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Turbulenz von Windkraftanlagen Turbulence of wind turbines

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1 Introduction

The current development of the global energy consumption brings up the question how future projects can catch up to the ever increasing demands. Planning, regulations and many other aspects of generating new energy sources keep all electricity providers and the official auditors occupied. Those auditions take away important time that could be invested in other parts of the current energy transition.

Wind energy was once again the most important energy source in 2024, contributing over 136TWh to net public electricity generation. The planned expansion of wind power did not meet expectations and fell way behind the scheduled 7 gigawatts capacity increase by November 2024. Only 2.44 gigawatts had been installed by that date. The electricity generation by fossil fuels continues to decline, which increases the importance of alternative energy sources even more. To continue the ongoing development, the capacity growth of renewable energy sources needs to keep up the pace or even speed up. In total, renewable energy plants generated 4.4% more in 2024 than in 2023. The share of renewable energy in the German energy mix rose from 55.3 to 56 percent [28]. The global transition to renewable energy is accelerating at an unprecedented pace, with wind and solar energy at its core. In 2024, the world installed a record 117GW of new wind capacity, driven by climate goals and the chance of energy independence. This expansion is not without its technical hurdles. As wind farms become larger and more complex, understanding and predicting aerodynamic phenomena like turbulence is no longer just an academic research topic, but also a critical factor for the economic viability and structural safety of these expensive assets. This thesis addresses the challenge of turbulence, a key variable that directly impacts the efficiency and longevity of wind turbines [21].

1.1 Motivation

Turbulence of wind turbines is one of many important factors during the decision process where a new wind turbine could be placed. The ambient and wake turbulences that occur during the operation time of a wind turbine directly influence the lifespan, safety, and possible energy generation. Understanding the impact turbulence has on a wind turbine during operation is essential to optimize the efficiency of the energy generation. Despite the importance in this regard, it is a very complex topic which still needs to be researched further. Companies like EMD-International offer such calculations at a high price.

Inaccurate turbulence assessments might result in significant consequences. Economically, it can lead to an overestimation of the Annual Energy Production (AEP), creating financial risks for investors when a wind farm under performs [26]. Wake-induced turbulence from close turbines can reduce a wind farm's total output roughly 10-25% [4]. Structurally, unanticipated turbulence is a primary driver of material fatigue on critical components like blades and gearboxes. This increases operational and maintenance costs and, in extreme cases could even lead to turbine failure. Therefore, developing more precise and accessible turbulence simulation tools is not just an incremental im-

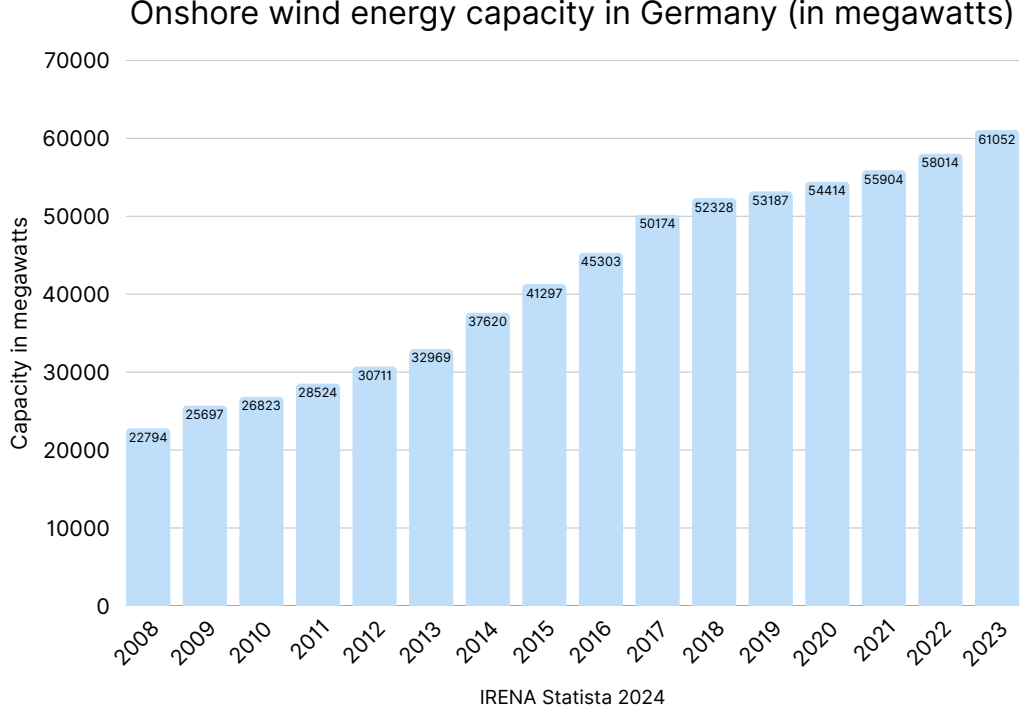


Figure 1: The onshore wind capacity in Germany from 2008 to 2023 is steadily increasing. But the previously big advancements slowed down in the past 6 years. Even though the capacity increased by 5.2% from 2022 to 2023, German wind capacity growth slowed down compared to 2012-2018.

provement, it is essential for reducing the risks of future wind turbine installations even further and ensuring the long-term reliability of our renewable energy infrastructure.

1.2 Related work

This paper is going to extend and improve the paper written by M. Kröker [24]. The applicable norms used in the industry and policies have not changed since the release of Kröker’s paper. The same DIN norms and documents are used for the calculations. Most importantly, the "Richtlinien für Windenergieanlagen, DIBt 2015"[7], where 2015 is still the last year of new additions or changes.

To develop the enhanced code, Kröker’s code base is evaluated in order to assess its current efficiency and identify potential improvements. Many components of the written code were already correctly implementing the formulas needed for the calculations based on the wind and turbulence data. The code was divided into multiple subdirectories including classes for the different formula sources, including DIBt Richtlinie für Windanlagen [7], DIN EN 1991-1-4/NA [8][9] and DIN EN IEC 61400-1 [10]. The different norms are explained and visualized in figure 3.

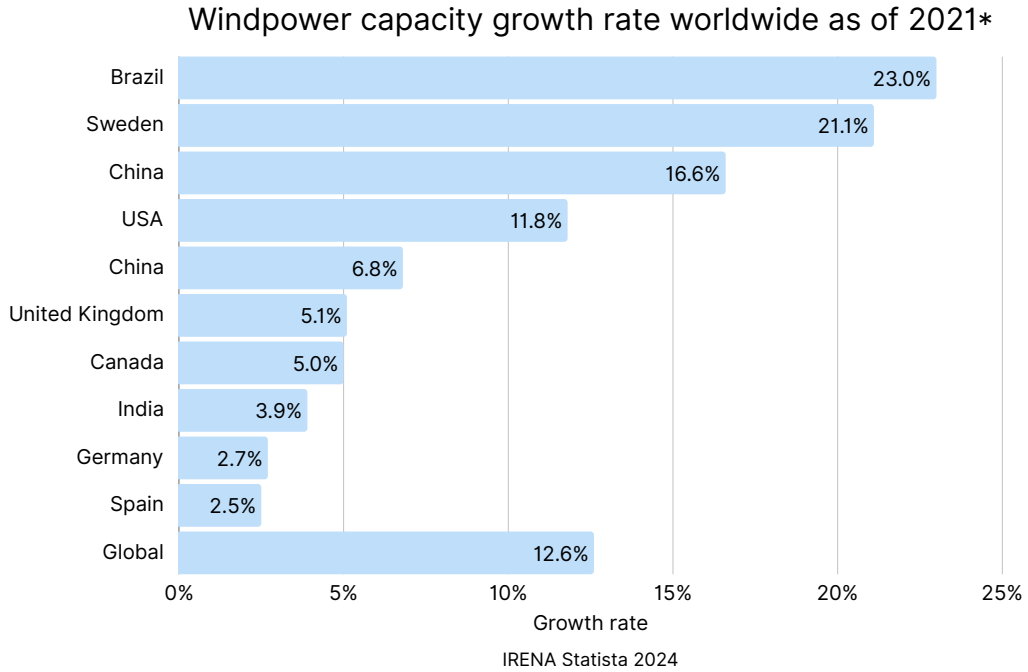


Figure 2: The growth rate of wind power capacity in 2021 shows that Germany falls behind a few other leading countries like Brazil, Sweden, China and the USA. As already mentioned in figure 1 the yearly wind power capacity grow in Germany has been stagnating for a few years already.

1.3 Contribution

This bachelor thesis aims to improve the already existing implementation of the Site Suitability simulation tool written by Marcel Kröker in his master thesis [24]. The turbulence analysis written by me is part of a larger windfarm simulation project called "WindFarm3D", developed by LuFG Theory of Hybrid Systems RWTH Aachen University, with contributions by multiple students. The module "turbulence_analysis" was developed and used for this thesis.

The resulting module is able to perform extensive wind and turbulence calculations for planned or existing wind parks. The integration into the WindFarm Simulations project offers future users a free and easy tool to do site suitability and turbulence simulations. While maintaining a high level of quality throughout the results, multiple sources of wind and topological data were implemented to ensure a quick and straightforward setup for new regions. This approach further reduces the investment of time, money, and resources required to begin. The possibility of quickly assessing whether a site is suitable for a certain wind turbine reduces the duration and costs of planning. In the past it was common practice to plan new wind turbine sites with large safety reserves, many of the sites were planned for wind zone 2 and international norm IEC 61400-1. Today, that is often not possible anymore because of the high price tag of new wind turbine sites. The average yearly wind speeds of wind zone 2 in the newly

planned areas are regularly not met anymore. Future wind turbine sites are planned for lower wind conditions. This more individual and needs-based planning results in lower construction costs and makes wind energy competitive compared to other forms of generation [29]. With the tool developed in the course of this bachelor thesis, the needed calculations will be available as an open-source tool to RWTH students at some point in the future.

1.4 Outline of this work

The remainder of this thesis is structured as follows: Chapter 2 reviews the foundational literature on wind farm planning and the physics of turbulence. Chapter 3 defines the key terms, concepts, and regulatory standards that lay the foundation of the analysis. Chapter 4 details the methodology, software architecture, and implementation of the "turbulence_analysis" module. Chapter 5 presents a case study validating the module's performance against industry tools for the Heidsiek wind farm. Finally, Chapter 6 summarizes the key findings and suggests directions for future research.

2 Literature Review

2.1 State of the Art in Wind Farm Planning

To plan and construct a new wind farm or extend an existing one can take several years and depends on quite a few steps. Planning normally takes between 4 and 5 years and only when all requirements have been met is the plan implemented. The requirements consist of many factors ranging from financial plans to the fulfillment of environmental appraisals. [31] The appraisals also include the turbulence appraisal, which is especially relevant for this thesis.

There are onshore and offshore wind farms, which can be differentiated by their positioning. Onshore wind farms are constructed on land and offshore wind farms in the sea. While offshore wind farms are more expensive and risky to construct, they also yield a higher energy generation per year because of the better wind conditions at sea. [1] But the goal is the same, to generate as much energy as possible while minimizing the required surface area.

2.2 Review of Site Suitability Factors

The process of finding a site for a new wind turbine is complex since it has a significant influence on its surroundings, especially the environment, animals, and humans around it.

2.2.1 Site Suitability

The suitability of a wind turbine site is crucial for ensuring the structural integrity and safe operation of wind energy generation systems. The design of a wind turbine

is dependent on the intended site or site type. Site assessment requires consideration of various factors, including wind, seismic, topographic, and soil conditions. Wind conditions are the primary external condition affecting structural integrity, including normal and extreme wind conditions. The topographical complexity of a site can cause distortion in the wind turbulence, deviating from design conditions. Other environmental conditions like temperature, air density, solar radiation, and many more also need to be taken into consideration, but that is part of a bigger scope and requires on site inspections. For this thesis, we focus on the central aspect of wind turbine site suitability in the following chapter 2.3.

2.2.2 Shadowcast

Shadowcast, also known as shadow flicker, refers to the intermittent shadows cast by the rotating blades of wind turbines. It typically occurs during sunrise and sunset, causing moving shadows to be cast on nearby structures or land. Haac et al. [22] modeled the impact of shadow flicker and concluded that only about 50% of residents even notice the flicker effect in their homes [24].

2.2.3 Noise propagation and optical impairment

In Germany, wind turbine sites are also strictly regulated regarding their noise and optical impairment. Noise is regulated by the general administrative regulation "TA Lärm", which enforces strict limits on the noise level, especially at nighttime in residential areas. This is often an important factor in choosing the minimum distance between residential areas and a turbine[2]. Beyond shadow flicker, the general visual dominance is a key consideration. German courts often use a guideline that a turbine's distance from a residence should be at least two to three times of its total height to avoid an overwhelming visual effect[25][22].

2.3 Wind & Turbulence

2.3.1 Wind turbine wake effects

Wind turbine wake effects describe the changes in the mean flow field, turbulence intensity, and turbulence structure that occur downstream of a wind turbine due to its operation. These effects from neighboring wind turbines significantly influence the loading, durability, and operation of other turbines within a wind farm. Wake effects are particularly important for fatigue and ultimate load calculations. The assessment of site suitability for a wind turbine within a wind farm must account for these deterministic and turbulent flow characteristics, considering single or multiple wakes and spacing between machines for all relevant wind speeds and directions.

