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Analyse und Verifikation der Turbulenzmodellierung nach Frandsen für die Standorteignung von Windkraftanlagen

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

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Contents

1 Introduction

Mitigating the effects of global climate change is one of the biggest current challenges. Its most serious effects include rising temperatures, warming and rising oceans, more severe storms, and increasing droughts [36]. One of the largest drivers of CO_2 emissions is still the energy sector [37]. Therefore, a transformation and decarbonization of the entire energy sector is essential. As of 2025, the share of renewable energies in Germany's total net electricity generation was about 57.1% [18]. Nevertheless, to limit the effects of climate change, renewable energy must still cover a significantly larger share of the energy supply.
Figure 1 shows the public net electricity generation in Germany in 2025 [18]. Wind energy was not only the largest source of public net electricity generation amongst renewable energies, but once again the largest source of net electricity generation overall, with onshore wind turbines contributing the most at about 25.2%. Although renewable energies are already a well-established source of energy in Germany, these numbers clearly show that a significant expansion of renewables in general, and wind energy in particular, is still necessary.
The expansion of onshore wind energy in a densely populated country such as Germany is challenging, because suitable space is limited and therefore should be used efficiently [32]. Wind farms should not only have an optimal layout for electricity generation, but but their sites must also be suitable for the planned turbines. Wind farms are becoming more complex, and turbines are becoming taller and more powerful. To determine site suitability, it is not sufficient that turbines can withstand the wind speeds at a site; turbulence effects and the loads generated by nearby turbines must also be taken into account. 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. This thesis aims to explain how site suitability must be determined in Germany by developing a simple tool to assess a given site automatically.

1.1 Motivation

In 2025, 958 onshore wind turbines with a total installed electrical capacity of about 5200 MW were commissioned in Germany [31]. This was the second-highest value in history and indicates that wind energy is once again on an upward trend in Germany. Predictions of further capacity expansion in 2026 and 2027 confirm this positive trend. This makes clear that efficient planning and approval procedures are needed. However, site assessments in the wind energy sector often still require several weeks to complete [1]. Since the number and complexity of wind farm projects are increasing, fast and accessible assessment tools are needed.
A site assessment includes the analysis of wind speeds, ambient turbulence and wake-added turbulence. Wake-added turbulence not only reduces power production of downstream turbines but also induces aerodynamic loads, leading to higher structural loads and consequently to accelerated fatigue. Therefore, this turbulence must be modelled

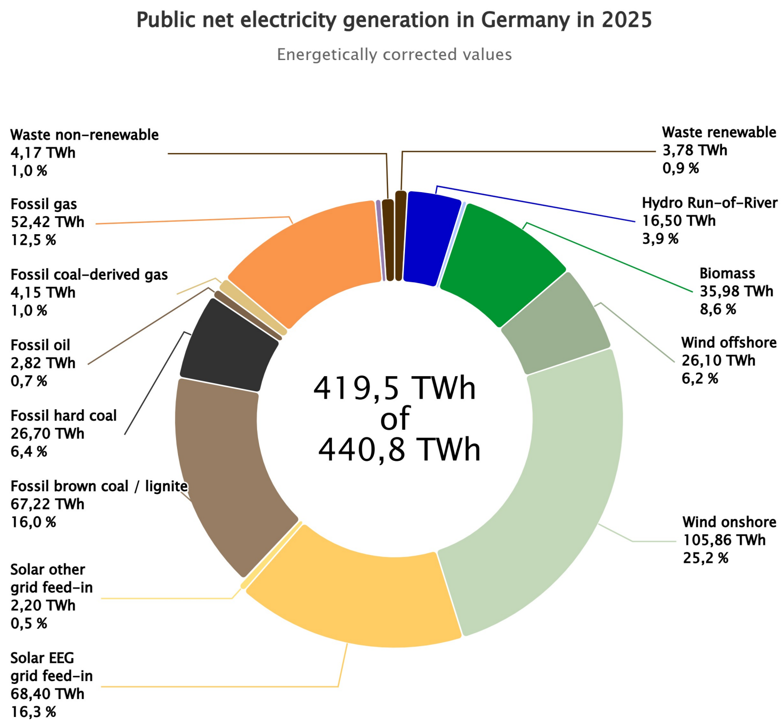


Figure 1: Public net electricity generation for Germany in 2025 [18].

precisely. There are already companies that offer tools for turbulence simulations, but these are typically not free to use and often require expensive licences. The goal of this work is to develop an accessible tool, based on freely available data sets that is comparable to professional site assessments and turbulence analyses.

1.2 Related Work

Wind farm planning consists of multiple relevant aspects including the analysis of wind resources at a site, noise propagation, and shadow flicker. This thesis focuses on the assessment of site suitability and analysis of turbulence at a site. The aim of this tool is to determine the suitability of a site in accordance with all relevant national and international guidelines. It should verify that the planned turbine type is designed to withstand the wind and turbulence conditions present at the considered location.
This tool was first implemented by Kröker, who developed checks to verify whether site parameters comply with all relevant national and international guidelines and standards [26]. In addition, a simple turbulence model was implemented. Weber improved this codebase by adding an accurate wind-data import based on stations of the Deutscher Wetterdienst and by integrating a more accurate data source for the topographical data of a site [39].

1.3 Contribution

In this thesis, the existing implementation of the turbulence simulation and site suitability assessment is improved and extended. A new method for modelling the ambient turbulence intensity is implemented, which also takes the actual land cover surrounding a turbine site into account. In addition, the tool is extended by multiple variants of the Frandsen turbulence model in order to represent the wake effects occurring within a wind farm [17].
The tool is intended to enable fast and accurate wind and turbulence calculations for planned or existing wind farms. It should accurately assess whether a site is suitable for a specific wind turbine type with respect to all relevant standards and precisely model the occurring turbulence. The implementation is later verified by comparison with real professional site assessments.

1.4 Outline of this Work

Section 2 presents the key aspects of wind farm planning that must be considered and existing tools in this field. Section 3 defines important terms and concepts while also providing an in-depth overview of the legal guidelines for site suitability assessment of wind farms in Germany. Section 4 provides details on the implementation and, in particular, the data sets used throughout the simulation. It also derives and explains the specific formulas and models implemented. The aim of Section 5 is to compare the developed implementation for site suitability assessment, including turbulence analysis, with real professional reports. For verification, the assessment and turbulence calculations of three different wind farm projects are compared with corresponding technical reports.

2 Literature Review

2.1 Aspects of Wind Farm Planning

The planning of a wind farm consisting of one or more nearby turbines in Germany is a complex process that often takes several years [4]. Several aspects must be taken into account, and construction can only begin once all relevant requirements are met. These requirements include expert assessments of noise levels, shadow impact, visibility, and the effect on the landscape. In addition, the wind and turbulence conditions must be evaluated, which is the focus of this thesis.

2.1.1 Site Suitability

The site suitability of a site provides information about whether a specific turbine type can withstand the conditions at a site [25]. Site assessment includes the evaluation of several environmental conditions. In addition to wind, parameters like temperature, humidity, and air density should be evaluated. Additionally, seismic, topographic, and soil conditions at the wind turbine site need to be considered. It shall be shown that the site-specific conditions do not compromise the structural integrity of the turbine. This thesis focuses on wind, turbulence, and topographic influences.

2.1.2 Shadow Flicker

The rotating blades of an operating wind turbine can cast periodic shadows, commonly referred to as shadow flicker [2]. These optical emissions are regarded as a potential source of annoyance for the surrounding neighborhood. In the approval process for wind turbines, it must therefore be assessed whether the requirements concerning periodic shadow flicker are met. In Germany, annual and daily limits apply to the maximum duration of exposure for residential buildings. For residential buildings, the annual limit is 30 hours, with a maximum of 30 minutes per day.

2.1.3 Noise Propagation

In addition to shadow flicker, wind turbine sites are also regulated with respect to noise emissions [3]. Noise generated by wind turbines is a social concern, as it may have negative effects on sleep quality. In Germany, the TA Lärm provides the regulatory guideline by defining noise immission limits that must not be exceeded in order to protect the surrounding population from harmful noise.

2.1.4 Wind Resource Assessment

Especially from the perspective of the operating company, the planning process not only includes legal regulations but also financial aspects. Despite the various restrictions, the wind energy potential at the considered location is also major factor. Wind resource assessment is the process of estimating the wind energy potential at one or more sites across an area [27]. It involves evaluating the wind conditions and site characteristics of a location and helps optimize the wind farm layout to maximize energy output.

2.1.5 Annual Energy Production

In the calculation of net annual energy production (AEP), wake effects must also be taken into account, as they result in energy losses [15]. In this context, more complex turbulence models than the analytical Frandsen approach are often applied to obtain more accurate results. Often, computational fluid dynamics (CFD) wind models are used.

2.2 Existing Tools

There are several commercial tools that focus on the planning and optimization of wind farm layouts. The most widely used ones are:

- **WAsP** (Wind Atlas Analysis and Application Program) [15]: This is a software developed by the Technical University of Denmark (DTU). It provides multiple modules that cover wind resource assessment, energy yield calculation that accounts for wake losses using a state-of-the-art CFD wind flow model, and suitability assessments.
- **windPRO** (EMD) [16]: This tool offers a broad range of functionalities, ranging from the import of wind measurements to site compliance assessment and layout optimization with respect to annual energy production (AEP). windPRO even supports the integration of WAsP CFD models for accurate energy yield calculations. In contrast to WAsP, windPRO also includes the simulation of environmental impacts such as shadow flicker and noise emissions.
- **WindFarmer** (DNV) [13]: This software includes wind climate analysis, wake modelling, and wind farm layout optimization with respect to AEP.

All of these tools are comparable to some extent in terms of their functionality. There are also freely available tools that are worth mentioning.

- **PyWake** [30]: This is an open-source, Python-based wind farm simulation tool, also developed by DTU. It is primarily intended as a research tool for investigating the interaction between turbines within a wind farm and the power production of the farm.

These tools are often used in professional reports that certify specific aspects of a site, such as site suitability or compliance with noise restrictions. In a later chapter, our model is compared with reports by I17-Wind GmbH & Co. KG [24]. The company produces reports on site suitability, noise emissions, and shadow flicker. For site suitability assessment, it uses an internally developed tool that is specifically tailored to German legal requirements. This tool also uses analytical turbulence models, including the Frandsen model.

3 Legal Guidelines for Site Suitability of Wind Turbines

This thesis focuses on wind and turbulence in the context of wind turbine site suitability in Germany. For this reason, in particular European and German standards and guidelines are important. The main relevant documents are the European standard DIN EN IEC 61400-1:2019 [25], the German standard DIN EN 1991-1-4 [11] together with its National Annex [12], and the German "Richtlinie für Windenergieanlagen" [9] issued by the Deutsches Institut für Bautechnik (DIBt).

3.1 Terms, Definitions, Concepts

3.1.1 Important Terms

Table 1 lists the most important terms and their definitions. Throughout this thesis, parameters associated with the turbine site are marked with the superscript S while turbine design parameters are marked with the superscript T. For example, $v_{ave}^{S}(z_{hub})$ stands for the average wind speed at hub height z_{hub} at the site, while $v_{ave}^{T}(z_{hub})$ denotes the design average wind speed of the turbine, which should not be exceeded by the corresponding site value.

3.1.2 Turbulence Intensity

Turbulence describes irregular fluctuations in wind speed [32]. The standard way to describe turbulence is with the definition of turbulence intensity. It is defined as the ratio of the standard deviation of the turbulent wind speed to the average wind speed.

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

The turbulence intensity can be computed for the longitudinal, lateral and vertical wind components, while the focus will be on the longitudinal component (along the mean wind direction). v_{ave} is the mean wind speed in longitudinal direction. While a low turbulence intensity indicates a rather consistent wind flow, a high turbulence intensity means that the wind is rather irregular.

3.1.3 Wake Effect

Wind conditions within a wind farm differ from the ambient wind flow [20]. A wake in a wind farm is the region downstream of a turbine. Roughly speaking, it is created by the rotor extracting energy from the incoming air to produce electricity. The wake behind a wind turbine is characterized by a lower wind speed and higher turbulence compared to the ambient wind flow. The increase in turbulence is commonly referred to as wake-added turbulence, while the reduction in wind speed is known as the wind speed deficit.

