for non-complex terrain.



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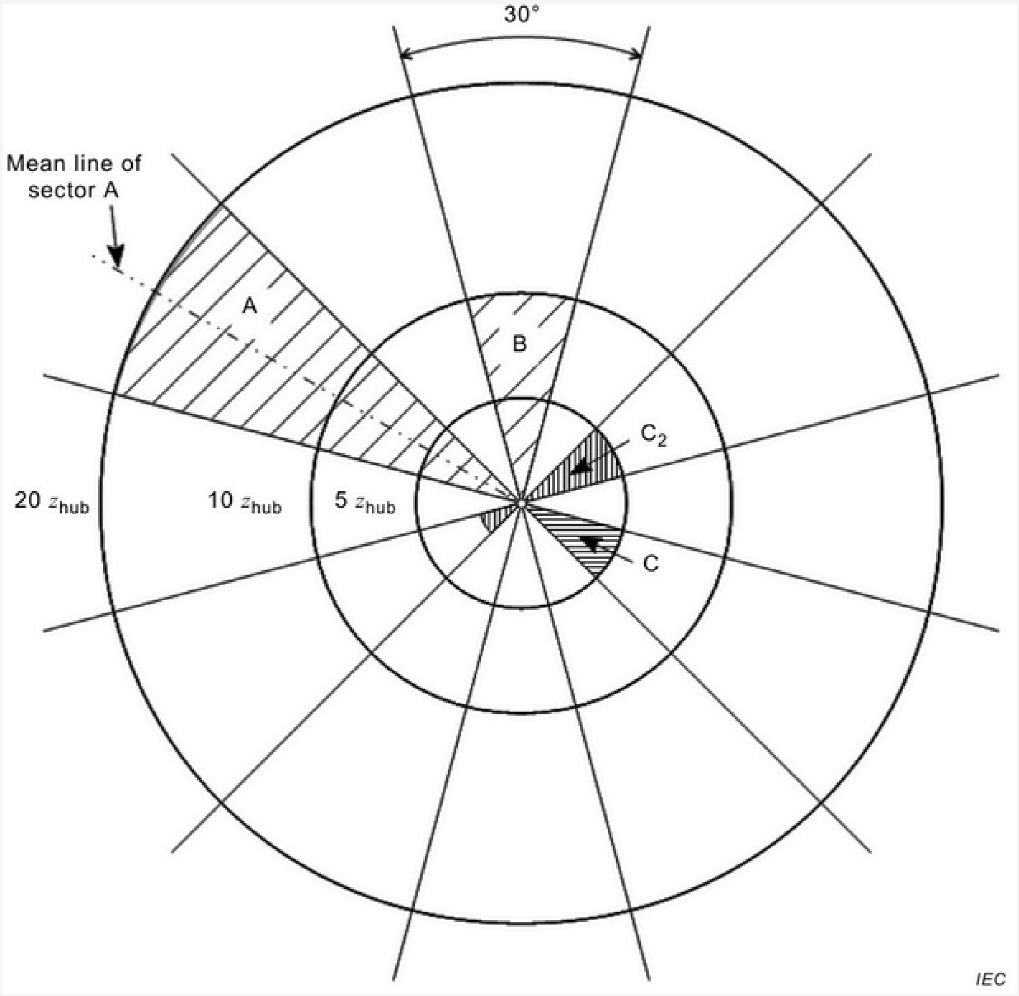
Topographical Complexity

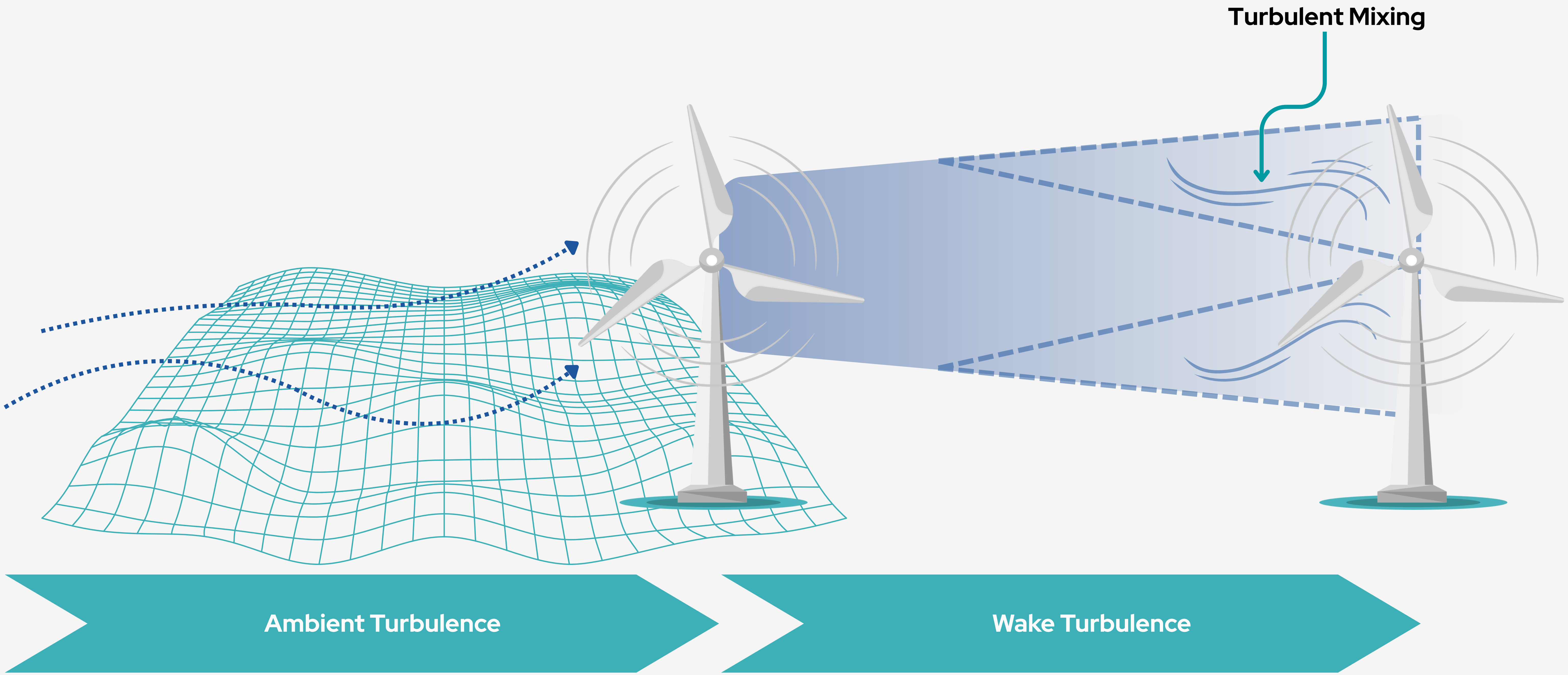
- **Inputs**
  - **Digital Elevation Model (DEM)** with less or equal to 50 meter grid.
  - **Hub height** (z hub) and **wind energy by sector** (12 x 30° wind-rose sectors)
- **Method**
  a. **Sectorize:** 12 x 30° and three radii: 5, 10 , 20 * z hub.
  b. Fit a plane per sector and radius. Compute slope and terrain variation vs the plane.
  c. Compute indices (energy-weighted)
     - TSI30 and TVI30 across 12 sectors using the sector energy shares.
     - TSI360 and TVI360 over the full 360°.
  d. **Decide complexity** by comparing each index at each radius with a given threshold table. If all indices are below the low level, the site is not complex. Otherwise Low/Medium/High complexity, by the worst exceedance.