2.3.2 Turbulence intensity models

Turbulence intensity ($I_v(z)$) is a key parameter describing the variable (fluctuating) portion of the wind at a height z . It is defined as the ratio of the wind speed longitudinal standard deviation (σ_1) to the average wind speed (v_{ave}), determined from the same set of measured data samples over a specified period:

$$I_v(z) = \frac{\sigma_1}{v_{ave}} \quad (1)$$

Turbulence represents random variations in wind velocity from 10-minute averages. The turbulent wind velocity field has three vector components:

- **Longitudinal:** Along the direction of the mean wind velocity.
- **Lateral:** Horizontal and normal to the longitudinal direction.
- **Upward:** Normal to both the longitudinal and lateral directions (tilted from the vertical by the mean flow inclination angle).

For standard wind turbine classes, the longitudinal turbulence standard deviation (σ_1) is assumed invariant with height. The lateral (σ_2) and upward (σ_3) components have minimum standard deviations relative to σ_1 :

$$\sigma_2 \geq 0.7\sigma_1 \quad (2)$$

$$\sigma_3 \geq 0.5\sigma_1 \quad (3)$$

2.4 Existing Tools and Methods for Wind Farm Optimization

While selecting a tool for this task, we can choose between commercial and open source software. In the commercial space, we have three bigger tools available: WindPRO(EMD International) [17], WindFarmer(DNV) [12] and OpenWind [30]. The first option WindPRO, is the software that was used as a verification for our results during the thesis. It is a powerful software for wind turbine project planning. Regarding open source software, there is the "WindFarm3D" by RWTH Aachen University, FLORIS by US National Renewable Energy Laboratory[27] and PyWake[13] by the Technical University of Denmark, which takes a similar approach to our WindFarm3D but with a more in-depth calculation of flow fields. Due to the high cost of commercial tools, the results could only be compared with those of WindPRO. During the thesis, access to an educational license was available.

3 Terms, definitions and concepts

This thesis focuses on wind and turbulence in relation to the site suitability of wind turbines. To determine whether a wind turbine meets local construction regulations and norms, reference is made to the international DIN EN IEC 61400-1:2019 [10], the European DIN EN 1991-1-4 [8], the German DIN EN 1991-1-4/NA [9], and the "Richtlinie für Windenergieanlagen" [7]. To maintain consistency with Kröker [24], letters in the superscript of parameters are used to denote the concepts to which they relate.

3.1 Glossary of important terms

Most important terms can be found in table 1.

3.1.1 Turbulence Intensity

Turbulence intensity is defined as the ratio of the standard deviation of the turbulent wind speed to the average wind speed, measured over a specified amount of time. In our case, the average wind speed (v_{ave}) is calculated over averaged 10-minute intervals [24]:

$$I_v(z) = \frac{\sigma_1(v)}{v_{ave}}$$

While DIN EN 1991-1-4 suggests the specific expression for determining $I_v(z)$, this formula is not applicable in Germany due to the wind profile considerations, which are explained further later in chapter 3.3.1. Instead, the turbulence intensity is derived from the terrain roughness category of a wind zone.

3.1.2 Weibull Distribution

The Weibull distribution is a statistical model used to describe the probability of different wind speeds at a given location. A key characteristic of this distribution is its shape parameter, denoted as k^S . This site-specific parameter is determined by fitting the Weibull distribution to the measured wind data for the location. The shape parameter is critical for the site suitability assessments performed in this thesis, as it is referenced in the regulatory standards for both complex and non-complex terrains. The turbine's design often assumes a Rayleigh distribution for wind speeds, which is a special case of the Weibull distribution where the shape parameter is exactly 2 [10].

Term	Definition
$v_{m50}(z)$	The function that defines the highest 10-minute average wind speed with a recurrence period of 50 years at height z above ground.
$v_{m1}(z)$	The function that defines the highest 10-minute average wind speed with a recurrence period of 1 year at height z above ground.
$v_{p50}(z)$	The function that defines the highest 3-second average wind speed with a recurrence period of 50 years at height z above ground.
$v_{ave}(z)$	The 1-year average wind speed determined with data of at least 1 year, at height z above ground.
v_r	The wind speed at hub height that is reached at the wind turbine's rated power.
$v_{ref} = v_{m50}^T(z_{hub})$	The reference wind speed of a wind turbine used to determine the turbine type and class.
$v_{b,0}$	The ground value for the basis wind speed. It is the highest 10-minute average wind speed at 10 meters above ground, with a recurrence period of 50 years.
v_b	The basis wind speed adjusted for the site's wind zone.
k^S	The shape parameter of the Weibull distribution of the site's wind data.
α^S	The profile exponent of the site. It is used to extrapolate wind speeds to all heights from a measurement at fixed height.
z_{hub}	The center hub height of a wind turbine above ground.
C_{CT}	The terrain complexity correction factor.
C_T	The rotor thrust coefficient of a wind turbine.
m_T	The Wöhler exponent of a wind turbine.
D_T	The rotor diameter of a wind turbine.
I_{ref}^T	The representative value of the design turbulence intensity at hub height.
$I_v(z)$	The turbulence intensity at height z .
$I_{eff}^{S,T}$	The effective turbulence intensity at turbine placement site. It depends on the ambient turbulence intensity and the wake turbulence intensity generated by nearby wind turbines.
$\sigma(v)$	The standard deviation of the wind speed at a speed of v m/s. Broadly speaking, it is defined as $\sigma = I(v) \cdot v_{ave}$.

Table 1: The most important symbols with their definitions while defining the site suitability model. [24]

3.2 Layered system of wind energy rules

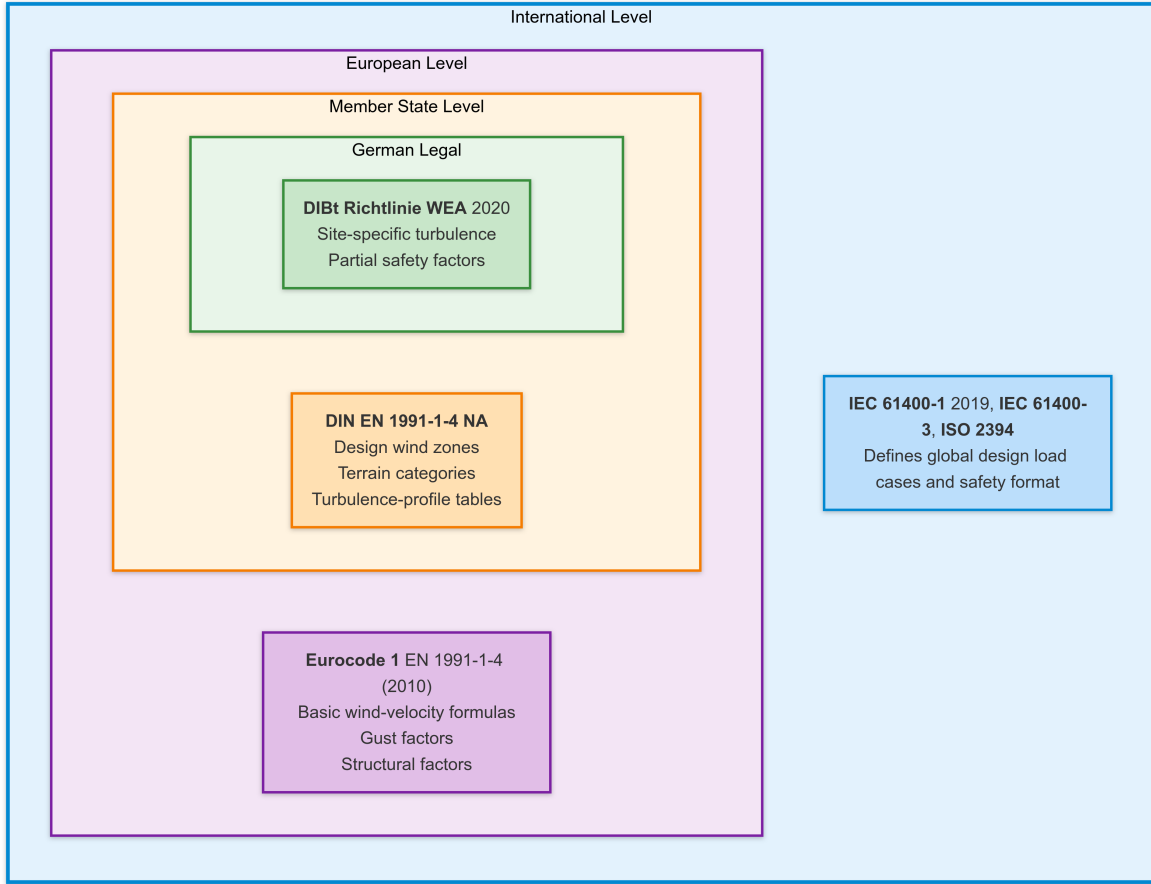


Figure 3: Hierarchical structure of wind turbine design standards from international to German specific standards, showing that every layer builds upon the layer above it.

3.3 DIN EN 1991-1-4 and NA

As already written by Kröker[24], DIN EN 1991-1-4[8] is a European norm that provides guidance on how to analyze wind conditions for the structural design of civil engineering works that are up to 200 meters high. Together, the national appendix[9] contains adjustments specific to Germany. This norm covers a wide range of topics related to wind engineering. However, to determine the turbulence of wind turbines for given wind data, only the parts of the norm relevant to this topic are considered. The national appendix introduces two ways to determine base calculation values for a site. Every region in Germany belongs to a wind zone (Section 3.3.1) and a roughness category (Section 3.3.2). Given a wind zone and roughness category, the highest 10-minute average wind speed at the site with a recurrence period of 50 years, defined as $v_{m50}(z)$ and the turbulence intensity function $I_v^S(z)$ at height z above ground can be calculated [24]. A wind speed with a recurrence period of 50 years describes a value

that is statistically expected to be exceeded only once every 50 years [8].

3.3.1 Wind Zones in Germany



(a) German wind zones map

Wind zone	$v_{b,0}$	$q_{b,0}$
WZ 1	22.5 m/s	0.32 kN/m ²
WZ 2	25.0 m/s	0.39 kN/m ²
WZ 3	27.5 m/s	0.47 kN/m ²
WZ 4	30.0 m/s	0.56 kN/m ²

(b) Basis wind speed $v_{b,0}$ and dynamic pressure $q_{b,0}$ for the four German wind zones.

Figure 4: German wind-zone classification: (a) spatial distribution and (b) associated design parameters.

The basis wind speed $v_{b,0}$ cannot be obtained automatically for a site in Germany, it has to be obtained manually by checking the wind map 4a given by the national appendix document[9]. For edge cases, where the site is close to two zone borders, the higher wind zone should be used. When the wind zone is determined by the user, it can be read in the table 4b. The parameter $v_{b,0}$ in the table will later be used as a representative value for the highest 10-minute average wind speed with a recurrence period of 50 years at a height of 10 meters: $v_{m50}(10m)$ [9].

3.3.2 Roughness Categories in Germany

Roughness categories represent an important classification system used in German wind energy assessments to categorize the terrain profile. These categories are defined

Roughness category	Description	z_0 [m]	α
1	Open sea or lakes with at least 5 km of open area in wind direction; smooth, flat land without obstacles.	0.01	0.12
"1.5" (Coastal)*	Special category for Germany, the category is in between category 1 and 2 .	0.03*	0.14*
2	Areas with small vegetation (e.g., grass) and scattered obstacles (trees, buildings) spaced more than 20x their height apart, typical farming land.	0.05	0.16
"2.5" (Binnenland)*	Special category for Germany, the category is in between category 1 and 2 describing "Binnenland", found across large parts of northern Germany.	0.10*	0.18*
3	Areas with uniform vegetation or buildings with distances less than 20 times their height between them, like villages, forests and industrial parks.	0.30	0.22
4	Areas where more than 15% of the surface is covered with buildings averaging more than 15m in height.	1.05	0.30

Table 2: The table shows all terrain roughness categories defined in DIN EN 1991-1-4 NA[9]. z_0 is the roughness length and α is the profile exponent. Both values are directly derived from the table. (*) Categories 1.5 and 2.5 are used only in Germany and the values are estimates since no value was given in the norm.

in the German national appendix and establish standardized parameters for wind calculations [9]. The German National Annex follows the European standard DIN EN 1991-1-4, which defines five primary roughness categories(0,I,II,III and IV) based on terrain characteristics and surface obstacles [8]. For this thesis, the focus is placed on the German Annex, which also introduces two additional specialized categories: "1.5 Coastal" and "2.5 Binnenland". Those two categories sit in between two categories and are used for transition areas between 1 and 2 or between 2 and 3. If a site is in range of three kilometers to a smoother terrain category, the smoother one should be chosen [9]. Descriptions and numbers can be seen in table 2.

When a roughness category is selected, several parameters become available for a site.

With the roughness exponent α the functions $v_{m50}(z)$, $v_{p50}(z)$ and $I_v(z)$ can be modeled for each category as follows [9].