Term	Definition
$v_{m50}(z)$	Value of the highest wind speed at height z, averaged over 10 minutes, with a return period of 50 years (annual probability of exceedance of 0.02)
$v_{m1}(z)$	Value of the highest wind speed at height z, averaged over 10 minutes, with a return period of 1 year
$v_{p50}(z)$	Value of the highest wind speed at height z, averaged over 3 seconds, with a return period of 50 years
$v_{ave}(z)$	Value of the annual average wind speed at height z, obtained by averaging the wind speed over several years
$v_{b,0}$	Fundamental value of the basis wind speed at 10 m above ground level with a return period of 50 years
V_R^T	Rated wind speed at which a wind turbine reaches its maximum power output
I_{ref}	Reference value of the turbulence intensity for the turbine's design turbulence intensity.
$I_v(z)$	Turbulence intensity at height z
I_{eff}	Effective turbulence intensity, defined as the average turbulence intensity that, over the expected lifetime of a turbine, results in the same fatigue effects as the prevailing site conditions.
σ	Wind speed standard deviation
$\sigma_{NTM}(v)$	Representative value of the wind speed standard deviation, given by the 90 % quantile for the given hub height wind speed v.
$\hat{\sigma}$	Estimated wind speed standard deviation
$\hat{\sigma}_\sigma$	Standard deviation of estimated wind speed standard deviation $\hat{\sigma}$
z_{hub}	Height above ground of the hub of a considered turbine
D^T	Rotor diameter of a considered turbine
m^T	Wöhler exponent of a considered turbine
$C_T(v)$	Wind-speed-dependent thrust coefficient of the considered turbine
C_{CT}	Terrain complexity correction factor of a site

Table 1: Most important terms and their definition

3.1.4 Directional Wind Characteristics

Since wind characteristics generally depend on direction, wind data are divided into a finite number of directional sectors [8]. Most typically, 12 sectors are used, each with a width of 30°, as depicted in Figure 2.
Let $\mathcal{S}$ denote the set of all wind samples, where each sample contains at least the wind speed and the wind direction. Let $\mathcal{S}_i \subseteq \mathcal{S}$ denote the subset of samples assigned to sector i. The frequency with which the wind comes from sector i can then be defined as:

$$f(i) = \frac{|\mathcal{S}_i|}{|\mathcal{S}|}$$

As wind energy is proportional to the wind speed cubed [19], the energy contribution of sector i can be defined as:

$$f_{energy}(i) = \frac{\sum_{s \in \mathcal{S}_i} v(s)^3}{\sum_{s \in \mathcal{S}} v(s)^3}$$

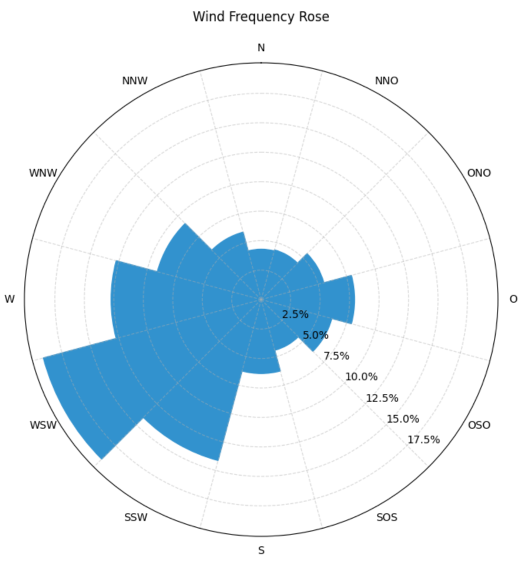


Figure 2: Wind frequency rose of wind farm Bever. Wind sectors have a width of 30°.

3.1.5 Weibull Distribution

The Weibull distribution is a continuous probability distribution often used to describe wind speed distributions [14]. It is characterized by two parameters: a shape parameter $k > 0$ and a scale parameter $A > 0$. The probability density function is given by:

$$pdf(v|A,k) = \begin{cases} \frac{k}{A}\left(\frac{v}{A}\right)^{k-1} e^{-\left(\frac{v}{A}\right)^k}, & v \geq 0 \\ 0, & \text{else} \end{cases}$$

Wind speed data are typically right-skewed, with a peak at low to moderate wind speeds. For many sites, the Weibull shape parameter is often around 2. The cumulative distribution function is given by [14]:

$$F(v|A,k) = \begin{cases} 1 - e^{-(\frac{v}{A})^k}, & v \geq 0 \\ 0, & \text{else} \end{cases}$$

As wind data is often divided into sectors, each sector can be modeled with its own Weibull parameters. The probability that the wind comes from sector i given a wind speed v can be computed by [14]:

$$p(i|v) = \frac{p(v|i)p(i)}{p(v)} = \frac{pdf(v|A_i, k_i) f_i}{\sum_{j=0}^{N-1} pdf(v|A_j, k_j) f_j}$$

where f_i is the frequency with which wind comes from direction i.

3.2 Wind and Terrain Conditions in Germany (DIN EN 1991-1-4 and NA)

DIN EN 1991-1-4 is a European standard that provides guidance for determining wind loads for the structural design of buildings and civil engineering works up to 200 m in height [11]. The National Annex contains adjustments specific to Germany [12]. Although the standard covers a wide range of topics related to wind engineering, this study focuses only on the sections relevant to determining site suitability for wind turbines.

3.2.1 Wind Zones in Germany

Germany is divided into four wind zones $(1-4)$, which categorize regions according to their characteristic wind conditions [12]. The fundamental basic wind velocity $v_{b,0}$ is defined as the 10-minute mean wind velocity at 10 meters above ground with an annual exceedance probability of 2 %. For a specific site, the applicable value of $v_{b,0}$ is determined by identifying the wind zone from the wind zone map (see Figure 3a) provided in the National Annex and subsequently selecting the corresponding value from the table (see Figure 3b).

3.2.2 Terrain Categories in Germany

In addition to the wind zone, a site can also be classified into terrain categories according to its terrain and surface characteristics. DIN EN 1991-1-4 defines five terrain categories, while the National Annex introduces two additional transitional categories and states that terrain category 0 is not used in Germany [11, 12]. Table 2 lists all relevant categories and their desriptions. Terrain category I is characterized by flat terrain, whereas terrain category IV represents a densely built-up area.

(a) Wind zone map for Germany [12].

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

(b) Basic wind speeds $v_{b,0}$ for the four German wind zones [12].

Figure 3: German wind zones with design parameters.

Based on the terrain category and wind zone, estimations are provided for the 10-minute extreme wind speed with a return period of 50 years, $v_{m50}(z)$, extreme gust wind speed, $v_{p50}(z)$, and the turbulence intensity $I_v(z)$, at height z. Additionally each category has an estimate for the roughness length z_0 on the surface.

Terrain Categories I, II, III and IV

$$v_{m50}(z) = \begin{cases} c_m \, v_b \left(\frac{z}{10}\right)^{\alpha} & \text{if } z > z_{\min} \\ v_{m,\min} \cdot v_b & \text{else} \end{cases}$$

$$v_{p50}(z) = \begin{cases} c_p \, v_b \left(\frac{z}{10}\right)^{\alpha_p} & \text{if } z > z_{\min} \\ v_{p,\min} \cdot v_b & \text{else} \end{cases}$$

$$I_v(z) = \begin{cases} c_I \left(\frac{z}{10}\right)^{-\alpha} & \text{if } z > z_{\min} \\ I_{v,\min} & \text{else} \end{cases}$$

The corresponding coefficients can be found in Tables 2 and 3. The values for the basis wind speed of each wind zone and can be taken from Table 3b. The formulas are derived from the wind profile power law and scale the basic velocity v_b of each wind zone from 10 m above ground to the desired height, typically the hub height. The National Annex explicitly states that, in Germany, the wind profile power law should be used instead of the commonly used logarithmic wind profile.

Terrain Category	**Description**	z_0 [m]	z_{min} [m]	α
I	Lakes or flat and horizontal area with negligible vegetation and without obstacles	0.01	2	0.12
Coastal	Between I and II. (Germany)	-	-	-
II	Area with low vegetation such as grass and isolated obstacles (trees, buildings) with separations of at least 20 obstacle heights	0.05	4	0.16
Midland	Between II and III. (Germany)	-	-	-
III	Area with regular cover of vegetation or buildings or with isolated obstacles with separations of maximum 20 obstacle heights (such as villages, suburban terrain, permanent forest)	0.30	8	0.22
IV	Area in which at least 15 % of the surface is covered with buildings and their average height exceeds 15 m	1.05	16	0.3

Table 2: Terrain categories and terrain parameters in Germany [12].

Cat.	z_{min}	α	c_m	$v_{m,\text{min}}$	α_p	c_p	$v_{p,\text{min}}$	c_I	$I_{v,\text{min}}$
I	2	0.12	1.18	0.97	0.095	1.61	1.38	0.14	0.17
II	4	0.16	1.00	0.86	0.12	1.45	1.30	0.19	0.22
III	8	0.22	0.77	0.73	0.155	1.27	1.23	0.28	0.29
IV	16	0.30	0.56	0.64	0.2	1.05	1.15	0.43	0.37

Table 3: Coefficients for terrain categories I, II, III and IV [12].

3.3 European Design Requirements for Wind Turbines (DIN EN IEC 61400-1:2019)

The IEC 61400-1:2019 is an international standard that specifies essential design requirements to ensure the structural integrity of onshore wind turbines [25]. Offshore installations are covered by IEC 61400-3. The objective of these standards is to provide an adequate level of protection against damage from all relevant hazards throughout the turbine's planned lifetime. In this thesis, the focus is placed on the requirements related to environmental loads, particularly wind and wind turbulence.

The DIBt Guideline allows the use of either DIN EN IEC 61400-1:2005-12 or DIN EN IEC 61400-1:2011, provided that requirements from different versions are not combined [9]. According to a press release issued by DIBt, the DIN EN IEC 61400-1:2019 version may now also be applied without restrictions [10]. To ensure that the analysis reflects the most current regulatory framework, the 2019 version is used exclusively in this thesis.

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	-	-

Table 4: Wind turbine wind speed classes according to IEC 61400-1:2019 [25].

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

Table 5: Turbulence categories according to IEC 61400-1:2019 [25].

3.3.1 Wind Turbine Categories

Wind turbines are classified according to their wind speed class (I, II, or III) and turbulence category (A+, A, B, or C) [25]. These classifications define the external wind conditions for which a wind turbine is designed. The wind speed class is characterized by two design parameters: the annual average wind speed at hub height, v_{ave}, and the reference wind speed at hub height, v_{m50}. While a turbine of class I is designed for sites with high wind conditions, class III turbines are intended for sites with lower wind speeds.

In addition to wind speed classes, turbines are categorized according to turbulence intensity, which describes the variability of wind speed at a site. Turbines of category A+ are designed to withstand very high turbulence intensity, whereas category C turbines are intended for sites with low turbulence intensity.

Furthermore, a special wind turbine class (S) may be defined for site-specific conditions, where the manufacturer specifies the relevant design parameters.

3.3.2 Extreme Wind Speed Model (EWM)

The extreme wind model (EWM) defines the extreme wind conditions that a wind turbine must withstand, typically caused by storms or rapid changes in wind speed and direction [25]. The model provides the extreme gust wind speed or extreme 10-minute average wind speed as a function of height above ground and is based on the reference extreme wind speed at hub height $v_{m50}(z_{hub})$. $v_{m50}(z_{hub})$ is often determined using DIN EN 1991-1-4 NA.

The IEC standard defines two possible models, of which only one may be applied: the steady extreme wind model and the turbulent extreme wind model.

Steady EWM	Turbulent EWM
$v^T_{p50}(z) = 1.4 \cdot v_{p50}(z) \cdot (\frac{z}{z_{hub}})^{0.11}$	$v^T_{m50}(z) = v_{m50}(z_{hub}) \cdot (\frac{z}{z_{hub}})^{0.11}$
$v^T_{p1}(z) = 0.8 \cdot v_{p50}(z)$	$v^T_{m1}(z) = 0.8 \cdot v_{m50}(z)$
$\sigma_1(v) = 0.11v$	

Table 6: Steady and turbulent extreme wind model as defined in IEC 61400-1:2019 [25].

The DIBt guideline defines the extreme wind speed model primarily as a turbulent extreme wind model based on the mean wind speed, while the steady model based on gust wind speed may be used as an alternative [9].

3.3.3 Normal and Extreme Turbulence Model (NTM & ETM)

The normal turbulence model describes the expected turbulence during normal wind turbine operation [25]. It defines the 90% percentile of the standard deviation of longitudinal wind speed as a function of the wind speed at hub height.

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

This can also be modelled with respect to the turbulence intensity using $I_{NTM} = \frac{\sigma_{NTM}}{v}$:

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

I_{ref} is the reference turbulence intensity and depends on the turbulence category of the turbine. The NTM is later used as an upper limit against which the site-specific turbulence conditions are compared.