Topographical Complexity

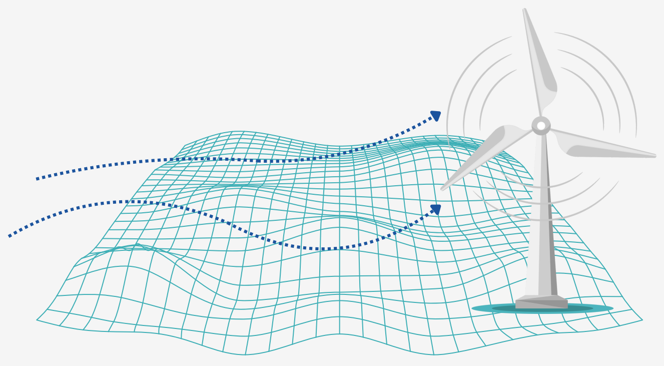
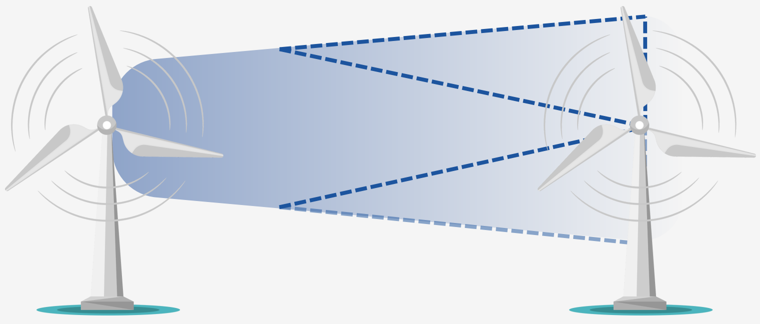
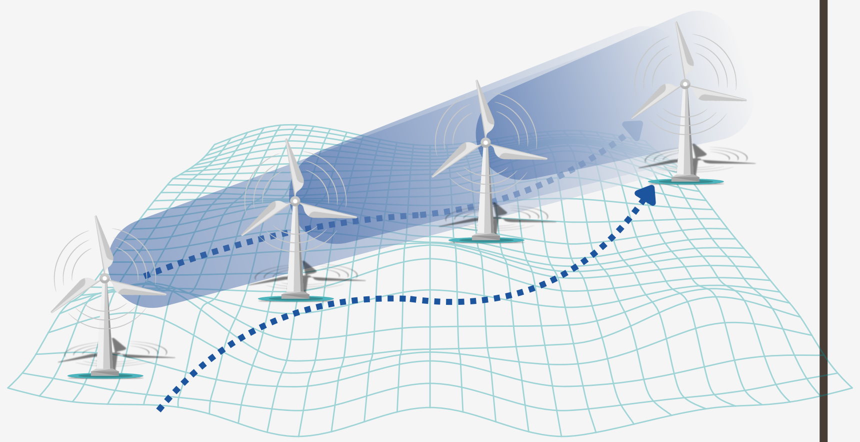
Radius	Sector amplitude of fitted plane	Threshold values					
		Terrain slope index (TSI)			Terrain variation index (TVI)		
		L	M	H	L	M	H
5 z_hub	360°	10°	15°	20°	2%	4%	6%
5 z_hub	30°						
10 z_hub							
20 z_hub							

Turbulence



Frandsen Model

- **Calculate effective turbulence intensity** experienced by a wind turbine operating within a wind farm environment

Ambient Turbulence	Additional Turbulence	Combine Turbulence	Effective Turbulence Intensity
$I_{rep}^{S}(v)$	$I_{add}^{T}(T_j \mid v)$	$I_{combined}^{T}(i \mid v)$	$I_{eff}^{S,T}(v)$
 The ambient turbulence at a given **site S** at a **wind speed v** is based on the **mean- and standard deviation of turbulence intensity**.	 Additional turbulence intensity contributed by each **upstream turbine** is determined based on the normalized distance between the turbines and the wind speed.	 The **ambient turbulence** and **wake turbulence** of each upstream turbine are **combined** to determine the **total turbulence intensity**.	The effective turbulence intensity is determined by summing the turbulence contributions across sectors, weighted by the directional wind distribution and adjusted by the Wöhler exponent.