Terrain Roughness Category 1

$$\begin{aligned}v_{m50}(z) &= \begin{cases} 1.18v_b \cdot \left(\frac{z}{10}\right)^{0.12} & \text{if } z > 2 \\ 0.97 & \text{else} \end{cases} \\v_{p50}(z) &= \begin{cases} 1.61v_b \cdot \left(\frac{z}{10}\right)^{0.095} & \text{if } z > 2 \\ 1.38 & \text{else} \end{cases} \\I_v(z) &= \begin{cases} 0.14 \cdot \left(\frac{z}{10}\right)^{-0.12} & \text{if } z > 2 \\ 0.17 & \text{else} \end{cases}\end{aligned}$$

Terrain Roughness Category "1.5" (Coastal)

$$\begin{aligned}v_{m50}(z) &= \begin{cases} 1.18v_b \cdot \left(\frac{z}{10}\right)^{0.12} & \text{if } 50 < z < 300 \\ 1.10v_b \cdot \left(\frac{z}{10}\right)^{0.165} & \text{if } 4 < z < 50 \\ 0.95 & \text{else} \end{cases} \\v_{p50}(z) &= \begin{cases} 1.61v_b \cdot \left(\frac{z}{10}\right)^{0.095} & \text{if } 50 < z < 300 \\ 1.51v_b \cdot \left(\frac{z}{10}\right)^{0.135} & \text{if } 4 < z < 50 \\ 1.33 & \text{else} \end{cases} \\I_v(z) &= \begin{cases} 0.14 \cdot \left(\frac{z}{10}\right)^{-0.12} & \text{if } 50 < z < 300 \\ 0.15 \cdot \left(\frac{z}{10}\right)^{-0.165} & \text{if } 4 < z < 50 \\ 0.17 & \text{else} \end{cases}\end{aligned}$$

Terrain Roughness Category 2

$$\begin{aligned}v_{m50}(z) &= \begin{cases} 1.00v_b \cdot \left(\frac{z}{10}\right)^{0.16} & \text{if } z > 4 \\ 0.86 & \text{else} \end{cases} \\v_{p50}(z) &= \begin{cases} 1.45v_b \cdot \left(\frac{z}{10}\right)^{0.12} & \text{if } z > 4 \\ 1.30 & \text{else} \end{cases} \\I_v(z) &= \begin{cases} 0.19 \cdot \left(\frac{z}{10}\right)^{-0.16} & \text{if } z > 4 \\ 0.22 & \text{else} \end{cases}\end{aligned}$$

Terrain Roughness Category "2.5" (Binnenland)

$$\begin{aligned} v_{m50}(z) &= \begin{cases} 1.00v_b \cdot \left(\frac{z}{10}\right)^{0.16} & \text{if } 50 < z < 300 \\ 0.86v_b \cdot \left(\frac{z}{10}\right)^{0.25} & \text{if } 7 < z < 50 \\ 0.79 & \text{else} \end{cases} \\ v_{p50}(z) &= \begin{cases} 1.45v_b \cdot \left(\frac{z}{10}\right)^{0.12} & \text{if } 50 < z < 300 \\ 1.31v_b \cdot \left(\frac{z}{10}\right)^{0.185} & \text{if } 7 < z < 50 \\ 1.23 & \text{else} \end{cases} \\ I_v(z) &= \begin{cases} 0.19 \cdot \left(\frac{z}{10}\right)^{-0.16} & \text{if } 50 < z < 300 \\ 0.22 \cdot \left(\frac{z}{10}\right)^{-0.25} & \text{if } 7 < z < 50 \\ 0.24 & \text{else} \end{cases} \end{aligned}$$

Terrain Roughness Category 3

$$\begin{aligned} v_{m50}(z) &= \begin{cases} 0.77v_b \cdot \left(\frac{z}{10}\right)^{0.22} & \text{if } z > 8 \\ 0.73 & \text{else} \end{cases} \\ v_{p50}(z) &= \begin{cases} 1.27v_b \cdot \left(\frac{z}{10}\right)^{0.155} & \text{if } z > 8 \\ 1.23 & \text{else} \end{cases} \\ I_v(z) &= \begin{cases} 0.28 \cdot \left(\frac{z}{10}\right)^{-0.22} & \text{if } z > 8 \\ 0.29 & \text{else} \end{cases} \end{aligned}$$

Terrain Roughness Category 4

$$\begin{aligned} v_{m50}(z) &= \begin{cases} 0.56v_b \cdot \left(\frac{z}{10}\right)^{0.3} & \text{if } z > 16 \\ 0.64 & \text{else} \end{cases} \\ v_{p50}(z) &= \begin{cases} 1.05v_b \cdot \left(\frac{z}{10}\right)^{0.20} & \text{if } z > 16 \\ 1.15 & \text{else} \end{cases} \\ I_v(z) &= \begin{cases} 0.43 \cdot \left(\frac{z}{10}\right)^{-0.3} & \text{if } z > 16 \\ 0.37 & \text{else} \end{cases} \end{aligned}$$

The value of α is already filled in to the functions, but can be taken from Table 2. The base wind speed v_b is set through the sites wind zone and can be taken from Table 4b. Since no custom rules are specified in the National Annex, it can be assumed that $v_b = v_{b,0}$. Accordingly $v_{b,0}$ from the given Wind Zone is equal to v_b .

3.4 DIN EN IEC 61400-1:2019

The international policy IEC 61400-1 is an international guideline which outlines minimum design requirements for wind turbines [10]. The German and European policies are partly based on it, while also extending it in some parts [24]. The policy is only for onshore wind turbine sites, for offshore installations the norm IEC 61400-3 needs to be used. Until now the DIBt Guideline allowed the usage of either DIN EN IEC 61400-1:2005-12 or DIN EN IEC 61400-1:2011, as long as the policies are not mixed. As recommended by a DIBt press release, the DIN EN IEC 61400-1:2019 version can also be used without any limitations. To ensure the analysis is up to date, the 2019 version is used exclusively [20].

The focus is placed on the relevant regulations and models related to wind turbulence analysis, which include the following. The parameters are divided into site-related and turbine-related categories. The site parameters that can be derived from DIN EN IEC 61400-1 are shown and visualized as a flowchart in figure 5. A distinction is made between input data, constant values derived from the norm, calculated values, and derived functions. The topographic data is combined with the wind energy distribution across twelve 30° sectors, denoted as $f_{\text{energy}}(i)$ where i is the sector index, and one combined 360° sector. This is used to calculate a terrain complexity rating at a site, as described in section 3.4.4. Depending on the complexity rating a constant turbulence structure correction factor C_{CT}^S is taken from the norm, where S indicates a site-specific value. Additionally the shape parameter k^S of a Weibull distribution fitted to the site's wind data is required for calculations [10]. The site-specific average wind speed function $v_{ave}^S(z)$ can be estimated using the wind profile power law [24]. Besides the site parameters, there are also turbine parameters, which depend on the turbine design. A wind turbine design consists of a turbine class and a turbulence category. The intention of these classes is to cover most applications. Depending on the turbine class and turbulence category, the turbines design average wind speed at hub height $v_{ave}^T(z_{hub})$, 50-year extreme wind speed at hub height $v_{m50}^T(z_{hub})$ and the turbines reference intensity I_{ref}^T can be derived from the norm, as shown in the flowchart 6.

Design wind speed class	$v_{ave}^T(z_{hub})$	$v_{m50}^T(z_{hub})$
I	10.0m/s	50.0m/s
II	8.5m/s	42.5m/s
III	7.5m/s	37.5m/s
S	custom	custom

Table 3: DIN EN IEC 61400-1 defines three wind classes for wind turbines. Wind class S is a custom class that can be used for special wind or other external conditions or as a special safety class. The turbine designer can specify custom values for the parameters then [10].

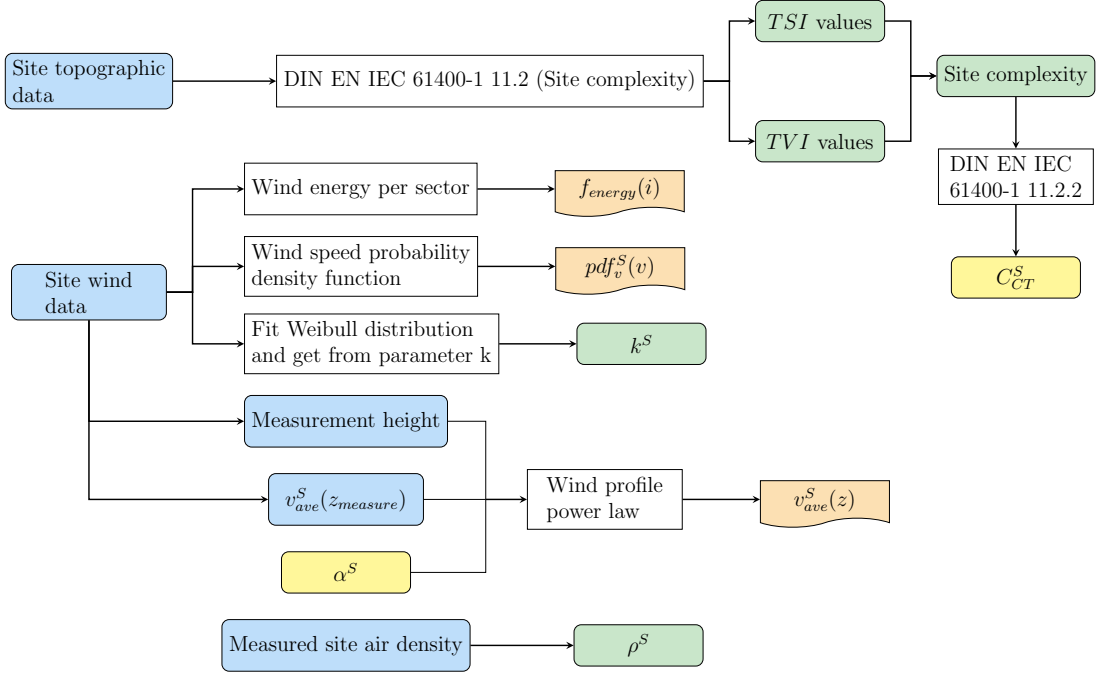


Figure 5: This flowchart shows the data flow for all relevant site parameters in DIN EN IEC 61400-1 [10]. Blue boxes represent manual data inputs, yellow boxes show constant values, green boxes are calculated or selected values and orange boxes are derived functions.

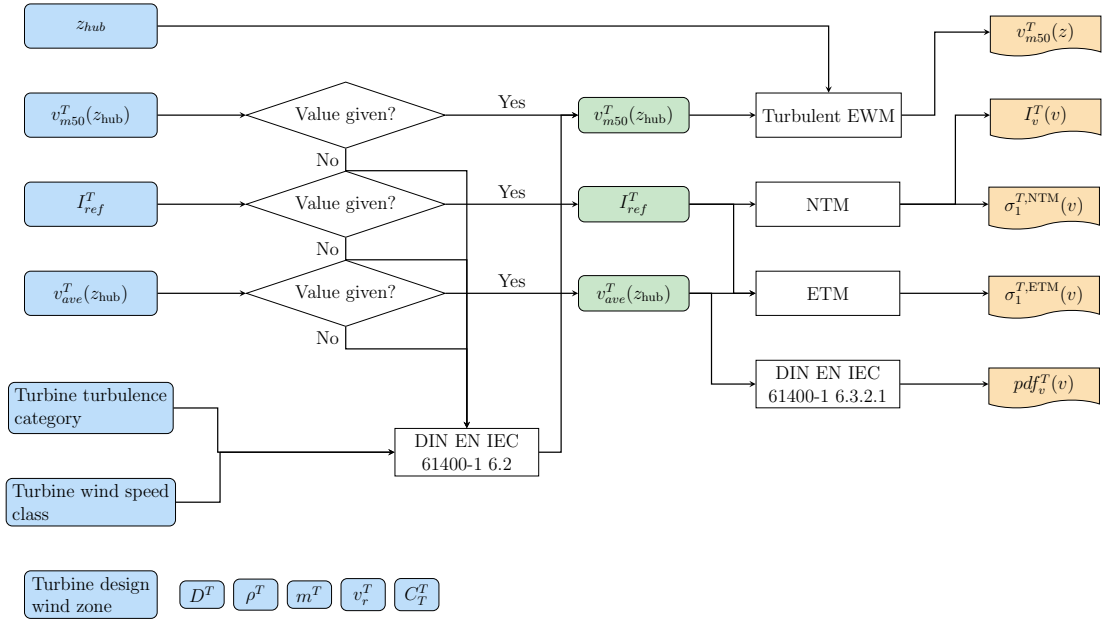


Figure 6: This flowchart shows the data flow for all relevant turbine parameters in DIN EN IEC 61400-1 [10].

Design turbulence category	I_{ref}^T
A+	0.18
A	0.16
B	0.14
C	0.12
S	custom

Table 4: The turbulence categories for wind turbine designs are also defined by DIN EN IEC 61400-1. The category A+ can withstand the highest turbulences, while category C turbines withstand the least turbulence [24][10].

3.4.1 Extreme wind model (EWM)

The EWM is used to define extreme wind conditions, such as those caused by storms or rapid changes in wind speed and direction, that a turbine T must withstand safely. The international standard IEC 61400-1 state that the EWM shall be either a steady or turbulent wind model. Both models depend on the reference extreme wind speed of a wind turbine at hub height $v_{m50}^T(z_{hub})$, it can be provided manually or taken from the turbine's wind speed class in table 3. Based on the international standard either the steady or the turbulent wind model can be used, but they are not to be mixed [10].

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

The standard deviation of the longitudinal wind turbulence σ_1 is calculated through $\sigma_1^T(v) = 0.11 \cdot v$. The DIBt guideline for wind turbines, while referring to DIN EN 61400-1 for general actions, specifies its own interpretation and application of the EWM for structural integrity proofs of wind turbine towers and foundations in Germany. The DIBt primarily defines the EWM as a turbulent extreme wind model [7].

3.4.2 Normal turbulence model (NTM)

The normal turbulence model represents the typical wind conditions that a wind turbine experiences during its operational lifetime. It primarily describes the varying, random component of wind speed, known as turbulence, around a mean wind flow. For German sites the NTM yields values for turbulence intensity ($I_v(z)$ or I_{ref}^T if z is the hub height of turbine T) and the standard deviation of the longitudinal turbulence component (σ_1) at hub height. The representative value of σ_1 at hub height is given by the 90% quantile for a specific hub height wind speed v . For the standard wind classes, it must be determined using the following formula:

$$\sigma_1^{T, NTM} = 0.75 \cdot I_{ref}^T \cdot v + 5.6 \frac{m}{s}$$

While IEC 61400-1 provides general models and formulas, for wind turbine sites in Germany, the DIN EN 1991-1-4 National Annex significantly modifies how turbulence intensity is to be calculated. Instead, for a German site, the turbulence intensity of a turbine $I_v^T(z)$ is to be determined based on the terrain roughness category as described in 3.3.2 [9][10].