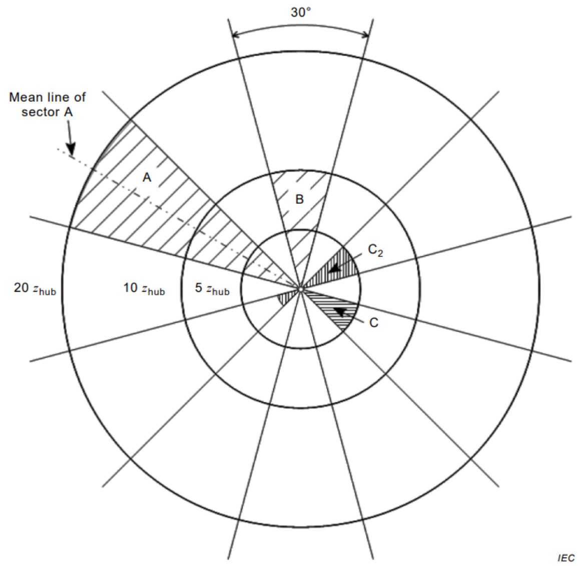
By contrast, the extreme turbulence model describes the extreme conditions of turbulence the turbine must withstand.

$$\sigma_{ETM}(v) = 2\frac{m}{s}I_{ref}\left(0.072\left(\frac{v_{ave}}{2\frac{m}{s}} + 3\right)\left(\frac{v_{ave}}{2\frac{m}{s}} - 4\right) + 10\right)$$

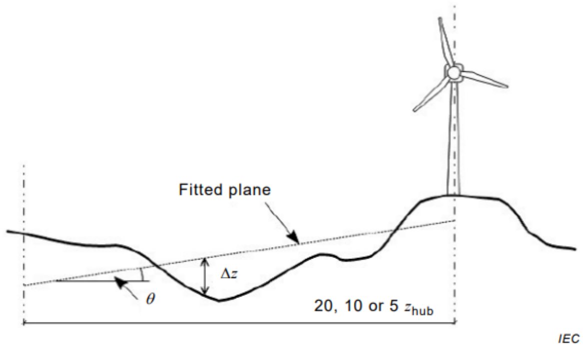
The corresponding value for the extreme turbulence intensity is $I_{ETM}(v) = \frac{\sigma_{ETM}(v)}{v}$.

3.3.4 Topographical Complexity

A site must be reviewed for the topographical complexity of its terrain, as terrain features directly influence the wind flow [25]. This can cause the actual turbulence conditions to differ from the standard design conditions. The complexity of the site is defined by the slope of the terrain and by deviations of the terrain surface from a plane. To assess the topographical complexity, a surface grid with elevation data should be used, with a resolution no greater than 50 m. The area around the turbine is divided



(a) Examples of 30° sectors for fitting the terrain data. For the circle sectors with radius $5z_{hub}$ the area used to fit the plane may be extended $2z_{hub}$ downwind [25].



(b) Schematic illustration of fitted plane with terrain variations and terrain slope [25].

into 30° sectors, and for each sector, as well as for radii of 5, 10, and $20 \cdot z_{hub}$, planes are fitted to the terrain. Figure 4a shows all 36 areas. Based on these fitted planes, the terrain slope and terrain variation are determined (see Figure 4b) and expressed through the terrain slope index (TSI) and terrain variation index (TVI). These indices are then used to classify the site as having low, medium, or high terrain complexity. The planes are typically fitted by minimizing the sum of squared differences between the plane and the terrain surface. To calculate TSI and TVI values, for each fitted plane, slope of the corresponding sector's middle line θ and standard deviation D_{TV} of the fitted plane to the terrain points are determined. Also a plane is fitted that covers the whole 360° circle area with a radius of $5 \cdot z_{hub}$, to determine TSI_{360} and TVI_{360}.

$$TSI_{30}(r) = \sum_{i=1}^{12} f_{Energy}(i) \cdot |\theta(i,r)|$$

$$TSI_{360} = \frac{5}{3}\theta_{360}$$

$$TVI_{30}(r) = \sum_{i=1}^{12} f_{Energy}(i) \cdot \frac{D_{TV}(i,r)}{r}$$

$$TVI_{360} = \frac{D_{TV360}}{3r}$$

A site is classified as **non-complex** when none of the calculated values violates any threshold given in 7 [25]. If a threshold is violated, the site is classified as **complex**

and assigned to one of the complexity categories (low, medium, or high) according to the highest threshold violated.
Depending on the complexity of a site, turbulence structure correction factors (C_{CT}) are introduced (see Table 8) to later correct the simulated turbulence intensity for topography effects.

Radius	**Sector amplitude of fitted plane**	**Threshold values (lower limit)**					
		Terrain slope index (TSI)			**Terrain variation index (TVI)**		
		L	**M**	**H**	**L**	**M**	**H**
$5z_{\text{hub}}$	360°	10°	15°	20°	2%	4%	6%
$5z_{\text{hub}}$	30°						
$10z_{\text{hub}}$							
$20z_{\text{hub}}$							

Table 7: Threshold values of the terrain complexity categories [25].

	Category		
	L	M	H
C_{CT}	1.05	1.10	1.15

Table 8: Values of turbulence structure correction factors depending on the terrain complexity category [25].

3.3.5 Effective Turbulence Intensity

The effective turbulence intensity, I_{eff}, is the average turbulence intensity that causes the same material fatigue over a wind turbine's lifetime as the varying turbulence conditions at the site [22, 25]. It combines ambient turbulence and wake-added turbulence generated by nearby wind turbines.

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

The formula computes the effective turbulence intensity for a given wind speed v by integrating turbulence contributions from all wind directions. Each contribution is weighted by how frequently wind comes from that direction at the given wind speed $p(\theta|v)$ and adjusted according to the fatigue properties of the turbine material m^T. The term $I_{combined}(\theta|v)$ denotes the total turbulence intensity from direction θ at speed v, including both ambient turbulence and wake-added turbulence caused by nearby turbines.
The Wöhler exponent is material- and component-specific [23]. Rotor blades made of fibreglass often have a Wöhler exponent of $m = 10$, while blades out of carbon fibre

have a value of $m = 15$. A larger Wöhler exponent stonger focuses directions with high turbulence intensity, causing the effective turbulence intensity to move closer to the maximum value, whereas a smaller exponent leads to a result closer to an average over all directions.

There are multiple models for estimating $I_{combined}$. While IEC 61400-1:2019 allows for multiple approaches, this work focuses on the Frandsen turbulence model and leaves other models for future work.

3.3.6 Site Suitability for Complex Sites

For sites that are classified as topographically complex (see 3.3.4) the full site-suitability assessment must be applied [25]. It allows to access whether a turbine is suitable for a specific site by comparing site wind parameters with turbine design parameter. It seperated into two checks: fatigue load suitability and ultimate load suitability. In the following, v_{ave} always refers to the average wind speed at hub height $v_{ave}(z_{hub})$.

Fatigue Load Suitability

(a) **Wind Speed Distribution:** The site's wind speed probability density function needs to be lower or equal than the turbine's design probability density function for all wind speeds between v_{ave}^S and $2v_{ave}^S$:

$$pdf_v^S(v) \leq pdf_v^T(v) \ \ \forall v \in [v_{ave}^S, 2v_{ave}^S]$$

If the shape parameter k of the site-specific Weibull wind speed distribution is greater than or equal to 1.4, the following equation must be fulfilled:

$$6.5 \cdot \frac{v_{ave}^S}{v_{ave}^T} - 4.5 \leq k \leq -6.0 \cdot \frac{v_{ave}^S}{v_{ave}^T} + 8.0$$

(b) **Wind Speed Standard Deviation:** For all wind speeds between v_{ave}^S and $2v_{ave}^S$, the wind speed standard deviation σ_{NTM} from the NTM used in turbine design is greater than or equal to the calculated effective wind speed standard deviation:

$$\sigma_{NTM}(v) \geq \sigma_{eff}(v) = I_{eff} \cdot v \ \ \forall v \in [v_{ave}^S, 2v_{ave}^S]$$

This can be formulated with respect to the turbulence intensity:

$$I_{NTM}(v) \geq I_{eff}(v) \ \ \forall v \in [v_{ave}^S, 2v_{ave}^S]$$

When calculating $I_{eff}(v)$ (see Section 4.2.2), the representative ambient turbulence intensity should be increased in order to account for the distortion of the turbulent flow by multiplication with the turbulence structure correction parameter C_{CT}.

(c) **Flow Inclination:** The wind energy weighted mean of the site flow inclination from all directions, shall be between $-8°$ and $+8°$. If no site data is available, the flow inclination can be replaced with $TSI_{30}^S(5z_{hub})$.

(d) **Height Exponent:** The energy weighted average of the site's vertical wind shear exponent α across all wind sectors, must be in range of 0.05 to 0.25.

(e) **Air Density:** For wind speeds greater than or equal to the rated wind speed V_R^T, the average site air density ρ^S must be less than the turbines design air density ρ^T. Instead, the following condition must hold:

$$\rho^T \cdot (v_{ave}^T)^2 \geq \rho^S \cdot (v_{ave}^S)^2$$

Ultimate Load Suitability

(a) **Wind Speed Standard Deviation:** The wind speed standard deviation σ_1 from the NTM used in turbine's design must fulfill the following equation for all wind speeds between 0.6 and 1.6 times the turbine's rated wind speed V_R^T:

$$\sigma_{NTM} \geq \hat{\sigma} + 1.28\hat{\sigma}_\sigma \;\; \forall v \in [0.6V_R^T, 1.6V_R^T]$$

with $\hat{\sigma}$ being the estimated mean value of the standard deviation of the longitudinal wind component at the site and $\hat{\sigma}_\sigma$ being the standard deviation of $\hat{\sigma}$. Here, the right-hand side of the inequality should be corrected using the turbulence structure correction parameter C_{CT}.

(b) **Extreme Wind Speed:** For the extreme wind speed the following equation should hold:

$$v_{m50}^T(z_{hub}) \leq v_{m50}^S(z_{hub})$$

Additionally,

$$\rho^T \cdot (v_{m50}^T)^2 \geq \rho^S \cdot (v_{m50}^S)^2$$

(c) **Extreme Ambient Turbulence:** It must be shown that the site-specific extreme ambient wind speed standard deviation does not exceed the ETM model (3.3.3). The extreme ambient wind speed standard deviation can be estimated with:

$$\hat{\sigma}_{ETM}(v) = \hat{\sigma} + k_p\hat{\sigma}_\sigma$$
$$k_p = 0.01(v_{ave} - 21)(v - 5) + 5$$

(d) **Wake Turbulence:** For wake conditions, it must be shown that, in the most critical direction, the maximum centre-wake wind speed standard deviation does not exceed that of the ETM model.

3.4 German Guideline for Wind Turbines by DIBt

The guideline "Richtlinie fur Windenergieanlagen" by DIBt sets out the requirements for verifying the structural integrity of wind turbine towers and foundations in Germany [9]. Although it also covers requirements for the tower, foundation, and safety concept, this work focuses on site suitability. While often referring to IEC 61400-1:2019, it also provides its own procedure for determining the site suitability of a non-complex site, which comes with several simplifications.

3.4.1 Site Suitability for Non-Complex Sites

When a site has been classified as non-complex according to chapter 3.3.4 and the terrain category is III or lower, the simplified method by DIBt can be used [9]. For terrain category IV, the site suitability method for complex sites (see Section 3.3.6) needs to be used. the DIBt method introduces the following simplifications:

- For terrain category I and II, the turbulence intesity $I_v(z)$ and v_{m50} can be modeled as follows:

$$I_v(z) = 0.128 \cdot (\frac{z}{10})^{-0.05}$$
$$v_{m50}(z) = 1.15 \cdot v_{b,0}(\frac{z}{10})^{0.121}$$

  When comparing these values with the approximations by DIN EN 1991-1-4 NA, v_{m50} is only lower for terrain category I and $I_v(z)$ is only lower for terrain category II. So only in these cases, the simplifications should be used.

- When no site-specific measurements are available, the following equation can be assumed for the annual average wind speed at height z:

$$v^S_{ave}(z) = 0.18 \cdot v^S_{m50}(z)$$

- For the site-specific air density a value of $\rho^S = 1,225kg/m^3$ can be assumed, if no measured data is available.

The site-suitability assessment of DIBt contains three steps [9]:

(a) **Average Wind Speed:** the site's annual average wind speed should be at least 5% lower than with turbine's design annual average wind speed:

$$v^S_{ave} \leq 0.95 \cdot v^T_{ave}$$

If the shape parameter k of the underlying Weibull distribution is greater than 2 it only must hold that:

$$v^S_{ave} \leq v^T_{ave}$$

(b) **Effective Turbulence Intensity:** The site's effective turbulence intensity should be lower or equal than the turbine's design turbulence intensity following the NTM (see 3.3.3) for all wind speeds between $0.2v^S_{m50}(z_{hub})$ and $0.4v^S_{m50}(z_{hub})$

$$I_{NTM}(v) \geq I_{eff}(v) \ \forall v \in [0.2v^S_{m50}(z_{hub}), 0.4v^S_{m50}(z_{hub)}]$$

(c) **Extreme Wind Speed:** It must hold that the site's wind zone is lower than or equal to the turbine's design wind zone, or the site's 50-year extreme wind speed $v^S_{m50}(z_{hub})$ is less than the turbine's design $v^T_{m50}(z_{hub})$.