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Frandsen Model Inputs

Category	Parameter	Definition
Turbine Parameters	m_T	**Wöhler Exponent** – Characterizing material fatigue behaviour of the most vulnerable part of the turbine.
	D_T	**Rotor Diameter** – of a wind turbine.
	C_T	**Rotor Thrust Coefficient** – Used in wake turbulence modeling, usually obtained through the manufacturer.
Site / Wind	v	**Wind Speed** – in m/s
	$pdf_v^S(\theta, v)$	**Directional wind distribution** – indicating the likelihood of wind from sector Theta at velocity v.
Layout	d_{T,T_j}	**Distance** – between the affected turbine T and the upstream turbine Tj.

Frandsen Model

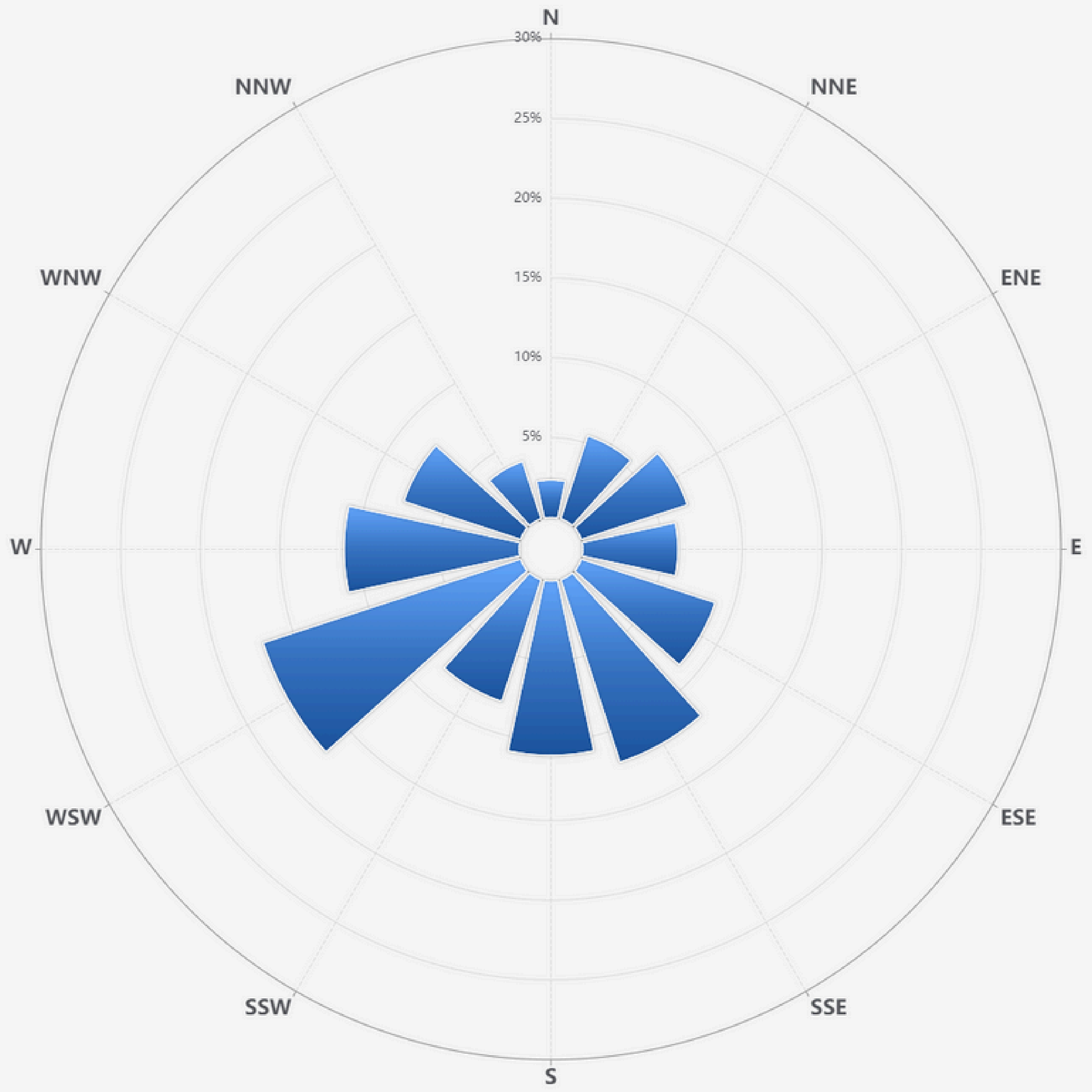
$$I_{add}^{T}(T_j, v) = \sqrt{\frac{0.9}{\left(1.5 + 0.3 \cdot d_{T,T_j} \cdot \sqrt{v}\right)^2}}$$

$$I_{rep}^{S}(v) = I_{\text{mean}}(v) + 1.28 \cdot I_{\text{stddev}}(v)$$

$$I_{combined}^{T}(i, v) = \sqrt{I_{\text{rep}}^{S}(v)^2 + \sum_{T_j \in S_{<10D}^{T}(i)} I_{\text{add}}^{T}(T_j, v)^2}$$

$$I_{eff}^{S,T}(v) = \left(\sum_{i=1}^{12} pdf_v^S(i, v) \cdot I_{\text{combined}}(i, v)^{m_T}\right)^{\frac{1}{m_T}}$$