3.4.3 Extreme turbulence model (ETM)

The ETM calculates the longitudinal component standard deviation (σ_1) of turbulence based on the given formula in IEC 61400-1:

$$\sigma_1^{T, \text{ETM}} = 2 \cdot I_{\text{ref}}^T (0.72 \cdot (\frac{v_{\text{ave}}^T(z_{\text{hub}})}{2} + 3) \cdot (\frac{v}{2} - 4) + 10)$$

$v_{\text{ave}}^T(z_{\text{hub}})$ and I_{ref}^T need to be taken from tables 3 and 4 based on the turbine's wind class and turbulence category [10][24].

3.4.4 Assessment of the topographical complexity

The assessment of topographical complexity at a site is important because a more complex terrain results in more wind distortions and turbulence. Topography directly influences critical wind parameters such as mean wind speed, turbulence intensity, and gust speed pressure [9]. Site specific investigations are necessary to determine if local turbulence increases, whether from the natural terrain or nearby structures like other wind turbines or buildings [7]. The results of an assessment primarily help to classify a site as not topographically complex. If a site is deemed "not topographically complex", standard or simplified procedures may be used to determine wind loads. If a site is topographically complex, more detailed and site specific calculations need to be undertaken [9][7]. To determine a site's complexity, the requirements of DIN EN IEC 61400-1 are applied [10]. Site complexity is characterized by the terrain's slope and variation of a plane. Planes are defined to fit the terrain within specific distances and 30° sectors around the wind turbine as seen in figure 7. The resolution of the surface grid should not exceed 50m.

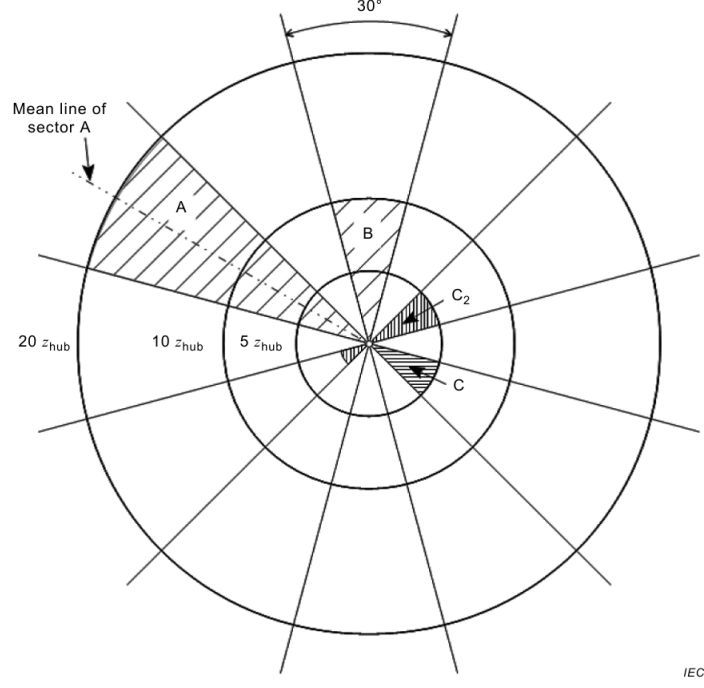


Figure 7: DIN EN IEC 61400-1:2019 includes an example on how a wind turbine site needs to be divided into radial sectors [10]. Into each of those sectors a plane is fitted. A sector with a radius of $5z_{hub}$ can be extended into the opposing sector by a range of $2z_{hub}$, an example of this can be seen at the label C_2

Terrain Slope Indices (TSI) and Terrain Variation Indices (TVI) are then calculated for every circle area ($5z_{hub}$, $10z_{hub}$ and $20z_{hub}$) using the defined slope and terrain variation. To calculate these indices, the predefined formulas for all $R \in \{5z_{hub}, 10z_{hub}, 20z_{hub}\}$ are used:

- $D_{TV}(i, R)$ is the standard deviation of terrain variation in the i th 30° sector.
- $D_{TV_{360}}$ is the standard deviation of terrain variation of the 360° circle area.
- The percentage of wind energy coming from a given sector i is defined like this[24]:

$$f_{\text{Energy}}(i) = \frac{\sum_{s \in S_i} v(s)^3}{\sum_{s \in S} v(s)^3}$$

- TSI_{30} and the full disc TSI_{360} [24]:

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

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

- TVI_{30} and the full disc TVI_{360} [24]:

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

$$TVI_{360}(R) = \frac{D_{\text{TV}360}}{3 \cdot R}$$

For every calculated value across all sectors and the full radius, it must be verified whether the given thresholds in Table 5 are violated. A site is classified as **not complex** if the calculated values are all below the low threshold 'L'. If a site violates any of the given thresholds, it needs to be considered complex. The site complexity level is the highest of all cases. Based on the complexity level, the terrain complexity correction factor needs to be selected from the following table 6.

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

Table 5: Threshold values for terrain classification based on radius of circle area and sector amplitude, showing terrain slope index (TSI) and terrain variation index (TVI) limits for Low (L), Medium (M), and High (H) categories.

3.4.5 Turbulence structure correction factor

C_{CT}^S	Terrain complexity			
	Not complex	L	M	H
	1.00	1.05	1.10	1.15

Table 6: The values for C_{CT}^S for each terrain complexity class [24][10].

The turbulence structure correction factor (C_{CT}) is used in assessing a wind turbine's structural integrity by referencing wind data. Specifically, in complex terrain, it increases the estimated 90% quantile of the wind speed standard deviation ($c\hat{\sigma}$) to account for the distortion of turbulent flow. Alternatively, the longitudinal turbulence intensity can be increased by the C_{CT} factor [10].

3.4.6 Effective Turbulence Intensity

The effective turbulence intensity $I_{eff}^{S,T}$ is a turbulence parameter that describes the wind conditions at a wind turbine site. It combines the ambient turbulence intensity and the wake turbulence intensity generated by nearby wind turbines [10]. Depending on the terrain roughness at wind turbine sites in Germany, simplified calculations can be applied based on the German guideline for wind turbines by DIBt [7], as further explained in 3.5. For complex turbine sites, the effective turbulence intensity is computed using the formula provided in DIN EN IEC 61400-1:2019:

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

The formula calculates the effective turbulence intensity at a wind turbine site by integrating turbulence contributions across all wind directions, weighted by their occurrence frequency and adjusted for material fatigue characteristics.

The expression $pdf_v^S(\theta|v)$ represents the directional wind distribution at a given Site S, indicating the likelihood of wind arriving from angle θ at velocity v . Meanwhile, $I_{combined}(\theta|v)$ captures the total turbulence experienced from direction θ at speed v , combining both atmospheric turbulence and wake-induced disturbances from neighboring turbines [10].

The parameter m^T is the Wöhler exponent, which characterizes the fatigue behavior of the turbine's most vulnerable part. This exponent can vary significantly with material composition: steel components typically exhibit a value of 6, fiberglass materials 10, and carbon-fiber composites reach 15 [24][10].

If 12 sector-bins of 30° width are created, the formula can be rewritten as follows, where the probability density function and the combined turbulence intensity depend on the sector i :

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

Since the norm does not specify which turbulence model should be used, the approach of Kröker [24] is adopted, and the Frandsen model is applied 3.4.7.

3.4.7 Frandsen Model

The turbulence model developed by Frandsen [19] is a more sophisticated model to calculate accurate estimates of wake exposure effects on wind turbines. This model accounts for both ambient- and additional turbulence generated by upstream turbines within a wind farm.

For a given turbine T , the model first identifies all upstream turbines within a set distance. Let $S_{<10D}^T(i)$ denote the set of turbines in the upwind sector i of turbine T that are located within a range of 10 rotor diameters. The combined turbulence

intensity for sector i at wind speed v is then calculated as:

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

where $I_{\text{rep}}^S(v)$ represents the ambient turbulence intensity and $I_{\text{add}}^T(T_j|v)$ represents the added wake turbulence intensity contribution from each neighboring upstream turbine T_j :

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

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

$$I_{\text{stddev}}(v) = \frac{1.92}{v} \cdot I_v^S(z_T^{\text{hub}})$$

The additional turbulence intensity contributed by an upstream turbine T_j depends on both the distance between turbines and the wind speed:

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

where $d_{T,T_j} = \frac{\text{distance between } T \text{ and } T_j}{D_T}$ is the normalized distance between turbines T and T_j , with D_T being the rotor diameter of turbine T .

Based on these formulas, the Frandsen model determines wake exposure by considering whether upstream turbines fall within the analyzed sector and the specified maximum distance. The exposure time percentage is derived from the wind data distribution. The overall effective turbulence $I_{\text{eff}}^{S,T}(v)$ can now be calculated [24][19]. This formulation aligns with the framework provided in IEC 61400-1:2019 Annex E for effective turbulence intensity calculations in wind farm environments [10].

3.4.8 Site suitability for complex sites

If a site is topographically complex, a full site suitability assessment based on IEC 61400-1 needs to be carried out. It consists of the two branches operational safety and structural integrity [10].

Operational safety A wind turbine is considered suitable for a specific site regarding fatigue loading if all of the following conditions are met.

1. **Wind Speed Distribution:** The site's wind speed probability density function, $p(v_{\text{hub}})$, must be less than or equal to the design's probability density function for all hub-height wind speeds, v_{hub} , within the range of the site's annual average wind speed, v_{ave}^S , and twice that value. This can be expressed as:

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

If the site's wind speed distribution is described by a Weibull distribution with a shape parameter $k \geq 1.4$, the following condition must also be satisfied:

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

2. **Wind speed standard deviations:** The design value for the longitudinal turbulence standard deviation from the Normal Turbulence Model (NTM), σ_1 , must be greater than or equal to the site's effective wind speed standard deviation, $\hat{\sigma}_{\text{eff}}$, for all wind speeds between v_{ave}^S and $2 \times v_{\text{ave}}^S$. The effective standard deviation accounts for ambient and wake-induced turbulence. The condition is:

$$\sigma_1(v_{\text{hub}}) \geq \hat{\sigma}_{\text{eff}}(v_{\text{hub}}) = I_{\text{eff}} \cdot v_{\text{hub}}$$

For sites in complex terrain, the site's estimated turbulence standard deviation must be increased by a turbulence structure correction parameter, CCT , to account for flow distortion.

3. **Airflow inclination:** The wind energy weighted mean of the site's flow inclination across all directions must be between -8° and $+8^\circ$. If site data is unavailable, the flow inclination is assumed to be equal to the terrain slope, θ , for each 30° sector within a radius of $5z_{\text{hub}}$ (potentially extended by $2z_{\text{hub}}$ downwind).
4. **Height exponent:** The energy-weighted average of the site's vertical wind shear exponent α across all 30° wind direction sectors and speeds during power production, must be in range of 0.05 to 0.25.
5. **Air density:** For wind speeds greater than or equal to the rated wind speed V_r , the average site air density ρ^S must be less than the turbines(T) design air density ρ^T . Alternatively, if the site air density is higher, the following condition must be true:

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

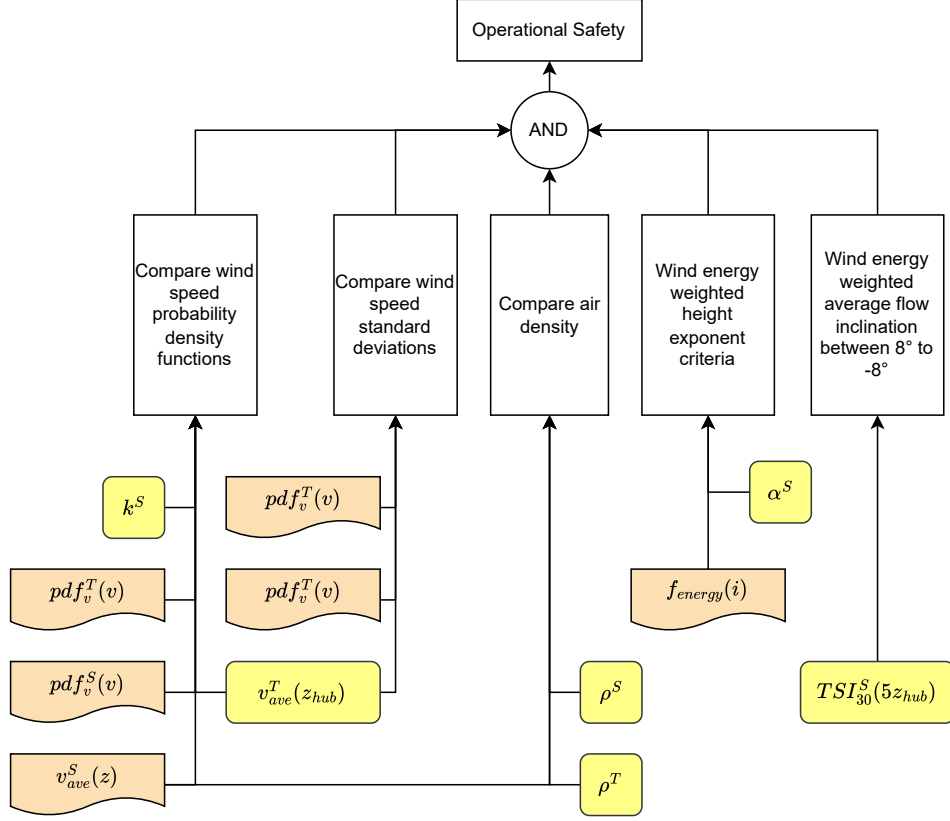


Figure 8: The flowchart for determining the operational safety of a turbine placed at a complex site [24].