4 Methodology

4.1 Data Collection and Processing

The suitability assessment and turbulence simulation require multiple datasets. In the following, the most important datasets get introduced.

4.1.1 Topographical Data

To assess the topographical complexity of a site, IEC 61400-1 requires elevation data with a resolution that does not exceed 50 m [25]. In the simulation, the Copernicus Digital Elevation Model (DEM) GLO-30 was used as the data source [6]. The Copernicus Digital Elevation Model is a Digital Surface Model representing the Earth's surface, including buildings, infrastructure, and vegetation. Copernicus DEM provides multiple resolutions and different areas of coverage: while EEA-10 provides a resolution of 10 m for Europe, GLO-30 and GLO-90 are global models with resolution of 30 m and 90 m. Figure 5 illustrates the differences between the resolutions [6]. As only GLO-30 and GLO-90 are freely available, GLO-30 is an appropriate choice for the simulation. The data is accessed through a public AWS S3 bucket managed by Sinergise. The provided geographic coordinates (latitude and longitude) are transformed from WGS84 into a local meter-based coordinate system. The elevation data is already provided in meters.

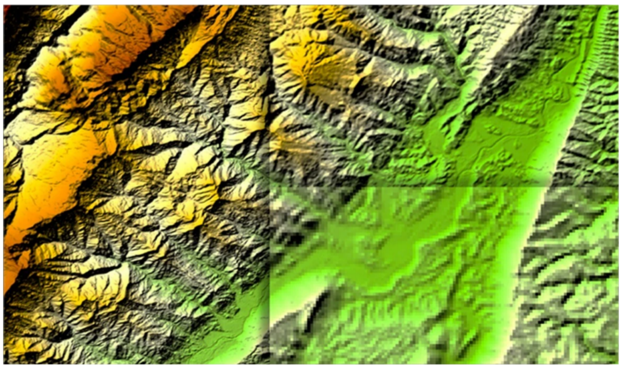


Figure 5: Copernicus DEM instances EEA-10 (left), GLO-30 (upper right) and GLO-90 (lower right) [6]

4.1.2 Wind Data

For an adequate assessment of site suitability and a precise simulation of turbulence, high-quality wind data is essential. The Deutscher Wetterdienst (DWD) provides free meteorological data, including wind speed and wind direction, and serves as the data source for the simulation [8]. Since IEC 61400-1 is based on wind speeds averaged over 10-minute intervals, only wind data with a 10-minute resolution is retrieved. The dataset contains 10-minute average wind speeds together with the corresponding wind direction sector. For this data, the DWD provides a network of roughly 275 weather

stations all across Germany (see Figure 6) with daily updated data. For the simulation, always the weather station closest to a site is selected. The data also includes a quality level (QN) for faulty or doubtful values. Whereas QN = 1 is mainly a formal check, QN = 3 indicates that the data has undergone automatic checking and correction. In the simulation, all values with a quality level lower than 3 are excluded.
If the available wind data is not sufficiently accurate, for example because the nearest station is located too far from the site, the user may alternatively provide self-measured wind data in the form of a Weibull distribution for each 30° sector.

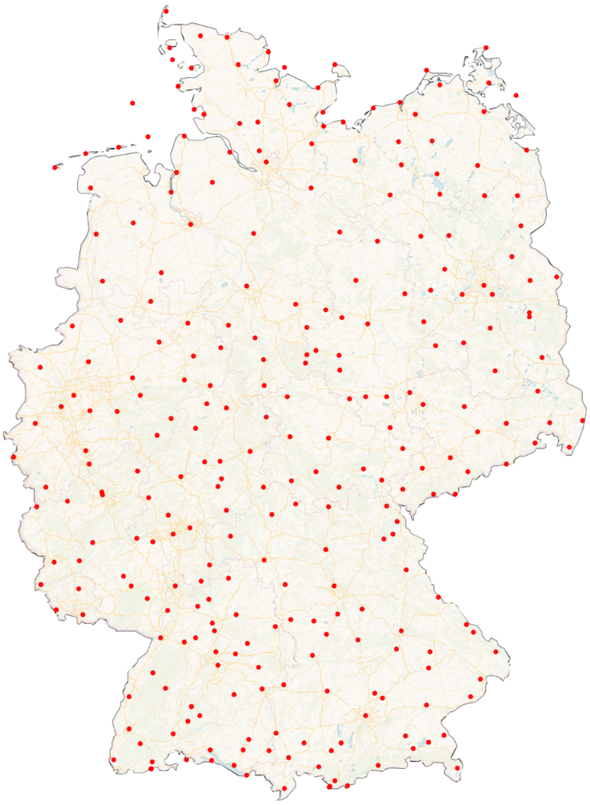


Figure 6: Available DWD wind stations in Germany [8].

4.1.3 Land Cover

The land cover around a site directly influences the wind flow and ambient turbulence intensity. To account for this in the simulation, the CORINE Land Cover 2018 dataset is integrated [5]. It classifies Europe into 44 different land cover classes, including urban areas, water bodies and forested areas. The dataset is available in vector and raster formats, while for simplicity, the raster version with a resolution of 100 m is implemented in the simulation.

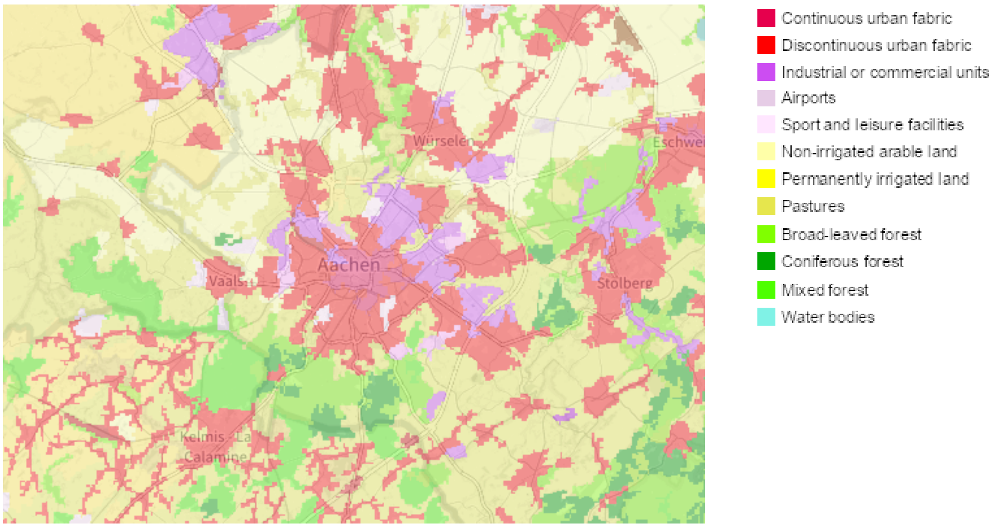


Figure 7: CORINE raster data for Aachen and suburbs [5]. The legend is reduced.

4.1.4 Wind Turbine Types

To assess the suitability of a turbine for a given site, not only the turbine type but also its technical specifications are relevant [25]. Unfortunately, no public dataset exists that contains turbine types along with all relevant specifications, since these data are only available in non-public manufacturer datasheets.

The required specifications for each turbine part of the turbulence-simulation are:

- Manufacturer and model name
- Hub height z_{hub}
- Rotor diameter D
- Rated wind speed V_R
- Turbine wind zone, wind speed class, and turbulence category or custom values
- Wöhler exponent m
- Thrust curve $C_T(v)$

At the current state, the simulation requires the specifications to be entered manually.

4.2 Model Development

4.2.1 Site Complexity Classification

The process systematically evaluates the terrain complexity around each turbine site using DEM data. To determine the TSI and TVI values for every turbine in a project, the area surrounding each turbine is first divided into 12 sectors of 30° each. Then, for each sector and each required radius $\{5z_{hub}, 10z_{hub}, 20z_{hub}\}$, only the DEM points lying within the respective area are considered. Based on these points, a plane is fitted by minimizing the sum of the squared distances between the points and the plane. Using this plane, the required values, such as the slope along the sector's center line and the standard deviation of the points, can be calculated in order to determine the TSI and TVI values as well as the site complexity, as described in Section 3.3.4.

4.2.2 Frandsen Turbulence Model

The Frandsen model is a frequently used model that is also mentioned in IEC 61400-1 Ed.4 [17, 25]. It considers both ambient and wake-added turbulence caused by upstream turbines. The maximum wake-added turbulence intensity is computed as follows:

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

with x being the distance between the two turbines, D the rotor diameter, and C_T the thrust coefficient of the wake-generating turbine. I_{add} is the maximal added turbulence intensity as it only occurs in the wake center (see Figure 8). The wake-added turbulence with respect to the angle between the wind direction and the line connecting the two turbines θ is modelled as:

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

with

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

and I_{rep} being the representative ambient turbulence intensity. The characteristic view-angle can be seen as the wake's angular opening, as depicted in Figure 8. It is modelled as follows:

$$\theta_w = \frac{1}{2}\left(\frac{180}{\pi} \cdot \tan^{-1}\left(\frac{1}{x/D}\right) + 10°\right).$$

Figure 8 shows an illustration of the wake cone angle and the variables used in the Frandsen turbulence model. A configuration is also shown, where the wind direction is slightly angled to the connecting line of the turbines.

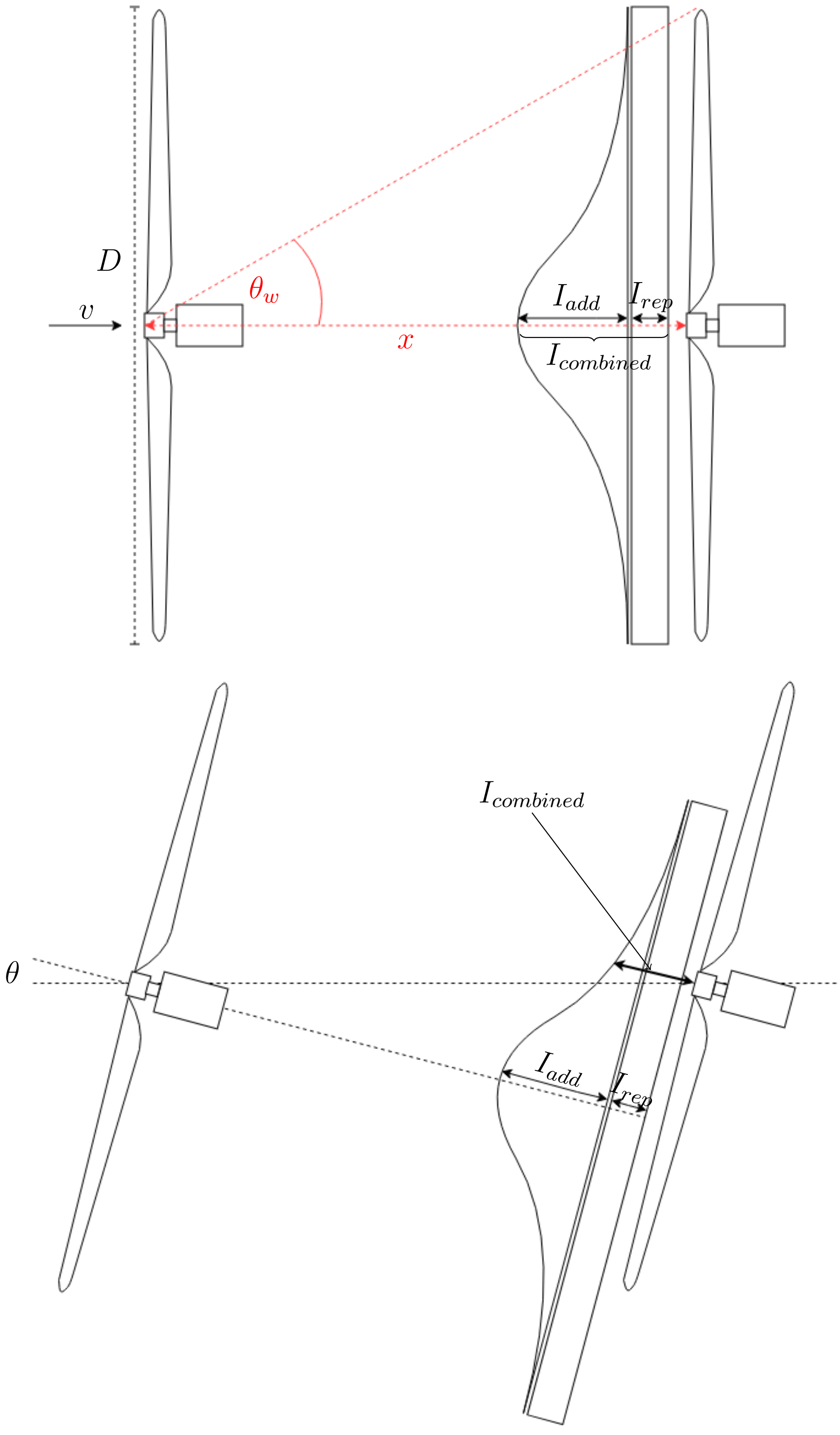


Figure 8: Schematic illustration of Frandsen turbulence model. Figure inspired from [32, 17]. The first figure shows a turbine in the wake center of another turbine. There, the maximal wake-added turbulence intensity I_{add} needs to be consired. I_{rep} is constant. θ_w is the characteristic view-angle. The second figure shows two angled turbines. θ is the angle between the wind direction and the connecting line of the turbines. Here, only a fraction of I_{add} needs to be considered.