Mean Wind Speed



Weibull Distribution

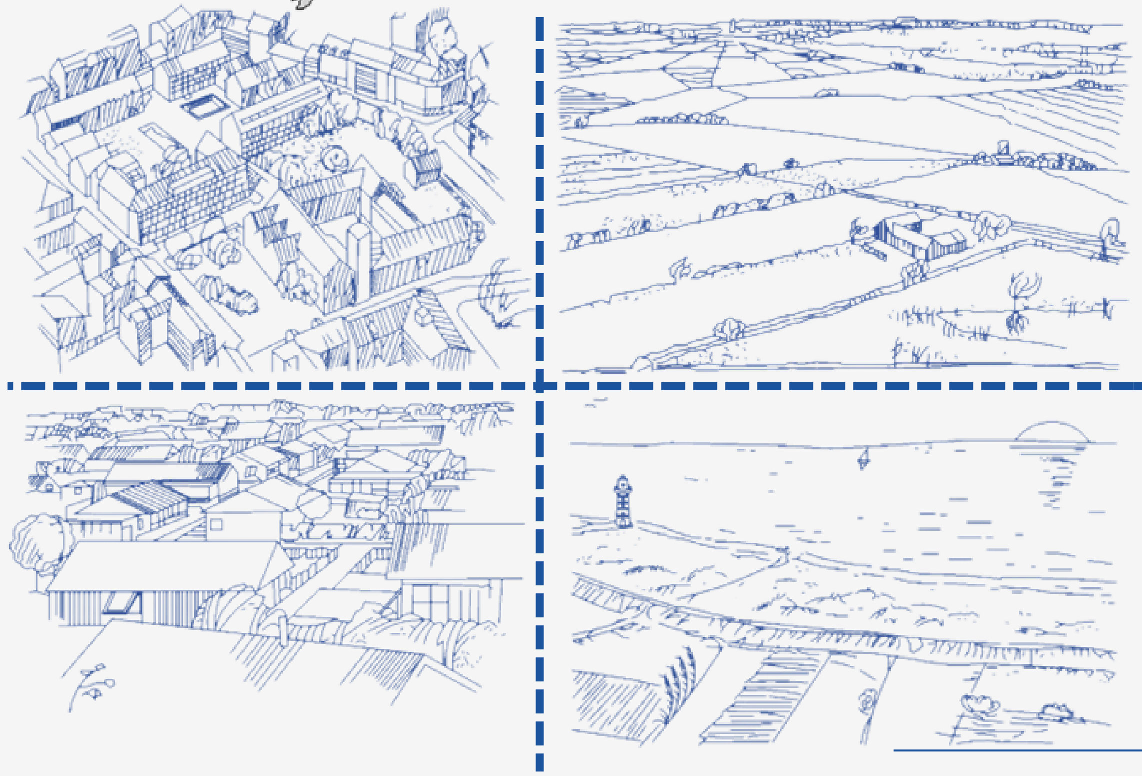
- Shape
- Scale

Power Scale
to Hub height

Mean wind speed: 4.84 m/s

Wind energy per sector

Extreme Wind Speed

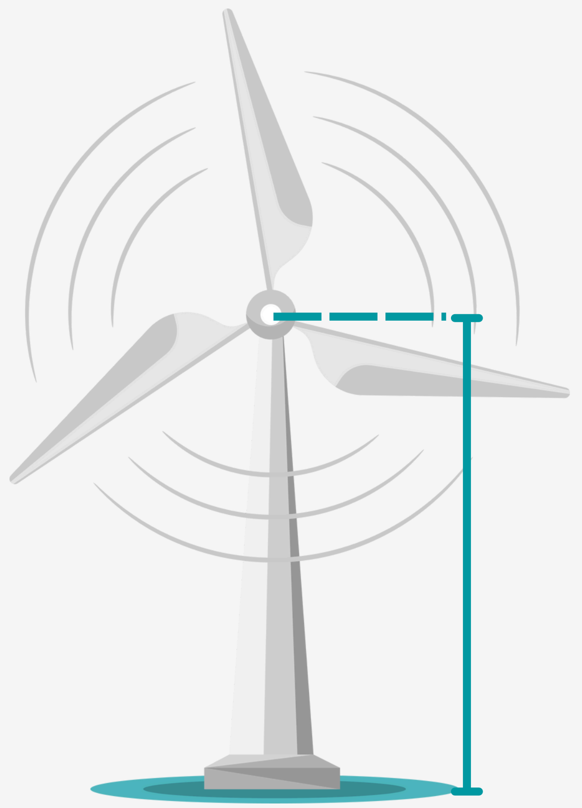


Wind Zone

DIN EN 1991-1-4/NA

Roughness Category

v_m50(z)

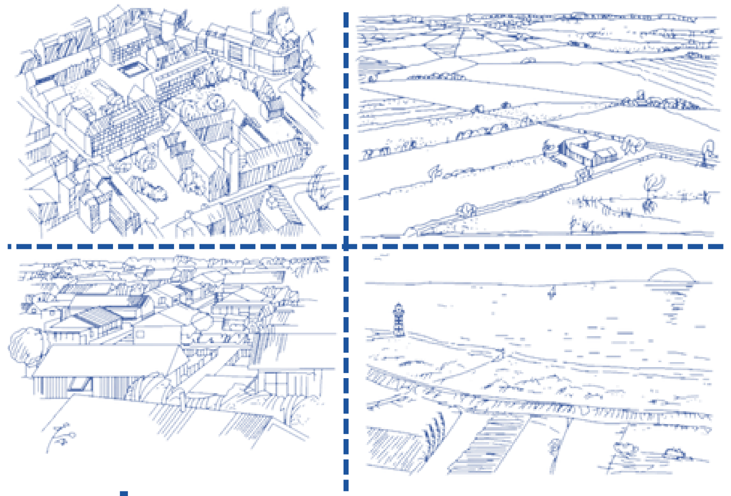


Turbine Hub heigth: h

v_m50(h)