Structural Integrity A wind turbine is considered suitable for a specific site regarding fatigue loading if all of the following conditions are met.

Compare Wind Speed Standard Deviation: For a wind turbine to be suitable at a site regarding ultimate loading, a condition must be met for all wind speeds between 60% and 160% of the turbine's rated wind speed (v_r^T).

The design value of the wind speed standard deviation, derived from the Normal Turbulence Model (NTM) and denoted as $\sigma_1(v)$, must be greater than or equal to the site's estimated 90th percentile of wind speed standard deviation:

$$\sigma_1(v) \geq \hat{\sigma} + 1.28\hat{\sigma}_\sigma \forall v \in [0.6v_r^T, 1.6v_r^T]$$

where:

- $\hat{\sigma}$ is the mean value of the standard deviation of the longitudinal wind component at the site.
- $\hat{\sigma}_\sigma$ is the standard deviation of $\hat{\sigma}$.

Extreme wind speed: The following equations need to be fulfilled:

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

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

Extreme Ambient Turbulence: The site-specific extreme ambient wind speed standard deviation must not exceed the value defined by the turbine's Extreme Turbulence Model (ETM)

Wake Turbulence: In wake situations, it must be demonstrated that the maximum center-wake wind speed standard deviation, $\hat{\sigma}_T$, in the most severe direction does not exceed the value from the ETM model

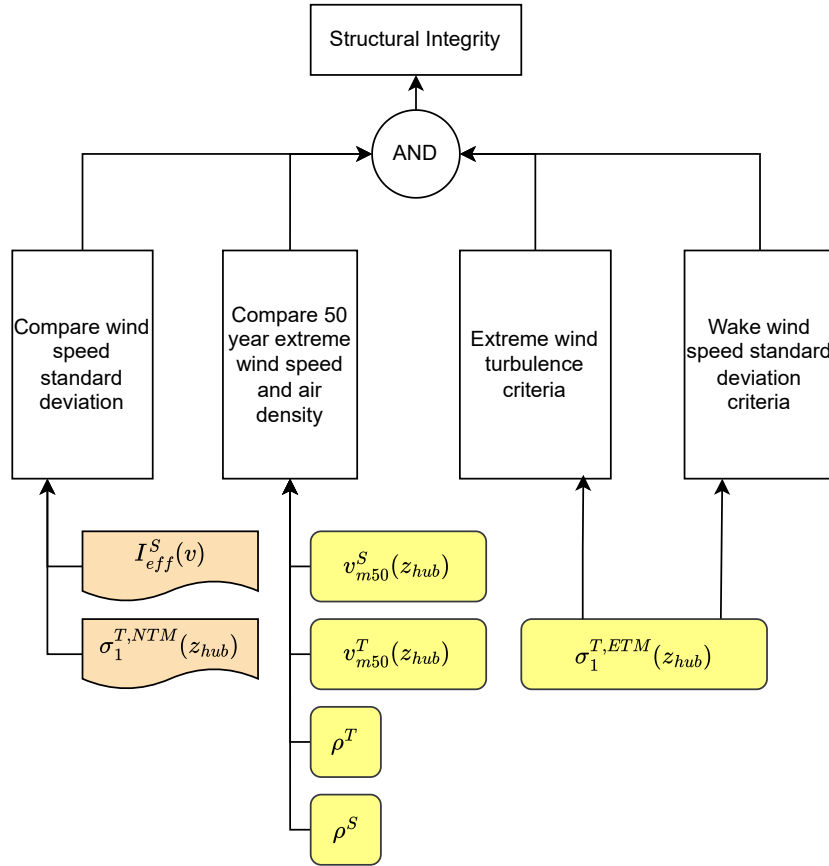


Figure 9: The flowchart for determining the structural integrity of a turbine placed at a complex site [24].

3.5 German guideline for wind turbines by DIBt

The guideline "Richtlinie für Windenergieanlagen" by DIBt establishes regulations for assessing the actions and verifying the structural stability of the tower and foundation

of wind turbines in Germany. It also specifies associated

safety factors for determining internal forces acting on the tower and foundation from the wind turbine. It integrates specific German national requirements and deviations into the broader European standards, ensuring that all Eurocode norms are applied in conjunction with their National Annexes in Germany. For non-complex sites in Germany, the DIBt guideline (in conjunction with DIN EN 1991-1-4/NA[9]) provides several simplifications and specific methods for calculating the necessary wind and turbulence information for a site suitability assessment.

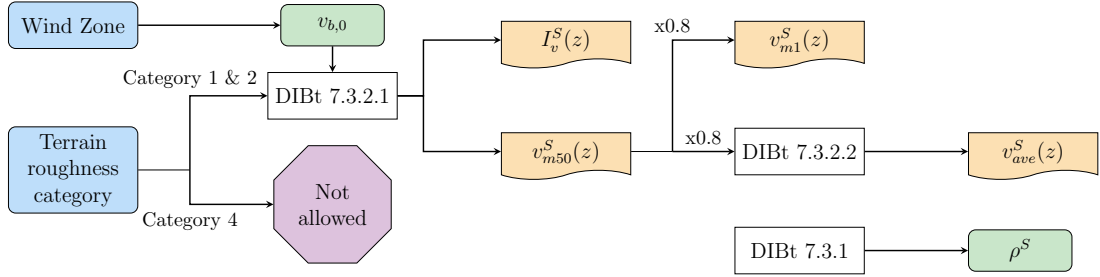


Figure 10: Blue boxes represent manual data inputs, yellow boxes show constant values or selected values and orange boxes are derived functions.

3.5.1 Key Simplifications and Conditions for Use in Non-Complex Sites

A simplified model by DIBt can be applied to a wind turbine site, which has been classified as non-complex. This classification is primarily determined by assessing topographical complexity according to the requirements of DIN EN IEC 61400-1 [10]. This classification is further explained in 3.4.4.

- **Wind and Turbulence Profiles (Terrain Categories):** For terrains classified as category 1 and 2, specific simplified formulas for the turbulence intensity function ($I_v(z)$) and the highest 10-minute average wind speed with a 50-year recurrence period ($v_{m50}(z)$) can be used [24]. If the terrain roughness category is 4 or higher, the entire DIBt guideline is not applicable, and the site suitability model for complex sites from DIN EN IEC 61400-1 3.4 must be used instead [10]. Roughness categories greater III are not allowed for these simplified calculations neither.

The simplified $v_{m50}(z)$ offers a lower estimate primarily for terrain category I or "coastal" sites. In other cases estimations from DIN EN 1991-1-4/NA 3.3 are used. Similarly, the simplified $I_v(z)$ is lower for all heights for terrain category II, but only up to 30 meters above ground for category I and "coastal". The calculations of the height profiles for mean wind speed ($v_{m50}(z)$) and turbulence intensity $I_v(z)$ for terrain roughness up to category III generally uses formulas from the table and formulas described in section 3.3.2.

- **Average Wind Speed:** If no lower site specific measurements are available, the 1-year average wind speed at hub height ($v_{ave}^S(z_{hub})$) can be estimated as 0.18 multiplied by $v_{m50}(z)$ for normal mainland sites. For sites on North Sea islands, this estimation changes to 0.20 multiplied by $v_{m50}(z)$. For Wind Zones 1 and 2, the annual average wind speed is to be set to the value of Wind Zone 3 [7].
- **Air Density:** If site-specific data is unavailable, a standard air density value of $\rho^S = 1.225 kg/m^3$ can be used [7].
- **Turbulence Category and Wake Effects:** For wind turbines designed for turbulence category A or higher, the wake effect from neighboring turbines can be neglected under certain conditions. These conditions are based on the normalized distance between turbines relative to the rotor diameter and the site's 50-year average wind speed at hub height $v_{m50}^S(z_{hub})$. The assessment of wake turbulence typically includes all turbines within 10 times their rotor diameter of the planned turbine [24][23].

The simplified DIBt method evaluates site suitability through four main criteria:

1. **Average wind speed criteria:** The site's average wind speed v_{ave}^S must be less than 0.95 times the turbine's design average wind speed v_{ave}^T . A special case allows marginal exceedance, so 0.95 to $1.00 \times v_{ave}^T$, if the Weibull shape parameter k is 2 or more [7].
2. **Extreme wind speed criteria:** The 50-year return period wind speed at the site must not exceed the turbine's design limits. This means the site's wind zone should be equal to or lower than the design wind zone, or the site's calculated $v_{m50}(z_{hub})$ must be lower than the turbine's design $v_{m50}(z_{hub})$ [7].
3. **Turbulence Criteria:** The site's effective turbulence intensity $I_{eff}^S(v)$ must be less than or equal to the turbine's Normal Turbulence Model $I_{NTM}^T(v)$ across all critical wind speed range $0.2 \cdot v_{m50}$ to $0.4 \cdot v_{m50}$ [24][7].
4. **Wake Turbulence:** The wake turbulence from all other sites closer than 10 times their rotor diameter needs to be considered in the effective turbulence calculation [7].

If any of these conditions are not met, a professional assignment based on load comparisons, usually performed by the turbine manufacturer, is required.

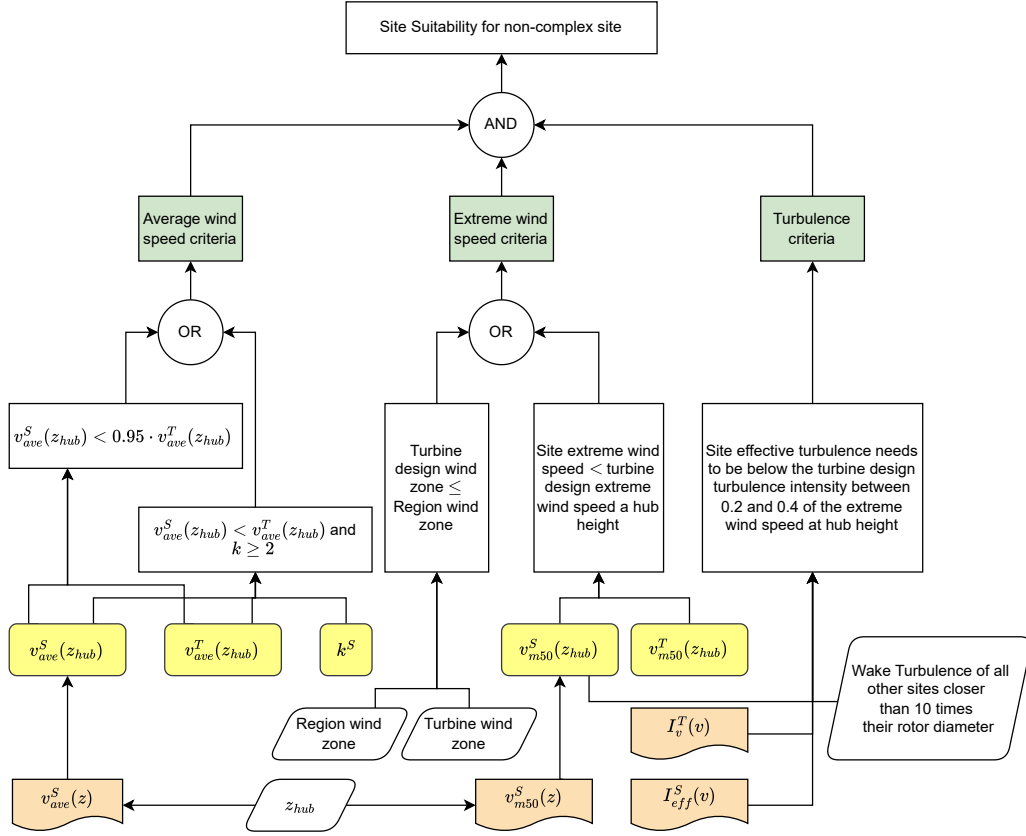


Figure 11: The flowchart for determining the operational safety of a turbine placed at a non-complex site [24].

4 Methodology

To correctly calculate and analyze the wind turbulence of a wind park and its wind turbines, the models and formulas from the previous sections were fully implemented in Python. This allows the generation of wind and turbulence reports for any wind turbine site. For the development of this module of the WindFarm3D Simulation project, Python version 12 was used, consistent with the rest of the project.

4.1 Introduction to the Methodology and Overall Approach

The overall computational framework of the turbulence analysis is a subset of needed calculations for a site suitability analysis. A dual path assessment strategy is employed to align with the regulations and possible simplifications by the used norms: a simplified evaluation for non-complex terrain sites following DIBt guidelines [7] and a comprehensive evaluation for complex terrain sites following DIN EN IEC 61400-1:2019 standards [10]. The chosen approach allows for a regulatory conform way to calculate a correct wind and turbulence report, while following the guidelines of the

given International, European, and German norms. This allows the tool to provide an efficient and accessible way for conducting site suitability and turbulence simulations while maintaining high quality.

4.2 Theoretical Foundation and Regulatory Framework

The code framework is divided into multiple classes and subclasses according to their function. As described in the previous chapters, several norms were used to obtain all required formulas. This separated norm structure is also represented in the code base. That makes it easy to review used formulas and models. And also allows future developers to easily switch between calculation methods or models used. For example, the Frandsen model [19] is just one of multiple possible wake calculation models that can be used.