4.2.3 Ambient Turbulence Intensity

The ambient turbulence intensity is strongly influenced by the wind conditions, topography, and land cover around a site. In the calculations of the effective turbulence intensity I_{eff}, IEC 61400-1 Ed. 4 does require the estimated 90% quantile of the ambient turbulence intensity to be calculated as [25]:

$$\hat{\sigma} + 1.28\hat{\sigma}_\sigma$$

We will model it with respect to the turbulence intensity where $I_{mean} = \frac{\hat{\sigma}}{v_{ave}}$ and $I_{stdv} = \frac{\hat{\sigma}_\sigma}{v_{ave}}$:

$$I_{rep} = I_{mean} + 1.28 I_{stdv}$$

where I_{mean} is the mean ambient turbulence intensity and I_{stdv} its standard deviation. When measured wind data is available, I_{rep} can be directly determined from the measurements. However, in the simulation the representative ambient turbulence intensity is calculated as follows.

First, for each turbine, land cover data is obtained from the CORINE dataset. For each land cover class, the European Wind Atlas provides suggest roughness lenghts z_0 [35]. Note that the roughness length is not a clean physical measurement, but rather a modelling parameter describing how rough the surface is. When dividing the area into sectors, for each sector a representative roughness value can be computed by weighting the roughness values appearing in each sector based on the distance and area. As raster data is used, each tile has the same area and only the distance becomes relevant. For now, a tile is assigned the weight $w = \frac{1}{(d+1.0)}$ where d is the distance from the turbine to the center of the tile. Other, more sophisticated weighting functions could also be used.

The ambient turbulence intensity can then be estimated according to the "Guidelines for Design of Wind Turbines" using the sector-specific roughness lengths [34]:

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

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. As before, other, more sophisticated functions are also possible.

As the guidelines require turbulence values for various wind speeds to determine site suitability, a method developed by the Risø DTU National Laboratory is applied to obtain I_{rep}. In the Wind Farm Assessment Tool, a wind-speed-dependent mean and standard deviation are assumed, which are likewise based on the NTM curve [14]:

$$I_{rep}(v) = I_{mean}(v) + 1.28 I_{stdv}(v)$$
$$I_{mean}(v) = \frac{15+3v}{3v}\frac{3}{4} I_{amb} = I_{amb}(0.75 + \frac{3.75}{v})$$
$$I_{stdv}(v) = \frac{1.44}{v} I_{amb}$$

4.2.4 Wake Turbulence Modelling

When accounting for wake effects in the effective turbulence intensity, the Frandsen model described above is used. There, the following details become relevant [17].

(a) When calculating the effective turbulence intensity for a specific turbine, only turbines located within 10 rotor diameters are considered. Turbines beyond this limit are excluded, as the wake effect is assumed to be negligible at such distances.

(b) The generated wake intensity strongly depends on the thrust coefficient C_T of the wake-generating turbine. Intuitively, the thrust coefficient describes how much momentum the turbine extracts from the incoming wind flow. A large C_T value, typically occurring at lower wind speeds, means that the rotor removes more momentum, which leads to a higher wake-added turbulence intensity. The thrust coefficient is turbine-specific and also depends on the wind speed. As the thrust curve of a turbine is often only published in non-public manufacturer data sheets, the curve can, according to Frandsen, be approximated based on the available wind speed v:

$$C_T(v) = \frac{7m/s}{v}.$$

Since this approximation can significantly overestimate the manufacturer data, it is strongly recommended to use the actual provided C_T curve whenever possible, even if it is difficult to obtain. As both the manufacturer-provided C_T curve and the approximated curve depend on the current wind speed v, the maximum wake-added turbulence intensity I_{add} also depends on v.

(c) If multiple wake-generating turbines are located within the same sector, only the turbine with the largest turbulence contribution is taken into account in the calculation.

4.2.5 Effective Turbulence Intensity

The effective turbulence intensity, I_{eff} combines ambient turbulence and wake-added turbulence generated by nearby wind turbines. The generic formula is [25]:

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

Since the wind directions are divided into 12 sectors of 30°, this expression can be reformulated as:

$$I^S_{eff}(v) = \left(\sum_{i=1}^{12} p(i|v) \cdot I_{combined}(i|v)^{m^T} \right)^{1/m^T}$$

The Frandsen model calculates $I_{combined}$ as a function of the angle between the wind direction and the line connecting the two turbines [17]. Since the wind direction is aggregated into 12 sectors, it is not immediately clear which angle should be chosen. Therefore, each sector is subdivided into n subsectors, and the turbulence intensity is evaluated separately for each subsector. To remain consistent with the Wöhler exponent m, the turbulence intensities are first exponentiated and only then averaged. Let $\theta_{i,k}$ denote the angle between the center of subsector k in sector i and the line connecting the two turbines. Then:

$$I_{combined}(i|v)^{m^T} = \frac{\sum_{k=1}^{n} \left(I_{rep}(v) \left(1 + \alpha \exp \left(- \left[\frac{\theta_{i,k}}{\theta_w} \right]^2 \right) \right) \right)^{m^T}}{n}$$

In this way, we assume that each subsector within a 30° sector has the same probability:

$$I_{eff}^S(v) = \left(\sum_{i=1}^{12} \sum_{k=1}^{n} \frac{pdf(i|v)}{n} \cdot I_{combined}(\theta_{i,k}|v)^{m^T} \right)^{1/m^T}$$

with

$$I_{combined}(\theta_{i,k}) = I_{rep}(v) \left(1 + \alpha \exp \left(- \left[\frac{\theta_{i,k}}{\theta_w} \right]^2 \right) \right)$$

This is the approach closest to the original Frandsen formulation.

As it can be noticed in Figure 9, an artificial bump occurs at the transition between two sectors. This is caused by the abrupt change in the ambient turbulence intensity, where only one constant value is available for each sector. Therefore, a second model is introduced, in which the ambient turbulence intensity value describes only the center of each 30° sector, while the values in between are obtained by linear interpolation.

However, the paper also states that using the maximum wake at the wake center over the characteristic wake angle θ_w produces approximately the same effective turbulence intensity as the detailed definition [32]. Therefore, a third turbulence model can be used in the simulation. The maximum wake in the center can be modelled as:

$$I_{max}(v) = \sqrt{I_{add}^2(v) + I_{rep}^2(v)}.$$

Using the same subsector method as before, this yields:

$$I_{combined}(\theta_n|v) = \begin{cases} I_{max}(v) & \text{if } \theta_n \leq \theta_w \\ I_{rep}(v), & \text{else} \end{cases}$$

with θ_w acting like the wake width angle.
To evaluate the usefulness of the subdivisions, the proposed approach is compared with a simpler reference model. In this model, no sector subdivision is applied. Instead,

the maximum wake turbulence intensity is assigned to the entire sector whenever an upwind turbine is present. This can be expressed as:

$$I_{combined}(i|v) = \begin{cases} I_{max} & \text{if sector } i \text{ contains an upwind turbine} \\ I_{rep}(v), & \text{else} \end{cases}$$

Figure 9 shows the turbulence intensity of a turbine located near to another turbine at an angle of approximately 52°. When wind comes from this direction, the turbulence intensity is contaminated with wake-effects. The figure compares the four implemented model variants: Original, Original with interpolated ambient turbulence, Angular Window, and Sectoral. For the first three models, a subdivision with $n = 30$ is applied, resulting in each subsector having a width of exactly 1°. Because the ambient turbulence intensity is only available for an entire sector, for the Original and Angular Window model, an offset in the wake-added turbulence can be seen at 45°.

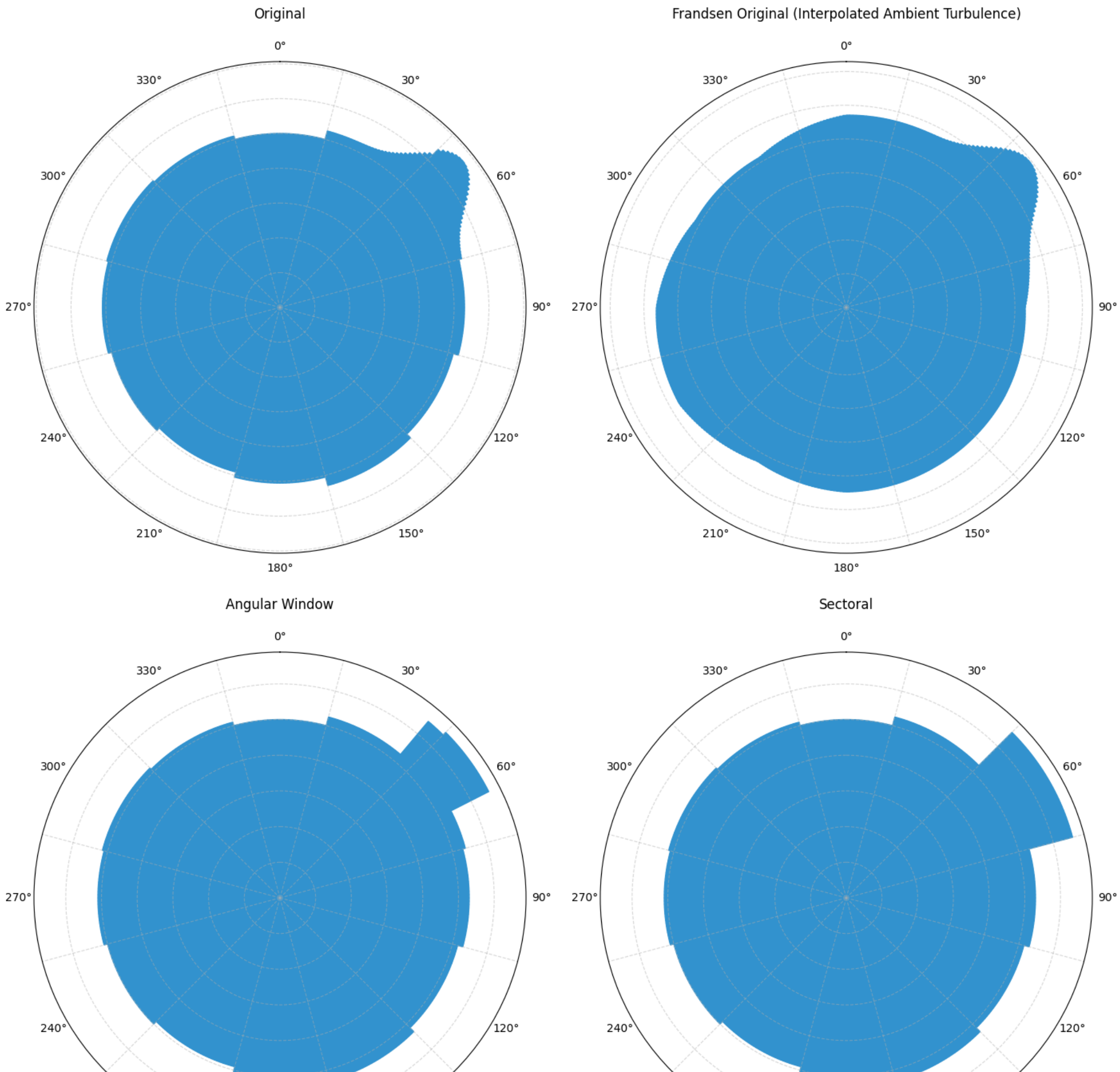


Figure 9: Visual comparison of four variations of the Frandsen turbulence model

5 Results and Verification

In this chapter, we compare the results of the implemented simulation with commercial site-suitability reports. The aim is to verify that our developed tool produces site-suitability assessments comparable to professional evaluations for the same turbines and sites. The comparison is based on three real projects in Germany. The reports were created by I17-Wind GmbH & Co. KG (I17) [24].

5.1 Wind Farm Berge (1 Turbine)

5.1.1 Site Description

The wind farm Berge is a project located in 49626 Berge, Lower Saxony [23]. It consists of a single planned turbine, with no other turbines within a radius of ten times its rotor diameter. The site is classified as wind zone 2 and terrain category II.