Extreme wind speed: 30.10 m/s

Extreme Wind Speed

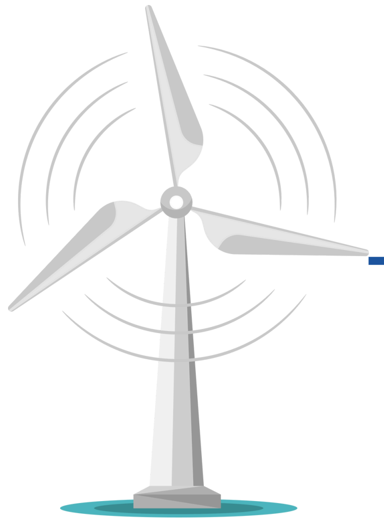


v_b Basis wind speed

Exponent α

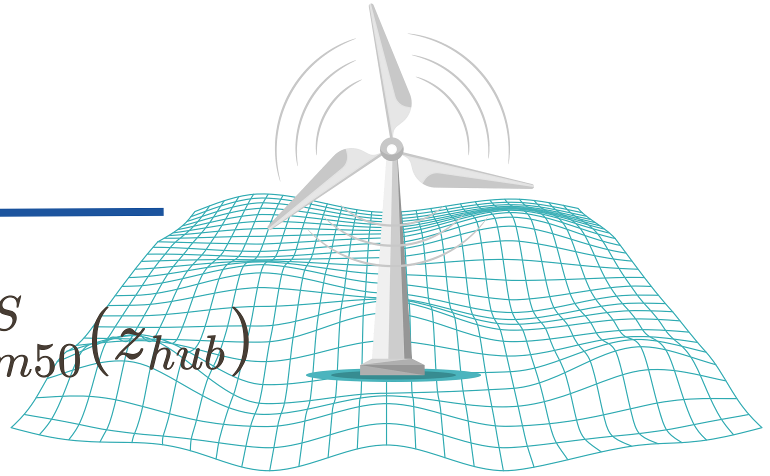
Coefficient C

$$C \cdot v_b \cdot \left(\frac{z}{10}\right)^{\alpha}$$



Turbine Design

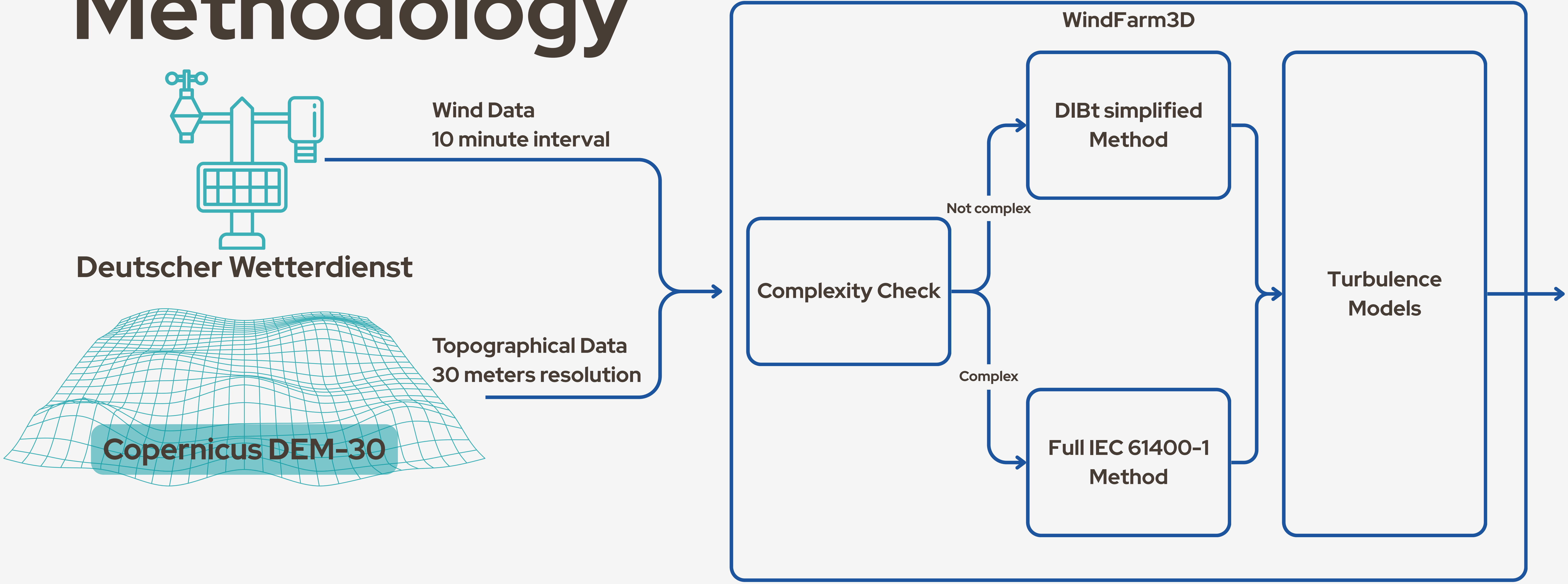
$v_{m50}^{T}(z_{hub})$ 10-Minute average wind speed with a 50-year recurrence period at hub height