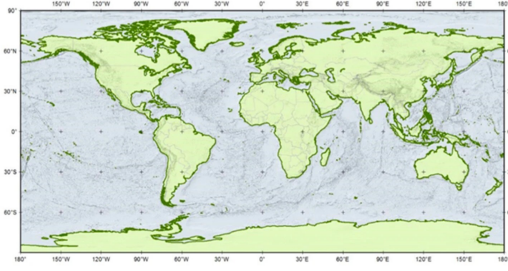
4.3 Data Collection and Preprocessing

To calculate the wind and turbulence evaluations of a wind turbine at any location, multiple datasets are required. First, topographic data of the site where a potential wind turbine placement is to be assessed must be obtained. Since the resolution of the surface grid must not exceed 50 meters [10], the Copernicus DEM - Global and European Digital Elevation Model [11] was selected, which offers a 10 meters, 30 meters and 90 meters resolution. To reduce computational requirements, the 30-meter resolution dataset was chosen, which is usable by the public without any restrictions. The second dataset includes the wind data at a given site. For this purpose, the "Deutscher Wetterdienst"(DWD) [6] was selected, which is a higher federal authority under the Federal Ministry of Transport. They offer the weather data collected by all their weather stations throughout Germany for free.

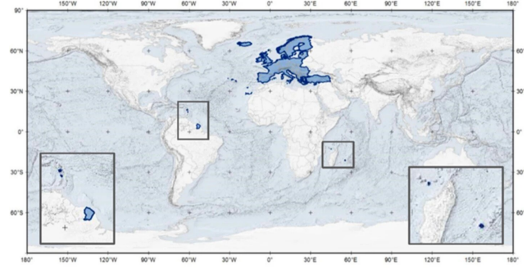
4.3.1 Topographical Data

During the thesis, a switch had to be made from the previous topographical data source, used by other modules in the project, a website called ViewFinderPanoramas [5]. The data they offered had a resolution of 90m, which is not detailed enough to be allowed as a terrain grid for the DIN IEC 61400-1 norm [10]. Therefore, the data source was switched to the European-funded Copernicus Digital Elevation Model (DEM) [11]. The Copernicus DEM is provided in 3 different instances: EEA-10, GLO-30, and GLO-90. The access to the 10m resolution instances is limited to a small subset of users with a specific user license. The GLO-30 dataset was adopted, as it provided faster computation times. The worldwide coverage of the GLO-30 is also much broader than EEA-10, as seen in figures 12.

To correctly replace ViewFinderPanoramas(VFP), a remapping of the data was needed, as the data obtained from the VFP API has a different format than the data received from the Amazon AWS S3 bucket containing the Copernicus DEM data. Based



(a) Land surface coverage within Copernicus DEM - GLO-30 and GLO-90 [11].



(b) Land surface coverage within Copernicus DEM - EEA-10 [11].

Figure 12: Copernicus DEM land surface coverage comparison.

on the Copernicus data, a three-dimensional point grid(latitude, longitude, and elevation), which includes the topographical data necessary for calculating terrain sloped indices and terrain variation indices, as further explained in 3.4.4. A visual representation of the terrain can be seen in figure 13. The coordinates were converted from latitude and longitude coordinates into UTM coordinates to allow continued use of the three-dimensional Cartesian coordinate system used throughout the simulation software [24].

4.3.2 Wind Data

The wind data for all calculations at a wind site are collected from the nearest DWD weather station. In Kroker’s thesis, the OneBuilding ”Typical Meteorological Years”(TMY) were used as a data basis[24]. While the approach of choosing the data of TMYs might include higher quality data, the hourly resolution is not precise enough for an accurate calculation. Most wind measurements, including mean wind speed, standard deviation, and direction, should be based on 10-minute averages [10]. That is why the DWD[6] was chosen for this thesis. They offer free and easily accessible weather data from many years in the past until today. The number of available stations is also significantly higher, which increases the likelihood of obtaining weather data closer to a wind turbine’s actual location. However, for some sites, the nearest weather station may still be too distant, potentially resulting in wind data that is not representative of the turbine’s conditions. To ensure that only high-quality wind data are used in the calculations, the instructions provided by the German Weather Service are followed. Each wind data point is classified into three quality categories:

1. $QN = 1$: Only formal audit.
2. $QN = 2$: Checked according to individual criteria.
3. $QN = 3$: Automatic audit and correction.

All data points below the highest quality category 3 were excluded from the calculations. The dataset’s columns include a timestamp, the mean wind speed of the last 10

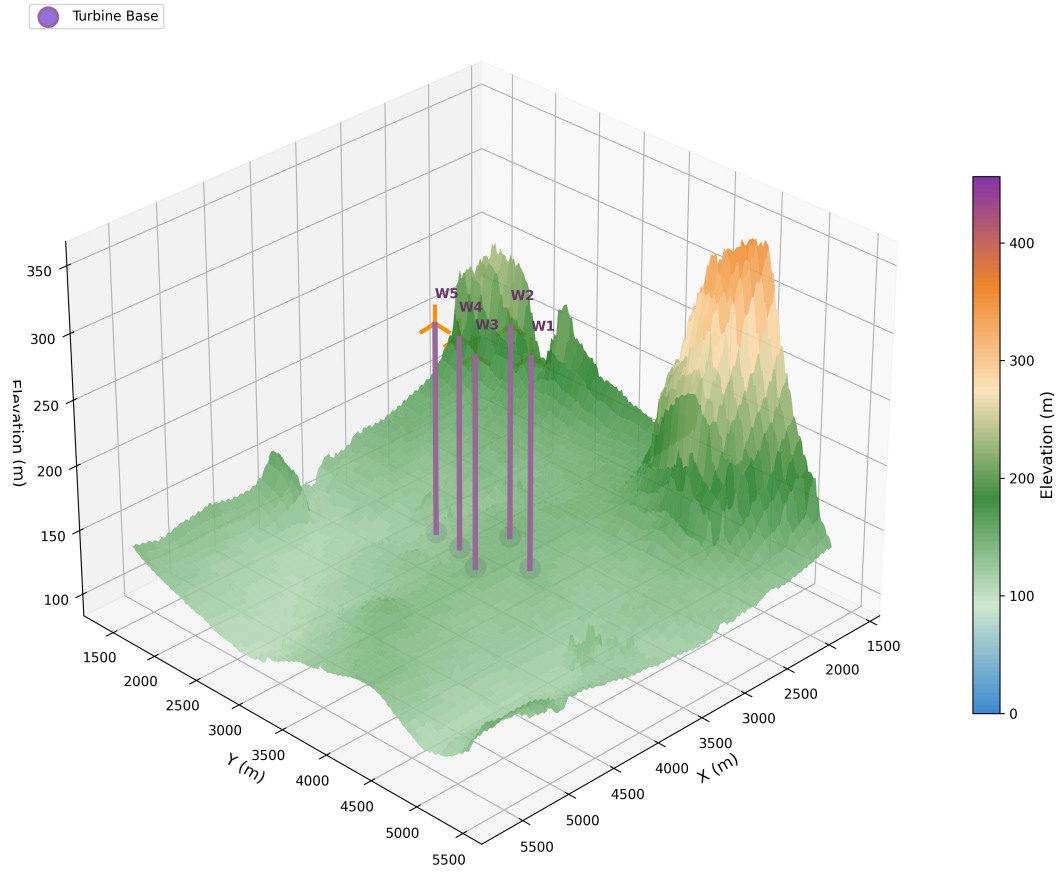


Figure 13: Terrain visualization of the planned wind park Heidsiek with 5 new wind turbines, further showcased in 5

minutes, and the mean wind direction of the last 10 minutes. If the online weather data is not available or too inaccurate for a specific site, the user can also supply custom measured data.

4.3.3 Wind Turbine Data

Existing wind turbines in a configured area are supplied by the German Federal Network Agency [3], and it includes some wind turbine types. The turbine types consist of multiple needed values:

- Turbine wind zone 3.3.1, wind speed class 3, and turbulence category 4.
- Hub Height
- Power Levels
- Rated wind speeds

4.4 Model Development and Implementation

Based on the input data and parameters, the implementation now sets the needed variables. All input data is checked before usage, to ensure all required inputs are valid and usable for the calculations. The validation process includes verification of turbine design parameters, site-specific data completeness, and configuration consistency across all modules

4.4.1 Site Complexity Classification

The process systematically evaluates terrain characteristics around each turbine location using Digital Elevation Model (DEM) data. The TSI quantifies the terrain inclination by analyzing the slope of fitted planes through terrain points. The implementation follows these steps:

1. Directional Sectorization: The area surrounding each turbine is divided into 12 sectors of 30° width, with sector 0 aligned to north (0°).
2. Multi Radius Analysis: For each sector, terrain points are analyzed at three distinct radii from the turbine, further explained and shown in section 7.
3. Plane Fitting Process: Using least-squares-regression via Singular Value Decomposition (SVD), a plane is fitted to the terrain points within each sector-radius combination. The plane equation $ax + by + cz = d$ minimizes the sum of squared vertical distances.
4. Slope Calculation: The slope angle α is calculated along the sector's middle line from the turbine base to the sector radius end.
5. Energy-Weighted TSI30: The wind energy-weighted average across all sectors using the absolute value of the calculated slope.
6. 360° Analysis (TSI360): A single plane is fitted through all points within $5 \times$ hub height radius, with the slope scaled by factor $\frac{5}{3}$.

The TVI quantifies terrain roughness by measuring the standard deviation of terrain heights relative to the fitted planes:

1. Residual Calculation: For each terrain point, the vertical distance to the fitted plane is computed.
2. Standard Deviation: The standard deviation σ of all residuals within a sector.
3. Normalized TVI: The standard deviation is normalized by the analysis radius.
4. Energy-Weighted TVI30 and 360° Analysis (TVI360): The TVI30 values are calculated through an energy-weighted average of the normalized terrain variation across 30-degree sectors and then the TVI360 is calculated using all points within $5 \times$ hub height, normalized by 3 times the radius.

For the $5 \times$ hub height sectors, opposing sector points $2 \times$ hub height are included to improve plane stability in areas with sparse terrain data. The final complexity rating is then determined by comparing the calculated values with table 5.

4.4.2 Ambient Turbulence Modeling

Ambient turbulence refers to random variations in wind velocity from the 10-minute wind speed averages collected in Section 4.3.2. When site-specific measurements are available, they can be specified, and the calculation will use the pre-collected values. This way, the representative turbulence intensities per sector can be directly applied without further modification. If custom measurements are unavailable, the Wind Atlas Turbulence (WAT) model is used. The WAT model is based on terrain roughness category and modified NTM formulation. So the NTM from IEC 61400-1:2019 [10] provides the design turbulence I_{ref}^T for verification of turbine T . I_{ref}^T is the reference turbulence intensity at $15m/s$, further explained in 3.4.2. For complex sites, not only the normal turbulence model is required, but also the extreme wind model (EWM 3.4.1) and the extreme turbulence model (ETM 3.4.3) are required.

4.4.3 Wake Turbulence Modeling

Wake turbulence accounts for the increased turbulence caused by upstream turbines. The implementation uses the Frandsen model with modifications for directional effects and wake expansion. It calculates wake-induced turbulence based on the thrust coefficient and the normalized distance between the wind turbines in a sector. The wake turbulence calculation process was implemented through the following systematic steps:

1. Distance Calculation and Filtering: Inter-turbine distances were calculated using euclidean geometry for all turbine pairs. a 10 rotor diameter filtering rule was applied to exclude turbines beyond this threshold, as wake effects become negligible at greater distances.
2. Directional Sector Analysis: Turbines were assigned to directional sectors to determine which upstream turbines affect downstream turbines for each wind direction. This sectoral approach ensures that only turbines within the relevant wind direction area contribute to the wake turbulence calculations.
3. Thrust coefficient: Thrust coefficients were obtained through linear interpolation from turbine-specific C_T curves when available. For cases where manufacturer data was unavailable, default approximations were applied based on typical turbine characteristics.
4. Wake Superposition: For scenarios involving multiple upstream turbines, a maximum superposition model was used, to combine the wake effects. This method selects the maximum turbulence contribution from all upstream turbines rather than summing effects, preventing overestimation of turbulence intensities.

To account for an increasing misalignment between wind directions and turbine alignment, a wake expansion model was added with the following components: Wake Strength Parameter, Wake Width Parameter, and Directional Modification Factor. These formulas ensure that wake effects are taken into account with a reduced factor, with increasing distance from the wake centerline, providing a more realistic turbulence estimation for turbines partially affected by upstream wakes. The implementation adheres to IEC 61400-1:2019 [10]. Currently, the Frandsen model is the only possible one, but this can be extended in the future.

4.4.4 Effective Turbulence Calculation

The effective turbulence calculation is the final step in determining the total turbulence intensity experienced by each turbine, combining both ambient and wake-induced turbulence contributions. This calculation also includes the Wöhler exponent to properly weight turbulence contributions based on their fatigue damage potential. As described in 3.5, some simplifications were applied for these calculations. For complex terrains, the implementation follows the IEC 61400-1:2019 guidelines for effective turbulence determination in complex terrain conditions.

4.5 Site Suitability Models

Based on Krökers work [24], most parts of the site suitability assessment code were re-implemented. It automatically selects the appropriate evaluation method based on terrain complexity. This section presents the two distinct methodologies: the DIBt simplified method for non-complex sites and the comprehensive IEC 61400-1 for complex terrain.

4.5.1 DIBt Simplified Method for Non-Complex Sites

The simplified model based on the "Richtlinie for Windanlagen" by DIBt is applied when all terrain complexity indicators fall below established thresholds, indicating a non-complex site. This approach evaluates site suitability through four primary criteria. The first criterion evaluates whether the site's mean wind speed remains within the turbine's design limits. The fundamental requirement is:

$$v_{ave}^{Site} \leq v_{ave}^T$$

A special case is when the site mean wind speed marginally exceeds the design values, so between 95% to 100% of the design limit. Then a Weibull shape parameter of 2 or more is required to allow the operation of the wind turbine at that site. This accommodation recognizes that sites with higher shape parameters exhibit more predictable wind distributions, reducing fatigue loading uncertainty [7][10].