ID	WGS84 (lat, lon)	Turbine Type	z_{hub} [m]	D [m]
W1	52.6004, 7.7448	Enercon E-175 EP5	162.0	175.0

Table 9: Turbine configuration of the wind farm Berge [23]

.

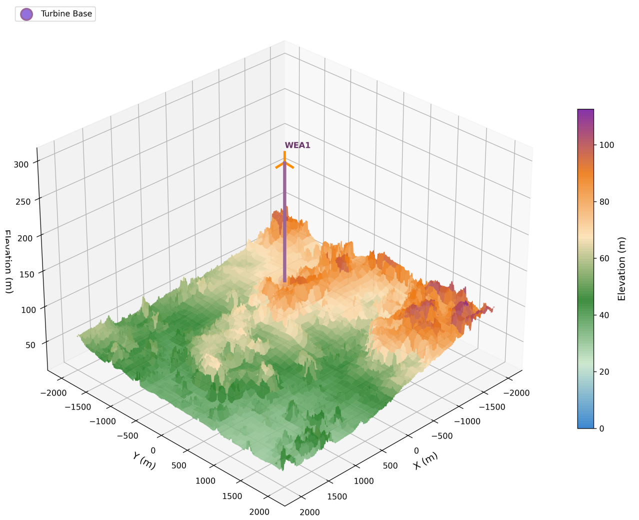
The turbine type has a custom wind speed class S and is designed for turbulence category A and wind zone 2. The declared design average wind speed, v^T_{ave}, is 7.8 m/s, while the declared design extreme wind speed, v^T_{m50}, is 42.5 m/s.

Wind Speed Class	Turbulence Category	Wind Zone	v^T_{ave} [m/s]	v^T_{m50} [m/s]	m
S	A	2	7.8	42.5	14

Table 10: Turbine design parameters for Enercon E-175 EP5, where m is the Wöhler exponent [23].

5.1.2 Topographical Complexity

The simulation computes the topographical complexity as described in Section 4.2.1. As none of the calculated values (see Figure 10b) exceeds the thresholds listed in Table 7, the site is classified as non-complex. I17 applies the same method to determine the site's topographical complexity [23]; however, it uses the Shuttle Radar Topography Mission (SRTM) as the digital elevation model [38]. This dataset also has a resolution of approximately 30 m, which is comparable to Copernicus GLO-30. The planes used for the assessment are likewise fitted by minimizing the least-squares error. Unfortunately, I17 does not report its computed TSI and TVI values. Nevertheless, it reaches the same conclusion, classifying the site as non-complex.



(a) Plot of 3D topography

	$5z_{hub}$	$10z_{hub}$	$20z_{hub}$
TSI_{30}	0.81°	0.59°	0.41°
TVI_{30}	0.39%	0.23%	0.12%
TSI_{360}	0.002°	-	-
TVI_{360}	0.17%	-	-

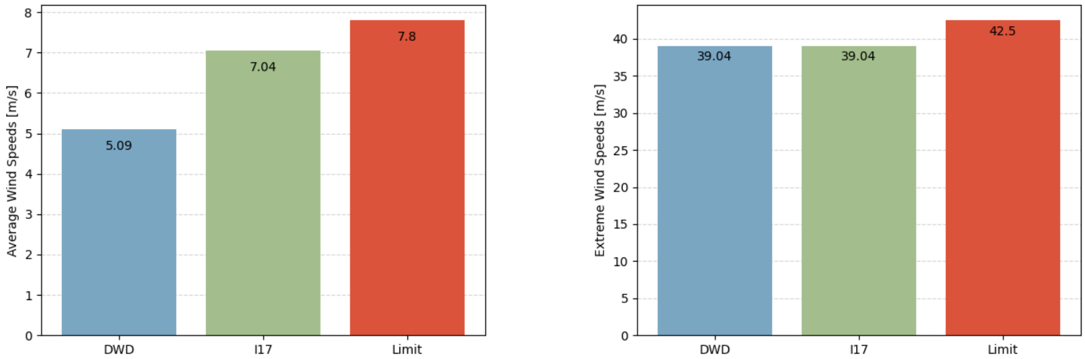
(b) TSI and TVI values

Figure 10: Topography at turbine W1 in Berge

5.1.3 Average and Extreme Wind Speed

Since both our tool and I17 classify the site as non-complex, both apply the simplified site-suitability method according to DIBt. While I17 uses wind data provided by the external consultant anemos, the simulation uses data from DWD wind station no. 15813 in Lingen-Baccum [23]. This station has a distance of approximately 25 km to the wind park in Berge [8]. As a result, different average wind speeds are obtained. Our simulation yields a value of $v^S_{ave} = 5.09$ m/s, whereas I17 reports a significantly higher value of 7.04 m/s. Nevertheless, both values are below the turbine design limit v^T_{ave} and also below $0.95 \cdot v^T_{ave}$. Therefore, the average wind speed requirement of DIBt is fulfilled.

The extreme wind speed v^S_{m50} is modeled using the formulas provided by DIN 1991-1/NA for wind zone 2 and terrain category II. This results in an extreme wind speed of $v^S_{m50} = 39.04$ m/s. I17 uses the same method and therefore obtains the same value. Since the turbine has a design limit of $v^T_{m50} = 42.5$ m/s, the extreme wind speed requirement of DIBt is also satisfied.



(a) Average wind speed (b) Extreme wind speed

Figure 11: Wind speeds at wind farm Berge from DWD and I17 compared to the turbine design limit

5.1.4 Ambient Turbulence Intensity

For the effective turbulence intensity at this site, no wake effects occur. This project is therefore particularly well suited for verifying the estimation of the ambient turbulence intensity based on the surrounding roughness length. In this respect, the approach implemented in our tool is comparable to the procedure used by I17 [23]. They also divide the area surrounding a turbine into 12 sectors and determine a roughness length for each sector based on the CORINE dataset and the corresponding roughness lengths provided in the European Wind Atlas. However, I17 does not further elaborate on the weighting function or the profile used to compute the ambient turbulence intensity from these roughness values. It is only stated that a procedure similar to that of the Wind Farm Assessment Tool is used to obtain I_{rep}.
According to DIBt, the effective turbulence intensity must be evaluated for wind speeds between $0.2v_{m50}^S$ and $0.4v_{m50}^S$, which breaks down to the interval $[7, 16]$ m/s. For a broader comparison, this interval is extended here to $[3, 20]$ m/s. Figure 12 shows the effective turbulence intensity simulated with our tool, the effective turbulence intensity reported by I17, and the turbine turbulence intensity limit based on the NTM for turbulence category A [23].
When comparing our results with those of I17, the curves appear to be very similar. The deviations seem to be constant for low and high wind speeds, exceeding the I17 values. The maximum difference occurs at 13 m/s and is approximately 2.49%, while the average difference is 2.06%. Both results remain well below the turbine limit and therefore satisfy the effective turbulence intensity criterion defined by DIBt.

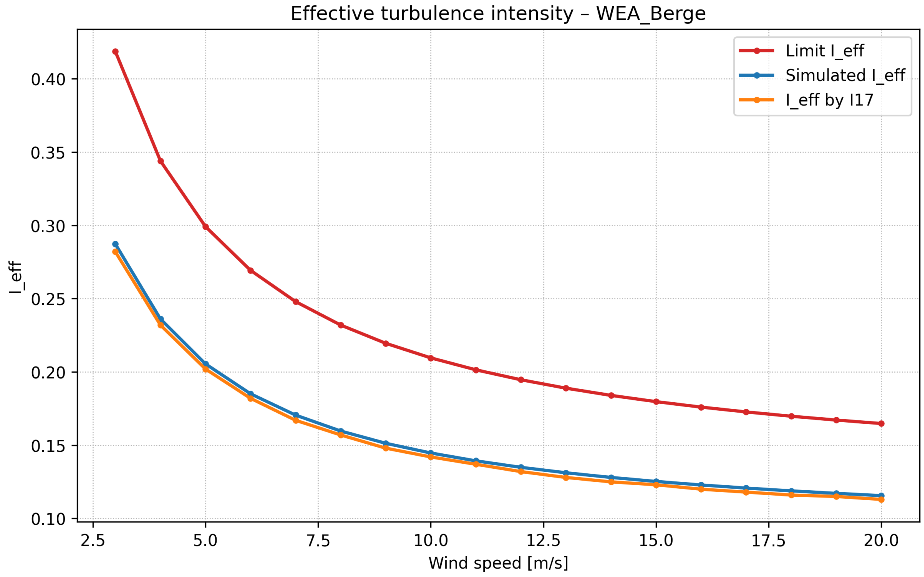


Figure 12: Effective turbulence intensity of turbine W1 at wind park Berge.

The results for this site successfully demonstrate that our simulation yields results comparable to those of commercial site-suitability assessments when no wake effects are involved and only the ambient turbulence intensity needs to be considered. The small differences may be caused by the use of different weighting functions for computing the roughness length of a sector around the site, or by differences in the profile used to derive the ambient turbulence intensity from the roughness length. Both assessments conclude that the location is suitable for the planned turbine.

5.2 Wind Farm Bever (2 Turbines)

5.2.1 Site Description

The wind farm Bever is a project located in 49219 Glandorf, next to the river Bever [22]. It consists of two planned wind turbines with a distance of 4.21 rotor diameters. For the effective turbulence intensity, only these turbines have to be considered. The site is classified as wind zone 2 and terrain category II. The configuration in Table 11 is depicted in Figure 13.

ID	WGS84 (lat, lon)	Turbine Type	z_{hub} [m]	D [m]
WEA1	52.0498, 7.9925	Nordex N149/4.0-4.5	164.0	149.0
WEA2	52.0534, 7.9997	Nordex N149/4.0-4.5	164.0	149.0

Table 11: Turbine configuration at wind farm Bever. [22]

The turbine type has both, a custom wind speed class and a custom turbulence category. It is designed for an average wind speed, v_{ave}^T, of 7.2 m/s and an extreme

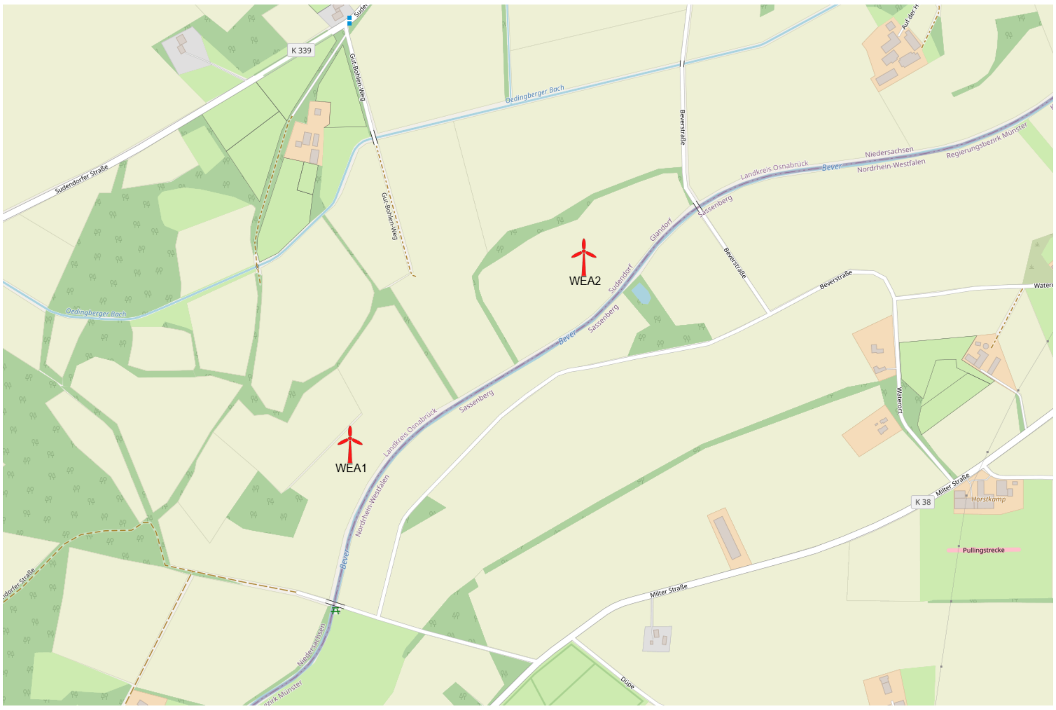


Figure 13: Turbines of wind farm Bever illustrated in a map. Map data from OpenStreetMap [29]

wind speed v^T_{m50} of 40.3 m/s. Since it has an custom turbulence category, the threshold values of the design turbulence intensity are not modelled through the NTM but are provided separately for each wind speed.