Turbine Site

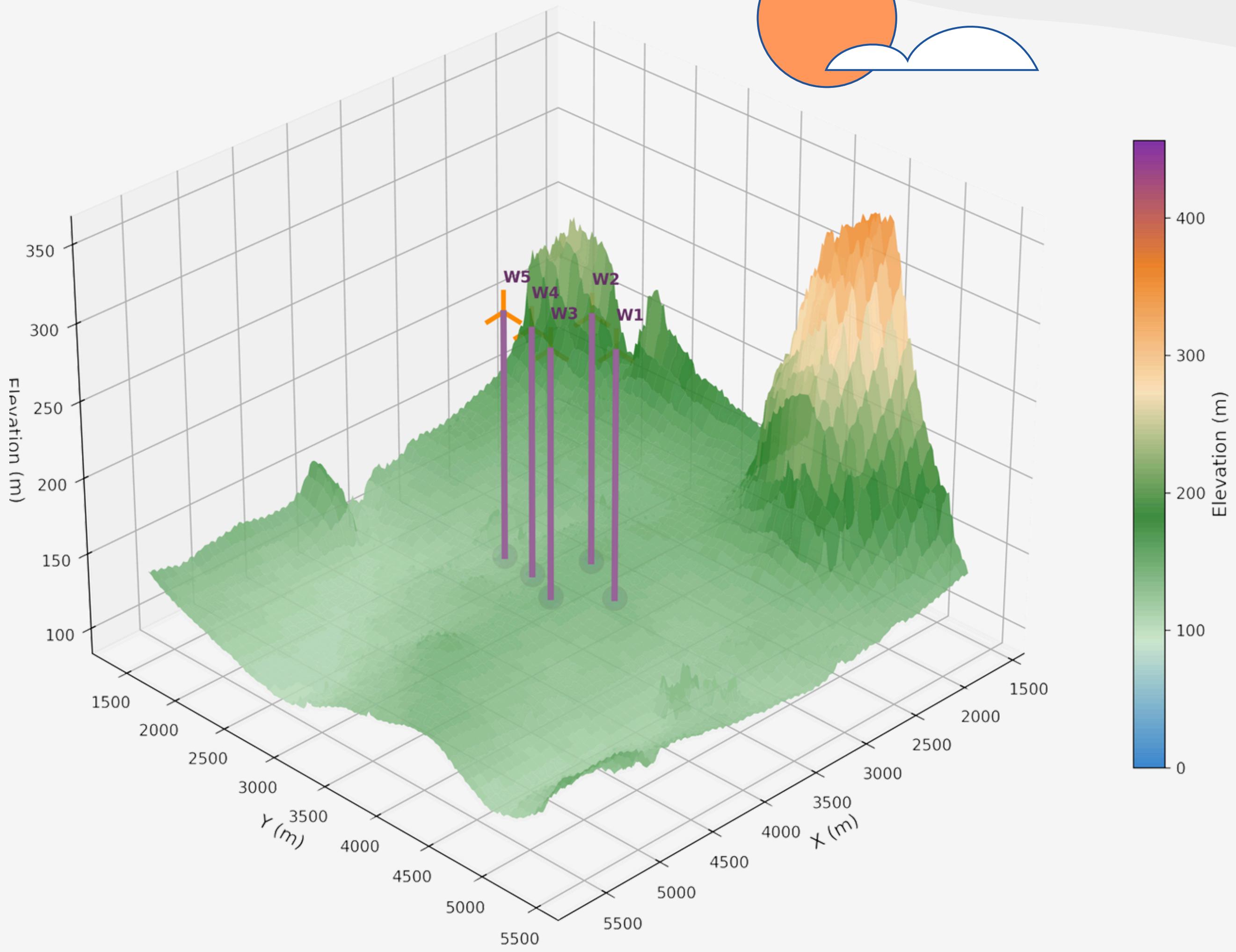
$v_{m50}^{S}(z_{hub})$ 10-Minute average wind speed with a 50-year recurrence period at hub height

Methodology

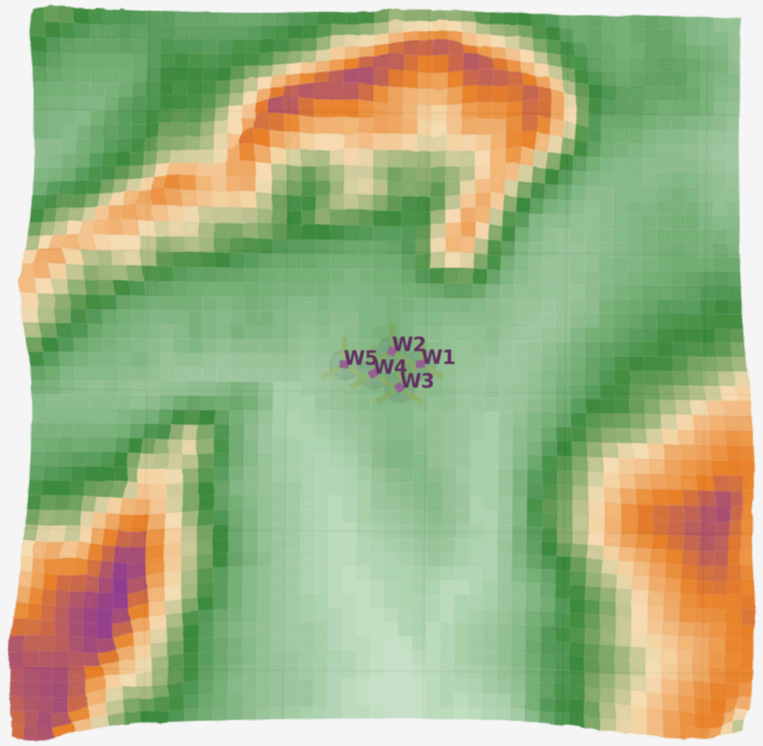


Validation: Case Study at Wind Farm Heidsiek

- **Objective:** Validate the accuracy against real-word industry tools.
- **Site:** Wind Farm Heidsiek - 5 Turbines, Salzhemmerdorf, Lower Saxony
- **Comparison Benchmarks:**
  - Professional Site Assessment Report (I17-GmbH)
  - Commercial Software (WindPro)
- **Note:** Assessments used different underlying wind data, minor variations are expected.