The extreme wind assessment ensures the 50-year return period wind speed at the site does not exceed turbine design limits. As already explained more in-depth in the previous chapters, the turbulence assessment compares effective turbulence intensity

at the site against the turbine’s Normal Turbulence Model across a critical wind speed range. The evaluation spans from $0.2 \cdot V_{m50}$ to $0.4 \cdot V_{m50}$ in $1m/s$ increments, ensuring:

$$I_{eff}^{site}(v) \leq I_{NTM}^T(v)$$

for all evaluated wind speeds. This range captures the wind speeds where turbulence-induced loads are most critical for structural integrity [10]. The theory behind this implementation is also visualized in 11.

4.5.2 Full Method for Complex Sites

Complex sites, categorized as Low, Medium, or High complexity, require comprehensive assessment following IEC 61400-1 standards. The process includes two evaluation categories: operational safety checks and structural integrity verification.

- **Operational Safety Checks:** The operational safety assessment ensures the turbine can maintain safe operation within the site’s environmental conditions through five evaluations. First the site’s wind speed distribution, typically characterized by a Weibull distribution, is compared against the turbine’s design assumption of a Rayleigh distribution. The comparison evaluates the cumulative distribution function across the range $[v_{ave}^{site}, 2 \times v_{ave}^{site}]$. The comparison ensures the site’s wind distribution does not produce load cycles exceeding design assumptions [10]. The effective turbulence standard deviation σ_{eff} is evaluated to ensure it remains within the turbine’s NTM limits. This verification is performed across the operation wind speed range of the average wind speed at the site and twice that average wind speed.
Third is the flow inclination verification. The mean flow inclination angle, derived from the *TSI30* analysis, must not exceed 8 degrees. Then the wind shear exponent also needs to be validated. The vertical wind profile exponent α must satisfy $0.05 \leq \alpha \leq 0.25$. This range includes very low shear ($\alpha = 0.05$, typical for offshore sites) to high shear ($\alpha = 0.25$, forested areas), ensuring the turbine design accounts for the vertical wind gradient. The last operational safety check is the air density constraint. This can also be seen in the flowchart 8.
- **Structural Integrity Checks:** The structural integrity assessment verifies the turbine’s ability to withstand both fatigue and extreme loads. This includes the Ambient Turbulence Modeling described in 4.4.2. The extreme wind conditions must then be verified. Three conditions must be satisfied for extreme wind events, the turbine design limits must be able to endure the 50-year mean extreme wind speeds, 50-year peak extreme wind speeds and the density-adjusted extreme wind load. These criteria ensure the turbine structure is able to withstand both sustained and gust loads during extreme wind events.
The final structural integrity check is the extreme turbulence model verification, in which it is evaluated whether extreme turbulence events at the site remain within design limits. This can also be seen in the flowchart 9.

This automated selection between the simplified and complex assessments allows for a cleaner and easily understandable data flow. And it also ensures efficient assessments for simple sites and comprehensive evaluations for complex terrain.

5 Case Study: Turbulence Assessment for wind farm Heidsiek

This case study for the wind farm Heidsiek near Salzhemmendorf in Lower Saxony, Germany aims to verify that the in the course of this thesis developed tool "Wind-Farm3D" reproduces site-suitability outcomes comparable to professional assessments for the same turbines and sites. The outcome data should be comparable to the data in the professional documents. However, the results are not identical, as all three assessments relied on different data sources. For this case study, the professionally created site suitability assessment created by I17-Wind GmbH(I17) & Co. KG [23] was replicated using the tool "WindFarm3D" as well as the commercial software WindPro (Version 4.0.547)[32]. The reports by I17 and WindPro apply two slightly different approaches, yet arrive at a similar result, as further explained in 5.2.

5.1 Sites, Turbines, and Datasets

The validation focuses on wind farm Heidsiek and the surrounding area. The input data sources comprise of the following datasets:

- EMD-WRF Europe+ (ERA5) [14]: "The EMD-WRF Europe+ (ERA5) dataset (or 'EMD-EUR+' for short) is our most accurate, high-resolution mesoscale dataset covering an Europe Plus domain". The dataset includes hourly wind data for the last 20 years, with additional data on elevation, air density and weibull parameters. The dataset is not free to use and has a subscription based licensing model. Through the educational WindPro license we were able to test this dataset for this case study. The nearest wind mast to the turbine sites was chosen for this case study.
- DWD 10 Minutes Recent Wind [6]: As described in 4.3.2, wind data by the German national weather service "Deutscher Wetterdienst" are used. The nearest wind mast to the turbine sites was chosen for this case study.
- I17 has commissioned an external company to gather on site wind data.
- NASA-DEM [15]: In WindPro the global elevation model by NASA was chosen. It offers the same 30 meter resolution as the Copernicus DEM GLO-30. The datasets are offering a comparable performance for European sites.
- SRTM1 [16]: For the site suitability assessment of I17 the Shuttle Radar Topography Mission (SRTM) dataset was used. It also offers a 30 meter resolution with a slightly worse accuracy then NASA-DEM.
- Copernicus DEM GLO-30 [11]: As already described in 4.3.1, our tool uses Copernicus DEM GLO-30, the global 30 meter resolution dataset by Copernicus. Described by EMD International as "[c]urrently, the best (highest quality) globally-available DEM source [...]" [17].

- Corine Land Cover [18]: To calculate a more realistic and precise roughness value for the turbine sites, the site suitability assessment of I17 utilizes the Corine Land Cover (CLC) dataset by Copernicus.

Nr.	Coordinates (Lat, Long)	Type	Hub Height	RD*	Rated Power
W1	52.0922403, 9.5850905	GE-5.5-158	161m	158m	5500kW
W2	52.0886566, 9.5825186	GE-5.5-158	161m	158m	5500kW
W3	52.0896451, 9.5898586	GE-5.5-158	161m	158m	5500kW
W4	52.0863411, 9.5871150	GE-5.5-158	161m	158m	5500kW
W5	52.0827362, 9.5852289	GE-5.5-158	161m	158m	5500kW

Table 7: Wind Turbine Specifications at wind farm Heidsiek. RD = Rotor Diameter

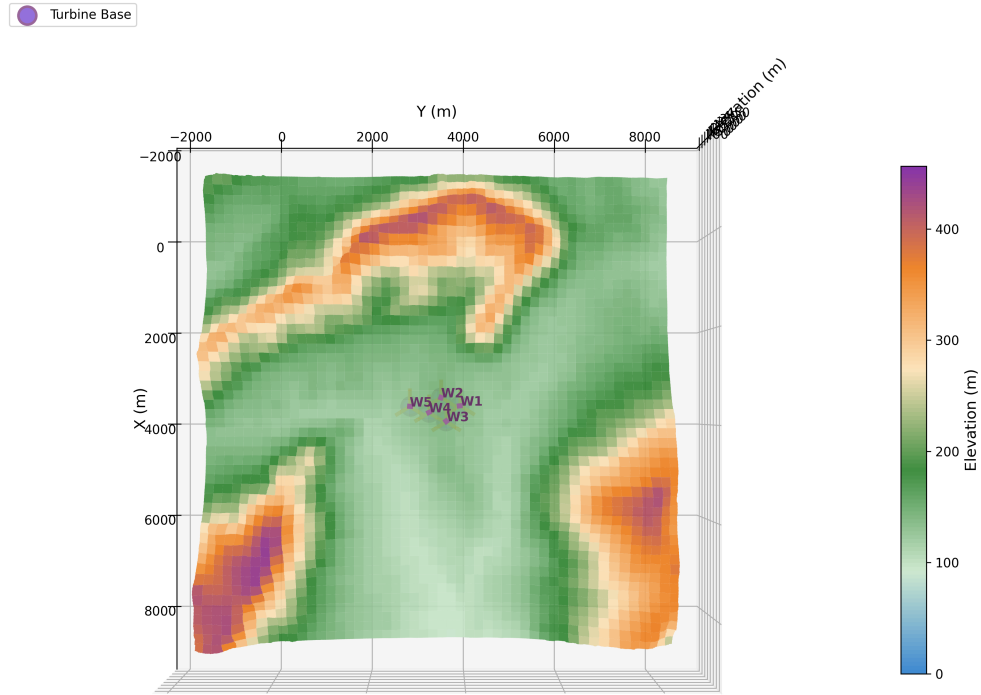


Figure 14: Top down view topography visualization of the planned wind farm Heidsiek with 5 new wind turbines.

5.2 Methods

For all three site suitability assessments, the Frandsen model has been used to calculate the effective turbulence intensity.

5.2.1 I17 Site Suitability Assessment

The I17 assessment utilizes a similar approach to the one described in the methodology 4. Depending on the complexity level of the sites, the simplified DIBt 3.5.1 or complex IEC 61400-1 3.4.8 approach is chosen. The topographical complexity analysis showed that the terrain is not complex, so they chose the simplified DIBt 2012 model.

5.2.2 WindPro

The full site suitability assessment in the software WindPro allows the user to select the IEC version. In this case, the most up-to-date version was chosen, which was also for this thesis: IEC 61400-1 2019. This is still comparable to the simplified model, since it mostly just adds some additional tests.

5.2.3 WindFarm3D

For the assessment, it was also concluded that all wind turbine sites are not topographically complex; therefore, the simplified DIBt model was applied.

5.3 Result Comparison

The calculations performed with the tool produced results that were very similar to those of the site suitability assessments by I17 and WindPro.

5.3.1 Site Complexity

All three assessments get to the same site complexity result as seen in table 8.

Table 8: Turbine Complexity Classification

Turbine ID	WindFarm3D	I17	WindPro
W1-W5	Not Complex	Not Complex	Not Complex

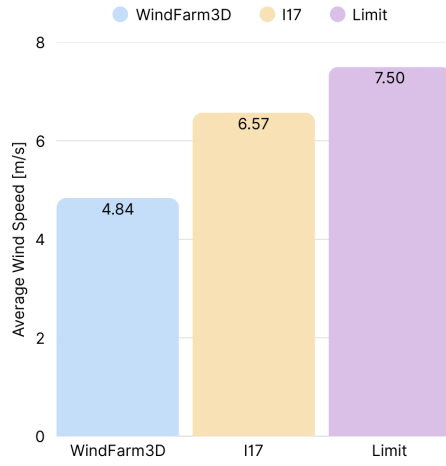
5.3.2 Average and Extreme wind speed

The calculation of the average wind speed is highly dependent on the available wind data. Since all three assessments used different wind data sources for the calculations, the results also differ. The WindPro site suitability document does not include a value for the average wind speed at a site, but the extreme wind speed is included. For all calculations, the relevant design parameters of the turbines were applied to ensure a comparable assessment. Those design parameters include the average wind speed at hub height of $7.5m/s$, extreme wind speed at hub height of $40.2m/s$, the standard air density of $\rho = 1.225$ and a Wöhler exponent of 14.

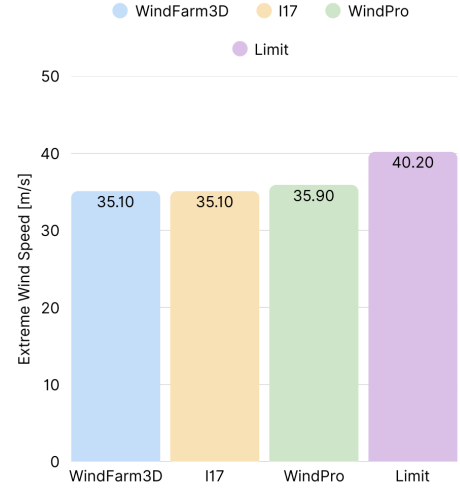
The average wind speed calculated was $\approx 4.48m/s$, which is below the specified limit of $7.5m/s$. The I17 report captured an average of $\approx 6.57m/s$. The difference is not

unexpected due to the use of different wind data sources. Their calculations were based on local measurements supplied by the client, whereas ours were based on wind data from the nearest wind mast of the "Deutscher Wetterdienst". But still both assessments pass the average wind speed criteria.

Since I17 report also estimates the extreme wind speed according to the wind zone(WZ1) and terrain roughness category(II), both results are $\approx 35.1m/s$. The result of $35.9m/s$ by software WindPro is slightly different, since it uses the approximation method POT-N & Gumbel. But all results show that the wind turbine sites are suitable regarding extreme wind speeds as well.



(a) Average wind speeds at the wind farm Heidsiek from the three data sources.



(b) Extreme wind speeds at the wind farm Heidsiek from the three data sources.

5.3.3 Effective Turbulence

The most relevant aspect within the scope of this research is the effective turbulence. All three assessments utilized the Frandsen model for the wake turbulence calculations. The results of the comparison can be seen in the line chart figure 16. The results are quite similar, particularly in the range between 7 and 15 meters per second. In the interval $[7m/s; 15m/s]$, the deviation between the results of this work and those of I17 is approximately 2.98%, while in the interval $[10m/s; 15m/s]$, the deviation compared to WindPro is only about 1.07%. The reference limit applied is the normal turbulence model, introduced in section 3.4.2, in the line chart called "NTM I_{ref} ".