Wind Speed Class	Turbulence Category	Wind Zone	v^T_{ave} [m/s]	v^T_{m50} [m/s]	m
S	S	2	7.2	40.3	14

Table 12: Turbine design parameters for Nordex N149/4.0-4.5, where m is the Wöhler exponent [22].

Although I17 does not provide any TSI and TVI values, both assessments classify both turbine sites as non-complex. Again, the simplified site suitability method by DIBt is used.

5.2.2 Average and Extreme Wind Speed

For this project, the focus lies on the comparison of the effective turbulence intensity where wake effects need to be incorporated in the simulation. We therefore use the same wind data I17 listet in their report [22]. As a result, both simulations yield the same v^S_{ave}. Additionally, both simulations use formulas in DIN 1991-1/NA for wind zone 2 and terrain category II to determine the site's extreme wind speed. For a hub height of 164 m, it results in an extreme wind speed of $v^S_{m50} = 39.11$ m/s.

5.2.3 Frandsen Subdivision

Before comparing the variations of the Frandsen model, the influence of the subdivision is first analyzed. For the configuration in Table 11, a reference turbulence simulation is performed for the Frandsen Original model, using a subdivision of $n = 3000$, which is assumed to approximate the original integral sufficiently well. The output consists of the effective turbulence intensity for both turbines at wind speeds from 3 m/s to 20 m/s.

This reference output is then compared with the outputs of simulations using smaller numbers of subdivisions, based on the average absolute difference over all simulated wind speeds and the maximum absolute difference.

Table 13: Average and maximum absolute differences in effective turbulence intensity for different numbers of subdivisions n, relative to the reference case $n = 3000$.

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 13 shows that both the average and maximum differences converge rapidly as the number of subdivisions increases. For $n = 4$, all differences are below 0.1%, while for $n = 15$, all differences are below 0.01%. These values, of course, depend on the considered configuration and number of wake-generating turbines. Therefore, the default value for the simulations is set to $n = 30$.

5.2.4 Sensitivity Analysis C_T Curve

An important input parameter is the turbine-specific C_T curve. As discussed previously, C_T curves are often difficult to obtain, since they are usually not publicly available and are instead contained only in non-public manufacturer datasheets. For the Nordex N149/4.0–4.5 turbine used in the wind farm Bever, a plausible C_T curve was found, but only from an unofficial source [40]. Therefore, it is relevant to investigate the influence of variations in the C_T values.

For turbine WEA1 in the Bever wind farm, the input C_T curve is varied by ±5%, and the resulting deviation in effective turbulence intensity is evaluated. Again, the Frandsen Original model is used. Figure 14 shows the effective turbulence intensity for all three C_T curves, as well as their deviation from the reference curve. The results

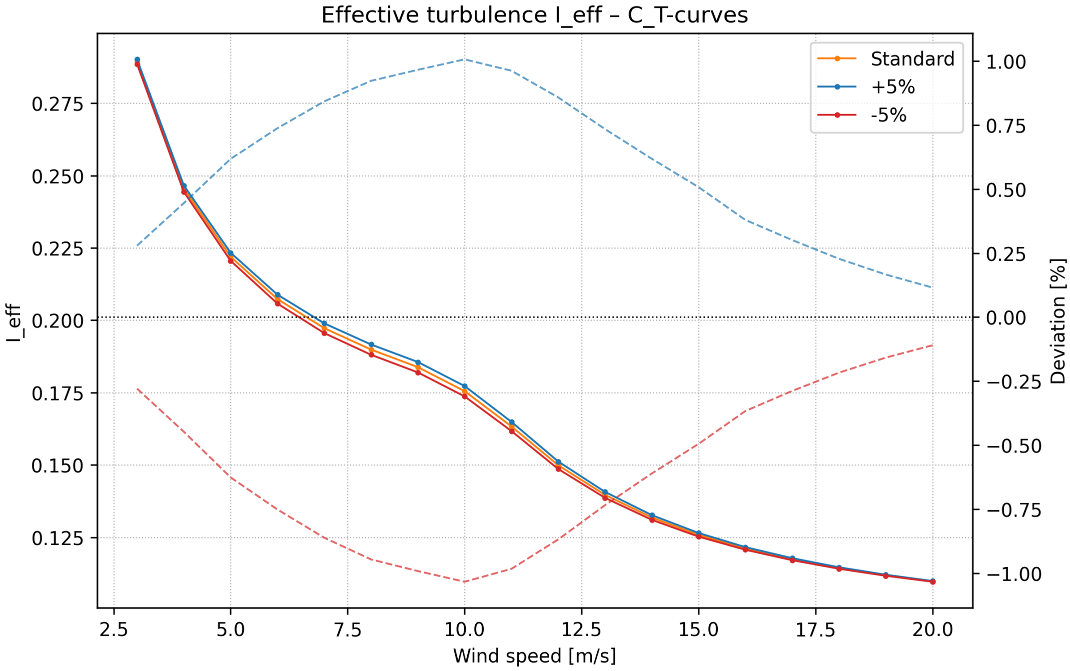


Figure 14: Effective turbulence intensity for turbine WEA1 in wind farm Bever with adjusted C_T curves

show that the deviation from the reference value is not constant, but depends on wind speed, reaching a maximum at around 10 m/s.

Furthermore, a 5% change in the C_T curve does not lead to a 5% change in effective turbulence intensity, but only to deviations ranging from 0.25% to 1.01%. Thus, variations in the C_T curve have a damped effect on the effective turbulence intensity. While an accurate C_T curve is important, small deviations are acceptable, as they only have a limited effect on the effective turbulence intensity.

5.2.5 Frandsen Model Comparison

To evaluate the variations of the Frandsen turbulence model, their results are compared with the I17 results for the wind farm Bever [22]. As before, the effective turbulence intensity is evaluated for wind speeds from 3 m/s to 20 m/s. Figure 15 shows the effective turbulence intensity predicted by all variations, together with the I17 results, for turbine WEA1 of the wind farm Bever.

The Frandsen Sectoral model consistently overestimates the I17 reference results for all considered wind speeds. It shows an average deviation of 3.84%, with a maximum deviation of 7.74% at 10 m/s.

In contrast, the Frandsen Original model clearly underestimates the reference results for wind speeds up to 17 m/s. Its average deviation is also 2.04%. The variation with interpolated values for the ambient turbulence intensity yields nearly the same values as the Frandsen Original approach, as the curves overlap over the entire wind speed

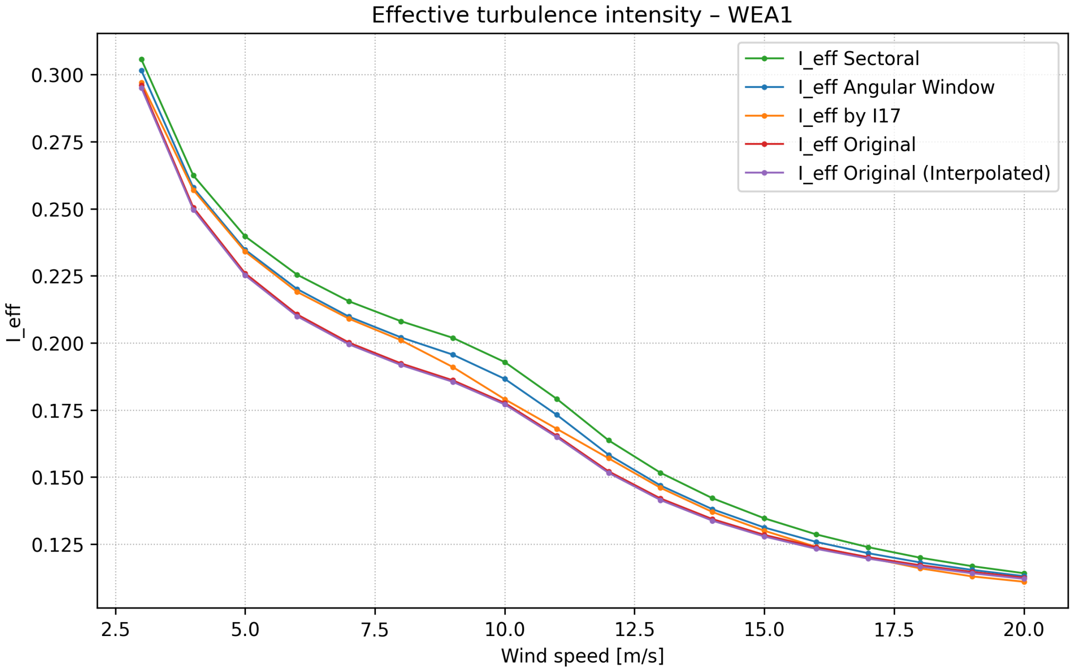


Figure 15: Effective turbulence for turbine WEA1 of all Frandsen variations and I17

range.

Lastly, the Frandsen Angular Window approach is closest to the I17 results. It matches the reference values well at low and high wind speeds, while the largest deviations occur at wind speeds around 10 m/s. Its average deviation is 1.40%, with a maximum deviation of 4.22% at 10 m/s.

Since the same wind data and configuration were used as in the I17 report, it is likely that I17 uses a different C_T curve. Figure 16 shows, in orange, an adjusted C_T curve that would be needed for our simulation to reproduce the same values for the turbulence intensity as I17. The blue curve shows the C_T curve from [40]. The largest visual difference is around 9–11 m/s, where the found curve is still relatively high, while the adjusted curve has already dropped noticeably. Apart from that, the curves have roughly the same shape. To assess which curve is more plausible, the C_T from the Nordex N149-5.X in 5.5 MW mode was obtained from a trustworthy source [28]. This turbine has the same rotor diameter as the planned N149/4.0-4.5, but has a higher rated power and can therefore generate more power at the same wind speeds. Thus, slightly higher C_T values can be expected. In terms of shape, this curve is more closely matches the adjusted curve, although it shows higher thrust values, as it can be expected. This supports the assumption that I17 may use a different C_T curve.

Nevertheless, all variations show a similar overall trend, with the Frandsen Angular Window approach providing the closest match to the I17 results. Regarding site suitability, the Frandsen Sectoral model would classify the site as unsuitable because

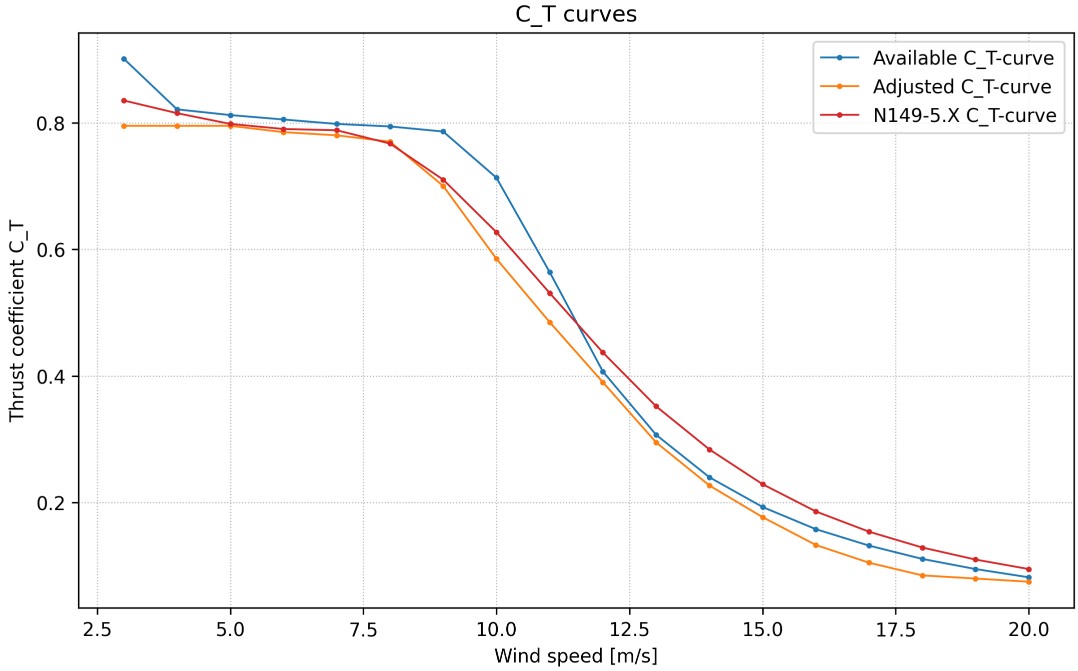


Figure 16: Comparison of the available, adjusted, and reference C_T curves. The adjusted curve was derived to reproduce the I17 turbulence intensity values.

the simulated turbulence intensity exceeds the turbine design limits. All other models, including I17, classify the site as suitable.

5.3 Wind Farm Glandorf (4 Turbines)

5.3.1 Site Description

The wind farm Glandorf is a project also located in 49219 Glandorf [22]. It consists of four planned wind turbines. For the effective turbulence intensity, only these turbines have to be considered. The site is classified as wind zone 2 and terrain category II.