Topographic Plot



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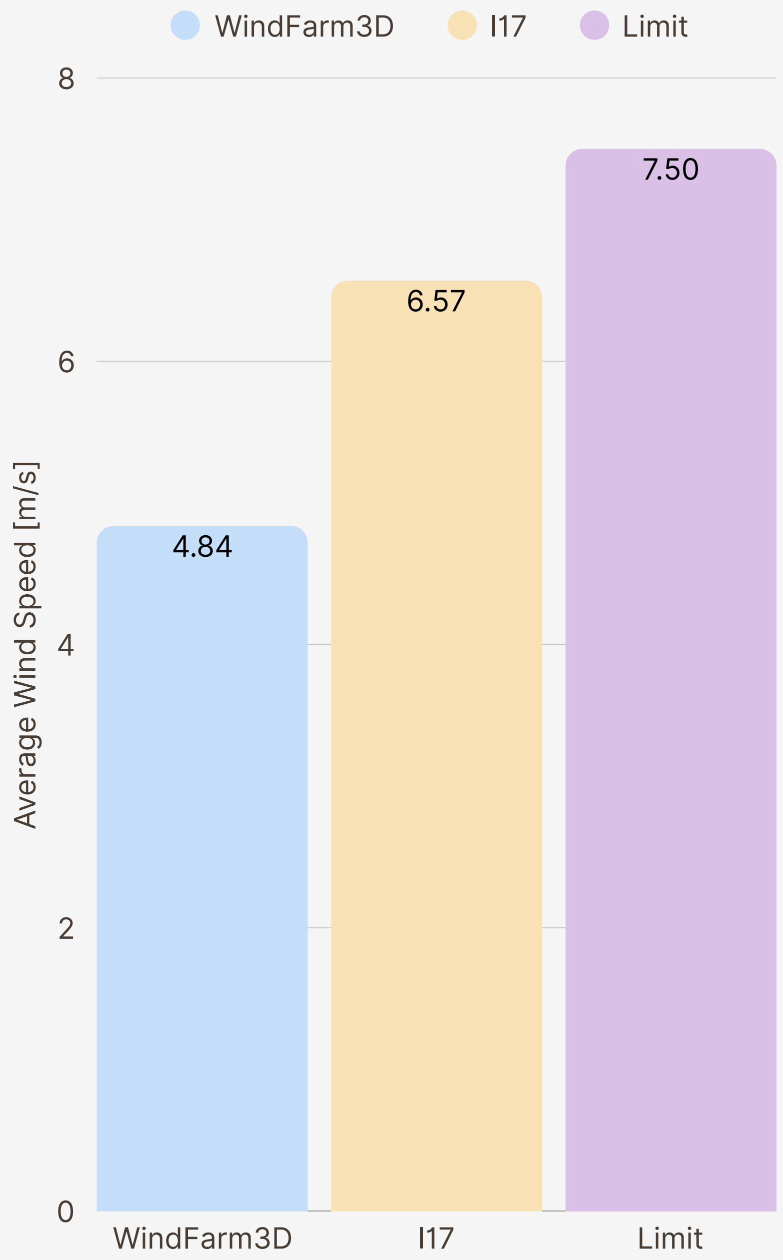
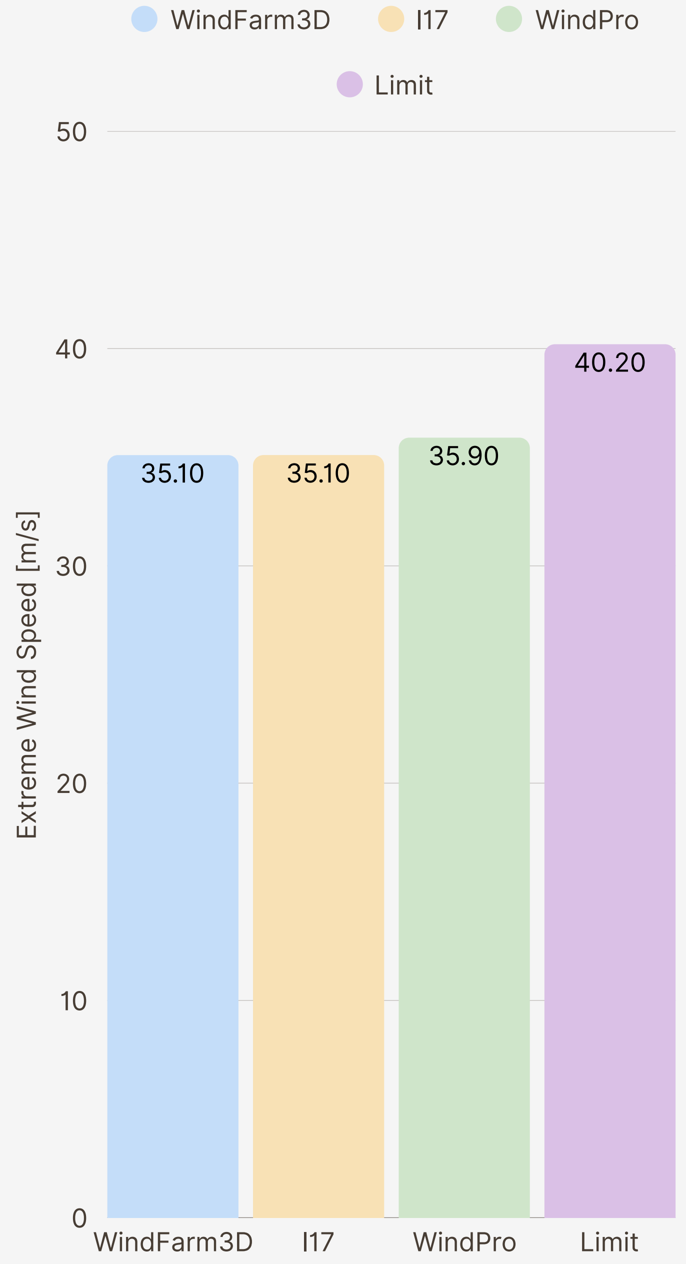
Results: Site Complexity & Wind Speed

- All three assessments correctly classify the site as “**Non Complex**”
- **Extreme Wind Speed**: WindPro uses a different method to calculate the value
- **Average Wind Speed**: Values differ due to data sources