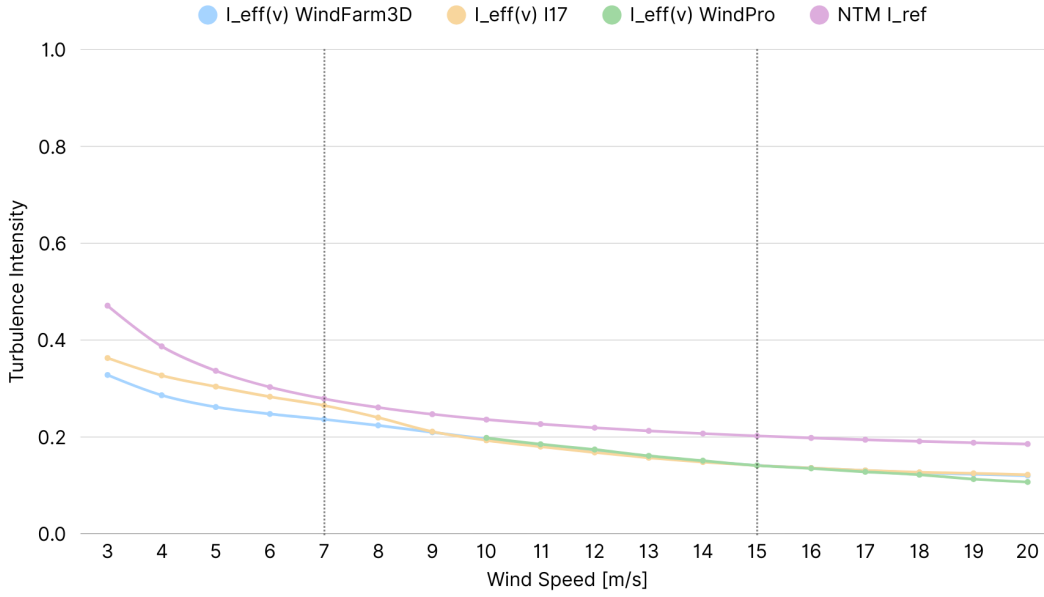


Figure 16: Line Chart of the effective turbulence calculations at the planned wind farm Heidsiek. The y-axis displays the calculated $I_{eff}(v)$ for the wind speed on the x-axis. The purple line shows the design reference turbulence calculated through the IEC NTM IA+ curve with $I_{ref} = 0.18$. The dotted lines at 7 and 15 meters per second show the relevant area for the suitability assessment. WindPro only printed the values in the interval [10m/s, 20m/s]

5.4 Conclusion

This case study successfully demonstrates that WindFarm3D produces site suitability assessments comparable to professional tools and consultancy reports for the wind farm Heidsiek. The validation against both the I17-Wind GmbH professional assessment and the commercial WindPro software shows promising results.

All three assessments consistently classified the five turbine sites as topographically non-complex, enabling the use of the simplified DIBt model. The extreme wind speed calculations showed a slight inconsistency ($35.1 - 35.9\text{m/s}$), attributable to different calculation methodologies (wind zone classification versus POT-N & Gumbel approximation).

Most significantly, the effective turbulence intensity calculations, the primary focus of this research, demonstrated excellent agreement. Within the critical wind speed range of $7 - 15\text{m/s}$, WindFarm3D's results deviated by only 2.98% from I17's professional assessment and merely 1.07% from WindPro's calculations. This minimal deviation validates that WindFarm3D can reliably assess turbulence-related site suitability despite utilizing different, more accessible data sources.

The variation in average wind speeds between assessments (4.48m/s for WindFarm3D versus 6.57m/s for I17) highlights the impact of data source selection. While I17 utilized commissioned on-site measurements, WindFarm3D employed publicly available

DWD weather data. Despite this difference, both assessments remained well within the $7.5m/s$ threshold, confirming site suitability.

These results validate WindFarm3D as a reliable alternative for preliminary turbulence assessments, particularly beneficial when commissioned on-site data is unavailable or cost-prohibitive. The tool's ability to leverage freely accessible datasets (Copernicus DEM GLO-30, DWD weather data) while maintaining professional-grade accuracy makes it valuable for early-stage wind farm planning and educational purposes.

6 Conclusion and Future Work

6.1 Key findings

The primary objective of this thesis was to develop and validate a robust turbulence analysis module for the WindFarm3D project, which was successfully achieved. The implementation features a regulatory compliant assessment framework that automatically distinguishes between non-complex sites, applying the simplified DIBt guideline, and complex sites, using the comprehensive DIN EN IEC 61400-1 standard.

The module’s accuracy was validated through a case study of the Heidsiek wind farm. The results demonstrated a high degree of correlation with both a professional assessment by I17-Wind GmbH and simulation from the commercial software WindPro. Crucially, all three assessments independently classified the site as topographically non-complex. The calculated effective turbulence intensity, the main focus of this work, showed excellent agreement with the commercial benchmarks. Within the critical wind speed range of 7 to 15 m/s, our tool’s results deviated by only $\approx 3\%$ from the professional on site assessment and $\approx 1\%$ from WindPro’s calculations. A significant finding is that this professional level accuracy was achieved using exclusively freely available public datasets, namely the Copernicus DEM GLO-30 and DWD weather data. While the choice of wind data source influenced absolute values such as the average wind speed (our tool calculated 4.48m/s versus 6.57m/s in the I17 report), the final conclusion on site suitability remained consistent and well within the turbine’s design limits. This validated the tool as a reliable instrument for preliminary site assessments.

6.2 Contributions to the Field

This research provides several key contributions to the field of wind farm planning and simulation:

1. It offers an open-source, accessible tool for site suitability and turbulence analysis. By providing a free alternative to expensive commercial software, it lowers the barrier to entry for academic institutions, students and smaller developers, improving access to high quality wind energy simulations.
2. Second, the tool helps accelerate the early stages of wind farm planning. Its ability to quickly generate reliable assessments using public data allows developers to efficiently screen multiple potential sites, identifying the most promising candidates for more detailed and costly on-site investigation.
3. Finally, the turbulence analysis module represents a significant enhancement to the WindFarm3D ecosystem at RWTH Aachen University. It integrates a critical, standards-compliant analysis capability that strengthens the project’s utility as a comprehensive platform for wind energy research and education. The work also serves as a practical validation of public datasets for achieving results comparable to industry-standard methods.

6.3 Further research

While this thesis successfully achieved its objectives, there are several promising enhancements and changes for future work that could further enhance the tool's capabilities and accuracy.

- **Integration of Advanced Roughness Data (CORINE):** As noted, a key enhancement would be the integration of the CORINE Land Cover dataset. This would enable the automated determination of terrain roughness categories based on detailed land cover data (e.g., forest, urban areas, water bodies). This would replace the current manual selection process and improve the precision of ambient turbulence calculations, which are highly sensitive to this parameter.
- **Implementation of additional wake models:** The current version calculates wake effects exclusively using the Frandsen model. Future work could involve implementing and comparing other industry-standard wake models (e.g. the Jensen model) or more advanced computational fluid dynamics (CFD) based models. This would provide users with greater flexibility and allow for model cross-validation.
- **Extension to Offshore Wind Farms:** The current framework is focused on onshore sites as per DIN EN IEC 61400-1. A valuable next step would be to extend its capabilities to the offshore domain by implementing the relevant standards.

References

- [1] EnBW Energie Baden-Württemberg AG. Offshore-Windparks – alle Fakten zur Windenergie auf See, 2024. URL <https://www.enbw.com/unternehmen/eco-journal/offshore-windparks-alle-fakten-zur-windenergie-auf-see.html#auf-einen-klick-vergleich-offshore-und-onshore-windkraftanlagen>.
- [2] Naturschutz und Reaktorsicherheit Bundesministerium für Umwelt. Sechste Allgemeine Verwaltungsvorschrift zum Bundes-Immissionsschutzgesetz (Technische Anleitung zum Schutz gegen Lärm - TA Lärm). Technical report, BAnz, 8 1998. URL https://www.verwaltungsvorschriften-im-internet.de/bsvwvbund_26081998_IG19980826.htm.
- [3] Bundesnetzagentur. Aktuelle Stromerzeugungseinheiten Übersicht, 2025. URL <https://www.marktstammdatenregister.de/MaStR/Einheit/Einheiten/OeffentlicheEinheitenuebersicht>.
- [4] Cesareo Contreras. Researchers measure impact of wind reductions on wind farm energy production, 3 2025.
- [5] Jonathan De Ferranti. Digital Elevation Data - with SRTM voids filled, 2022. URL <https://viewfinderpanoramas.org/dem3.html#wip>.
- [6] Deutscher Wetterdienst. 10 Minutes Recent Weather Data for Germany, 2025.
- [7] DIBt. Richtlinie für Windanlagen, 2015. URL https://www.dibt.de/fileadmin/dibt-website/Dokumente/Referat/I8/Windenergieanlagen_Richtlinie_korrigiert.pdf.
- [8] DIN Deutsches Institut für Normung e. V. DIN EN 1991-1-4 Einwirkungen auf Tragwerke - Teil 1-4: Allgemeine Einwirkungen - Windlasten, 12 2010.
- [9] DIN Deutsches Institut für Normung e. V. DIN EN 1991-1-4/NA Nationaler Anhang - Einwirkungen auf Tragwerke - Teil 1-4: Allgemeine Einwirkungen - Windlasten, 12 2010.
- [10] DIN Deutsches Institut für Normung e. V. DIN EN IEC 61400 Windenergieanlagen - Teil 1: Auslegungsanforderungen, 12 2019.
- [11] DLR e.V. and Airbus Defence and Space GmbH. Copernicus DEM, 2022. URL <https://dataspace.copernicus.eu/explore-data/data-collections/copernicus-contributing-missions/collections-description/COP-DEM>.
- [12] DNV. Wind farm design & analysis software WINDFARMER, 2025. URL <https://www.dnv.com/about/>.

- [13] DTU Wind Energy. PyWake, 2018. URL <https://topfarm.pages.windenergy.dtu.dk/PyWake/>.
- [14] EMD International. EMD-WRF Europe+ (ERA5), 12 2019. URL [https://help.emd.dk/mediawiki/index.php/EMD-WRF_Europe%2B_\(ERA5\)](https://help.emd.dk/mediawiki/index.php/EMD-WRF_Europe%2B_(ERA5)).
- [15] EMD-International. NASA-DEM, 8 2020. URL <https://help.emd.dk/mediawiki/index.php/NASA-DEM>.
- [16] EMD-International. Shuttle Radar Topography Mission, 2020. URL https://help.emd.dk/mediawiki/index.php/Shuttle_Radar_Topography_Mission.
- [17] EMD-International. EMD-International - Distributor of windPRO, 2024.
- [18] European Environment Agency (EEA). CORINE Land Cover, 2018. URL https://land.copernicus.eu/en/products/corine-land-cover?tab=technical_summary.
- [19] Sten Tronaes Frandsen. Turbulence and turbulence-generated structural loading in wind turbine clusters. Technical report, Denmark. Forskningscenter Risoe, 2007.
- [20] Gremium DKE/K 383. Stellungnahme zu DIBt Richtlinie Windenergie und der neuen Edition der DIN EN IEC 61400-1:2019, 4 2021. URL <https://www.dke.de/de/arbeitsfelder/energy/normenhinweise/verwendung-din-en-61400-1-mit-dibt-richtlinie-windenergieanlagen>.
- [21] GWEC Team. Wind industry installs record capacity in 2024 despite policy instability. Technical report, GWEC, 4 2025. URL <https://www.gwec.net/gwec-news/wind-industry-installs-record-capacity-in-2024-despite-policy-instability>.
- [22] Ryan Haac, Ryan Darlow, Ken Kaliski, Joseph Rand, and Ben Hoen. "In the shadow of wind energy: Predicting community exposure and annoyance to wind turbine shadow flicker in the United States". *Energy Research & Social Science*, 87(102471), 2022.
- [23] I17-Wind GmbH & Co. KG. Gutachten zur Standorteignung von WEA nach DIBt 2012 im Windpark Heidsiek. Technical report, I17-Wind GmbH & Co. KG, 12 2021. URL www.i17-wind.de.
- [24] Marcel Kröker. *Planning and Site Suitability of Wind Farms*. PhD thesis, RWTH Aachen University, 2022.
- [25] Länderausschuss für Immissionsschutz. Hinweise zur Ermittlung und Beurteilung der optischen Immissionen von Windenergieanlagen. Technical report, Erich Schmidt Verlag GmbH & Co. KG, 2002.

- [26] Joseph C.Y. Lee and M. Jason Fields. An overview of wind-energy-production prediction bias, losses, and uncertainties. *Wind Energy Science*, 6(2), 2021. ISSN 23667451. doi: 10.5194/wes-6-311-2021.
- [27] National Renewable Energy Laboratory. FLORIS Wake Modeling & Wind Farm Controls, 2023. URL <https://nrel.github.io/floris/>.
- [28] Bruno Prof. Dr. Burger and Claudia Hanisch. German Net Power Generation in 2024: Electricity Mix Cleaner than Ever, 1 2025. URL <https://www.ise.fraunhofer.de/en/press-media/press-releases/2025/public-electricity-generation-2024-renewable-energies-cover-more-than-60-percentage.html>.
- [29] Christian Schumacher. Standorteignung schneller nachweisen, 11 2024. URL <https://www.windindustrie-in-deutschland.de/fachartikel/standorteignung-schneller-nachweisen>.
- [30] UL LLC. Openwind - Wind Farm Modeling and Layout Design Software, 2025. URL <https://www.ul.com/software/openwind-wind-farm-modeling-and-layout-design-software>.
- [31] Bundesverband WindEnergie. Planung von Windenergieanlagen, 2024. URL <https://www.wind-energie.de/themen/mensch-und-umwelt/planung/>.
- [32] WindPro 4.0.547. SITE COMPLIANCE-Hauptergebnis WindPro, 2025. URL www.emd.dk, .