ID	WGS84 (lat, lon)	Turbine Type	z_{hub} [m]	D [m]
WEA1	52.09410, 7.93874	GE 3.6-137	131.4	137.0
WEA2	52.09095, 7.93957	GE 3.6-137	131.4	137.0
WEA3	52.08853, 7.94741	GE 3.6-137	131.4	137.0
WEA4	52.08612, 7.94433	GE 3.6-137	131.4	137.0

Table 14: Turbine configuration at wind farm Glandorf [21].

The turbine type has a custom wind speed class and is designed for turbulence category B. It is designed for an average wind speed, v_{ave}^T, of 7.5 m/s and an extreme wind speed v_{m50}^T of 39.3 m/s.

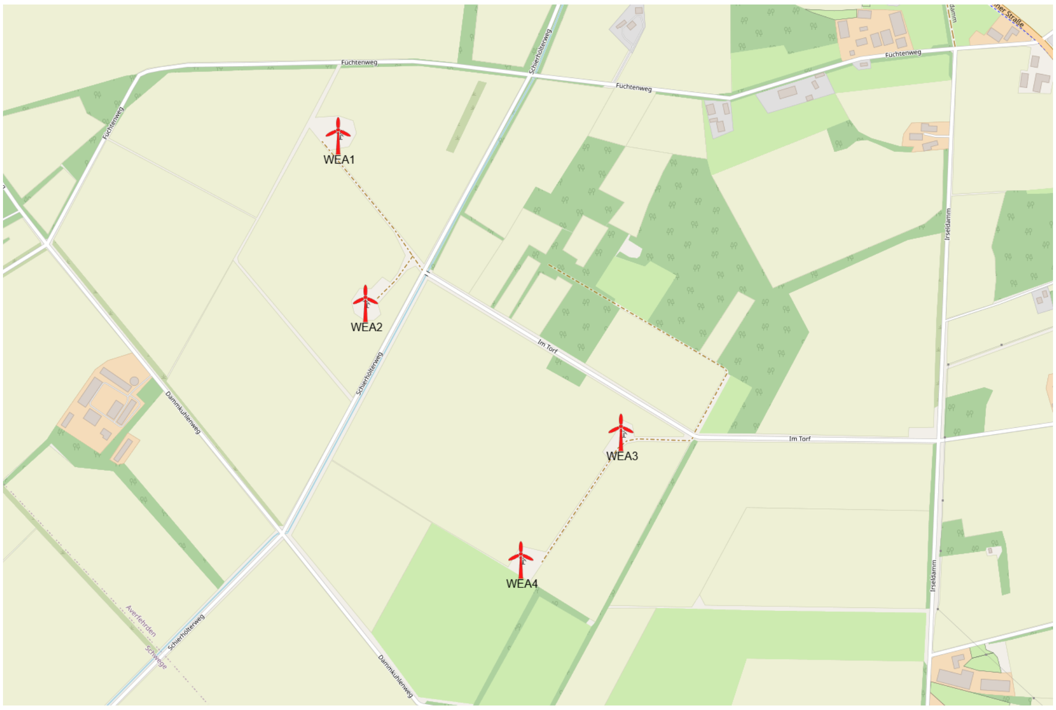


Figure 17: Turbines of wind farm Glandorf illustrated in a map. Map data from OpenStreetMap [29]

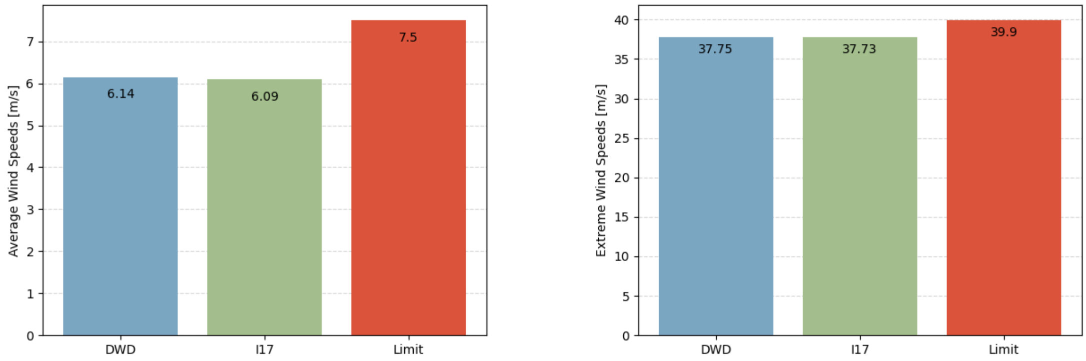
Wind Speed Class	Turbulence Category	v_{ave}^T [m/s]	v_{m50}^T [m/s]	m
S	B	7.5	39.3	10

Table 15: Turbine design parameter for GE 3.6-137, m being the Wöhler exponent [21].

Although I17 does not provide any TSI and TVI values, both assessments classify all turbine sites as non-complex. Again, the simplified site suitability method by DIBt is used.

5.3.2 Average and Extreme Wind Speed

I17 again uses wind data provided by an external consultant while we use data from DWD station no. 01766 Münster/Osnabrück [21]. This station has a distance of approximately 17 km to the wind farm Glandorf. For this site, the wind data yield nearly identical values for the average wind speed v_{ave}^S with I17 reporting 6.09 m/s and DWD yielding a value of 6.14 m/s. For the extreme wind speed v_{m50}^S both, I17 and our tool, use formulas provided by DIN 1991- 1/NA for wind zone 2 and terrain category II. The values of the extreme wind speed slightly differ because we use the exact hub height of 131.4 m and I17 presumably a rounded value of 131 m. Figure 18 shows wind speed values and that they do not exceed the turbine design limits.



(a) Average wind speed

(b) Extreme wind speed

Figure 18: Wind speeds at wind farm Glandorf from DWD and I17 compared to the turbines design limit [21].

5.3.3 Effective Turbulence Intensity

For the simulation of the effective turbulence intensity, the same wind data is used that is provided by the assessment of I17, so that wind data can be excluded as a source of differences. The turbulence model used is Frandsen Angular Window.

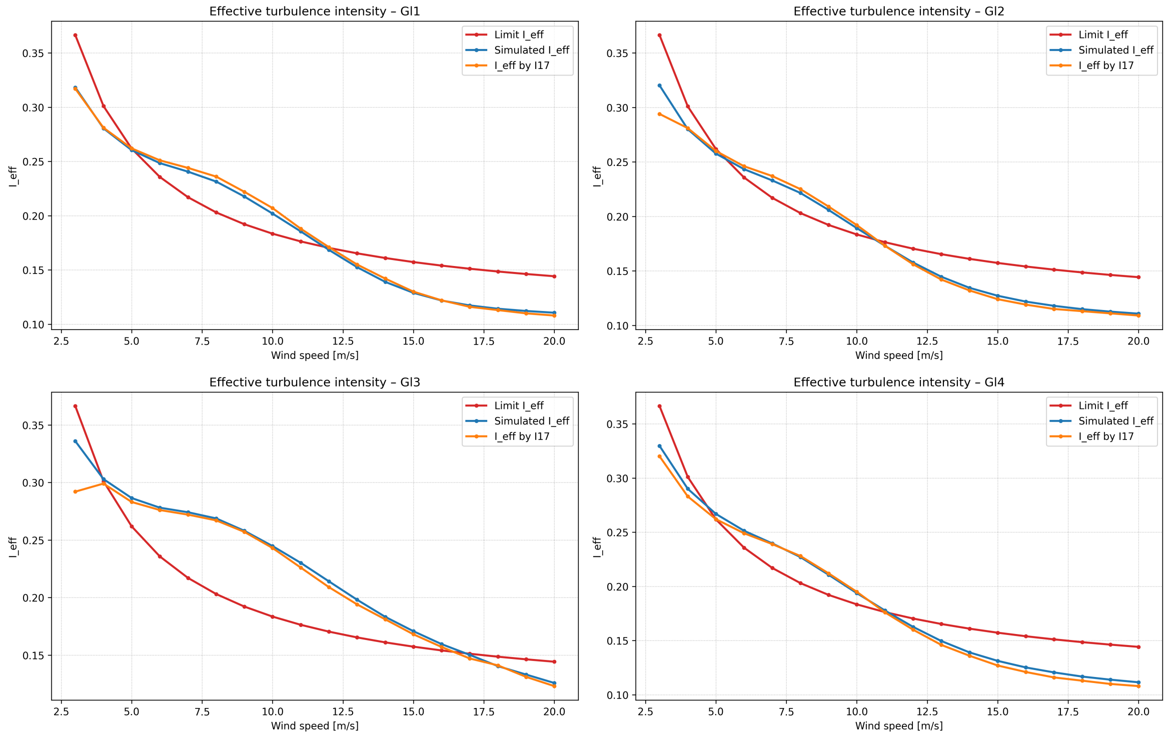


Figure 19: Effective turbulence intensity for all four turbines at wind farm Glandorf

Figure 19 shows that the simulated I_{eff} nearly follows the same path as the values of I17. All turbine sites have a average deviation below 2.15% For WEA2 and WEA3 one can notice a strong deviation at wind speed 3 m/s. Because this shape of the curve is unplausible, this may indicate an error in the I17 report. The small differences in the curve could result from different formulas used in the ambient turbulence intensity or in the parameters of the Frandsen model. While our tool automatically calculates the characteristic view angle based on the formula in Frandsen, many tools fix this wake angle at 21.6°. When looking at the intersections between the turbulence intensity curves and the NTM curve, it can be seen that the I17 curve and our curve intersect the NTM curve at approximately the same wind speeds, resulting in exceedances of the NTM limit at exactly the same wind speed values.

5.4 Conclusion

This section has shown that our implemented tool yields results for the site suitability assessment and turbulence calculations that are comparable to those of professional reports by I17. For wind farm Berge, the estimated ambient turbulence intensity deviates only slightly, which could result from differences in the formulas used to convert roughness length into ambient turbulence intensity. When comparing values for wake-added turbulence intensity, the Frandsen Angular Window approach matches the I17 results most closely, while the Frandsen Original (and Interpolated) approach consistently underestimates and the Sectoral approach overestimates the results. However, the comparison also shows that the results are sensitive to the available wind data and the turbine-specific C_T curve.

6 Conclusion

6.1 Future Work

Although the tool already achieves results comparable to professional reports, several improvements could be integrated.

- The ambient turbulence intensity depends on the roughness lengths of the area surrounding a wind turbine site. Since the weighting function and the formula used to derive the representative turbulence intensity produce comparable results, both approaches could be revised or reconsidered. In particular, a formula for modelling ambient turbulence that is independent of the empirical parameter A_x would be beneficial, as it would remove an additional source of uncertainty from the simulation.

- Additionally, in 2026, the Bundesverband WindEnergie e.V. published an evaluation of a round-robin test on the determination of ambient turbulence intensity [33]. The aim of the study was to assess the comparability and consistency of ambient-turbulence assessments performed by different consultants using identical input data. As part of future work, this location could be analysed with the proposed tool and the obtained results could be contextualised within the findings of the study. This would provide a benchmark for evaluating how the proposed approach compares with established professional methods for estimating ambient turbulence.

- At the current stage, the tool supports only variations of the Frandsen turbulence model for assessing the effective turbulence intensity of a turbine. Additional turbulence models, such as the TNO turbulence model [7], could be integrated. Furthermore, Frandsen model provides an analytical description of wake-added turbulence. This approach could be extended by using more complex models, such as computational fluid dynamics (CFD), which describe wake-added turbulence and must be solved numerically. Such models are expected to represent the effective turbulence intensity more accurately.

- Unfortunately, all reports used to verify our tool were for non-complex sites in wind zone 2 and terrain category II. A more extensive comparison, including the site suitability method for complex sites, would be beneficial. Furthermore, the comparison was limited to one consultant, I17. A comparison with a broader variety of site assessments could further validate the tool.

6.2 Key Findings

The goal of this thesis was to implement a tool for assessing the site suitability of wind farm projects, including wind speed and effective turbulence calculations. The simulation results were intended to be comparable to professional reports. The developed tool is consistent with all relevant legal guidelines, including IEC 61400-1:2019 and the DIBt guideline.

The performance of the tool was validated through a comparison with three site assessments of real wind farm projects for which professional reports by I17 were available. It was observed that the underlying wind data could differ because different data sources were used. This can lead to different values for the average wind speed at a site and also affects the effective turbulence intensity. However, when the calculations are based on the same wind data, the values of the effective turbulence intensity are very similar, following the same trend with deviations below 2%. Also, same results for the topographical complexity and extreme wind speed were obtained.

This result is particularly remarkable because our tool relies exclusively on freely available public datasets, such as Copernicus DEM GLO-30, DWD weather data, and CORINE land cover data.

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