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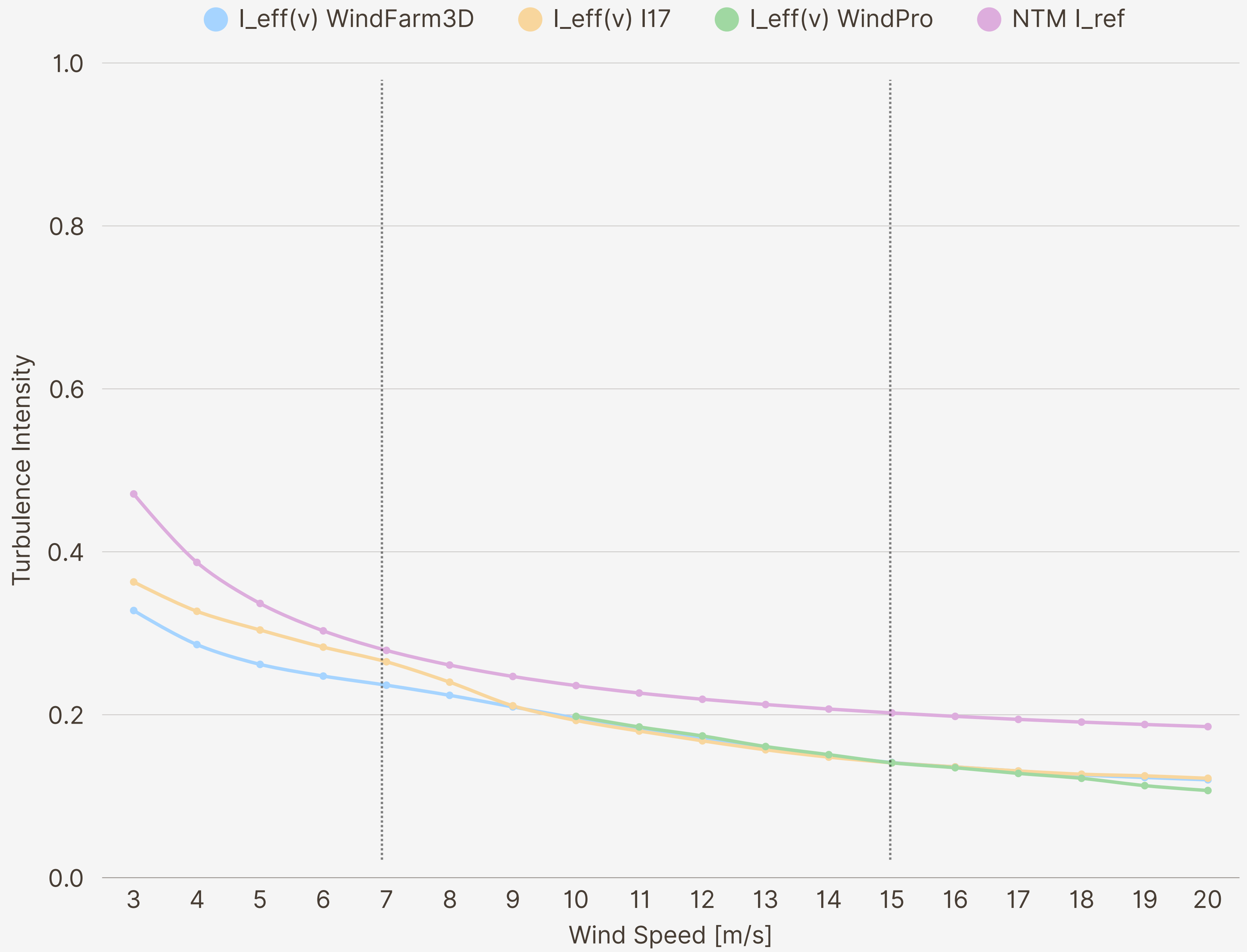
Results: Effective Turbulence

- The curves of WindFarm3D, WindPro and the I17 Report are near identical.
- **Quantified Accurcay** (In critical 7-15m/s range):
  - ~1.1% deviation from WindPro
  - ~3.0% deviation from professional report
- **Conclusion:** WindFarm3D produces reliable and accurate results using only free, public data.



Key Findings

- **Standards-compliant module developed.** Selects DIBt simplified path for non-complex sites and IEC 61400-1:2019 full workflow for complex terrain.
- **Case Study (Heidsiek)**: All 5 turbine locations classified not topographically complex by WindFarm3D, I17 and WindPRO → DIBt simplifications applicable.
- **Effective turbulence matches industry tools.** Deviation ≈2.98% vs I17 in 7-15 m/s and ≈1.07% vs WindPRO in 10-15 m/s range. All results of the case study remain below the NTM design curve across the critical range.
- **Wind speeds confirm suitability. Mean wind**: 4.84 m/s (WF3D, DWD Data) vs 6.57 m/s (I17, on-site), both below the design limit of 7.5m/s. **Extreme wind** ≈35.1-35.9 m/s consistent across methods.
- **Methodology & data.** Implements TSI/TVI complexity metrics, Frandsen model for ambient and wake turbulence with sectoring. Uses **Copernicus DEM GLO-30** + **DWD 10-min** wind data.
- **Impact.** Open, accessible alternative to commercial tools - Fast early-stage screening and an improved WindFarm3D ecosystem for research.

Conclusion & Future Work

Conclusion:

- Flexible and modular Python module.
- Validated data correctness through case study.
- Proved that professional-grade results are achievable using free, public data sources.

Future Work:

- **Automated Roughness:** Integrate CORINE Land Cover dataset for more precise, automated terrain category detection.
- **Expanded Wake Models:** Implement and compare alternative models to assess different scenarios
- **Offshore Wind Farms:** Extend capabilities by implementing relevant norms.

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THANK YOU

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Roughness Categories

Roughness Category	Terrain Description	Coefficient	Exponent	Minimum Height
I	Open sea, smooth, flat land	1.18	0.12	2.00m
II	Farming land, scattered obstacles	1.00	0.16	4.00m
III	Villages, forests, industrial parks	0.77	0.22	8.00m
IV	Dense city areas	0.56	0.30	16.00m

Wind Zones

Wind Zone	Basis Wind Speed	Dynamic Pressure
1	22.5 m/s	0.32 kN/m^2
2	25.0 m/s	0.39 kN/m^2
3	27.5 m/s	0.47 kN/m^2
4	30.0 m/s	0.56 kN/m^2

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Wind Profile Power Law

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

- z is the height of the wind measurement.
- z-hub is the hub height of the wind turbine.
- Alpha is the profile exponent from the site's roughness category.

Additional Turbulence Formulas

$$I_{mean}(v) = \frac{3v \cdot I_v(z_{hub})}{3v + 15}$$

Mean Ambient Turbulence Intensity

$$I_{stddev}(v) = \frac{1.92}{v \cdot I_v(z_{hub})}$$

Standard Deviation of Ambient Turbulence Intensity

$$I_v(z) = \begin{cases} 0.43 \cdot \left(\frac{z}{10}\right)^{-0.3} & \text{if } z > 16 \\ 0.37 & \text{else} \end{cases}$$

For calculating the **turbulence intensity function** for German sites the DIN EN 1991-1-4 National Annex approach is usually used. This function is derived from the site's terrain roughness category and wind zone. Terrain Roughness Category 4 is used here as example