WENDY aims at unravelling the factors triggering social acceptance of wind farms through an in-depth analysis at three dimensions: social sciences and humanities, environmental sciences and technological engineering.

WENDY KEY PERFORMANCE INDICATORS

D3.4: WENDY Key Performance Indicators
WP 3, T 3.4
Author: Centro de Investigación de Recursos y Consumos Energéticos (CIRCE)

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Technical references

Project Acronym	WENDY
Project Title	Key Performance Indicator
Project Coordinator	CIRCE FUNDACION CIRCE CENTRO DE INVESTIGACION DE RECURSOS Y CONSUMOS ENERGETICOS jperis@fcirce.es
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Deliverable No.	D3.4
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Executive summary

This study aims to analyze the factors involved in calculating the estimated wind farm output, micro-siting options, and project feasibility. This research will be used to determine the most influential parameters or Key Performance Indicators (KPIs), which will later be included in the Wendy tool and the single multivariable KPI.

The factors have been divided into three fundamental groups (wind, technical, and economic) to carry out the analysis, i.e. factors that are related to the wind resource and, therefore, directly influence production. The most important factor is wind speed, but also the turbulence intensity, wind distribution, the wind vertical profile, and other environmental aspects, such as temperature and humidity, which are included in the air density.

The technical aspects mainly influence a project's costs and the wind turbines' location. Turbine characteristics and terrain characteristics were also analyzed.

The main costs of installation and operation are studied to analyze the project's feasibility and the income obtained from the sale of the energy generated. All this is included in a KPI, being the LCOE (Levelized Cost of Energy). This parameter can summarise the project’s techno-economic performance because apart from indicating its viability, it includes both production and cost aspects.

Once the parameters have been analyzed, a study of their sensitivity to production is carried out. The existing energy losses are also studied to carry out a detailed production analysis.

The analysis examined the general production losses that occur during the standard operation of the wind farm. These losses include instances when turbines are halted for maintenance, due to malfunctions, or because of electrical losses. The study also considered additional, site-specific production losses. These are instances when the turbines are stopped because the site conditions surpass the turbines' specifications. For example, when there is high wind or the temperature is outside the operating range, either because it is especially high (heat stress) or low (icing). Special mention is made of the losses due to the blockage effect, which refers to how the wind behaves when the wind farm is of considerable size or when there are many projects next to each other. Finally, the effect of curtailment is analyzed, being stoppages or losses of energy from the turbine due to operating conditions, such as the wake effect, for the environment to protect birds or bats, or stoppages due to social issues, such as flickering, noise, etc.

In the same way that the different aspects of production are analyzed, these are also assessed for the location of the wind turbines or microsite. In this aspect, the selection of the machine, the layout in which the wind direction and the wake effect studied above intervene, and all the mitigation strategies mentioned in the curtailment are analyzed.

Finally, the most relevant factors are summarised as KPIs indicating their sensitivity and effect on production estimates. This summary allows for determining which parameters are to be included in the Wendy tool and the single multivariable KPI to be worked on in the next WP4 work package.

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1. Introduction

In recent decades, renewable energy sources have gained significant attention as part of the proposed solutions to combat climate change [1], reduce dependance on fossil fuels and gain energy independence. Among the existing renewable energy sources, wind energy has emerged as one of the most promising and rapidly growing sectors in the global energy landscape [2]. The success and effectiveness of wind energy projects depend greatly on the careful consideration of various factors, including wind resource availability, terrain complexity, environmental considerations, and economic feasibility [3–5]. In this document the main parameters that can influence the final energy production of a wind farm are analyzed. Additionally, an examination is presented on how results can vary based on these parameters, and recommendations regarding layout design are provided.

There are several parameters related to wind characterization, additional to average wind speed, that greatly influence the expected energy production of a wind farm. Furthermore, in addition to wind characterization, other aspects need to be considered to obtain an adequate financial estimation [6,7], including construction and operational cost [8,9], energy prices [10], environmental factors [11–13] and the reached consensus between all the involved stakeholders: wind farm owners and inhabitants of the area [14,15]. This last aspect is very important, as one of the objectives of the present project is to find the best consensus between all wind energy stakeholders.

Ultimately, all these parameters will be evaluated as Key Performance Indicators (KPIs) to obtain simple measurements that will permit users to identify the optimal area for a wind energy project and design the best layout from a societal, environmental, technical and economical point of view.

Both onshore and offshore wind farms are referred to in this study. Regarding the wind turbine type, this report focuses on horizontal axis wind turbines, since up to the date, vertical axis wind turbines are still being developed and seems a better option only in low wind and turbulent environments such as urban areas [16], that are out of scope in this project.

This report aims to provide a comprehensive analysis of wind energy production, covering technical, economic, and environmental/social aspects, while also identifying key parameters and KPIs to aid decision-making and site selection. This section provides an overview and sets the context for the report. Then influential parameters are explained in the following three sections. Resource Assessment: In this section, an assessment of available wind resources is conducted. Technical Analysis: focuses on the technical aspects of wind energy production. Economic Analysis: This section 4 delves into the economic considerations related to wind energy projects. After that, a sensitivity study is done in Section five. It involves conducting a sensitivity analysis to identify the parameters that have the most significant impact on wind energy production. All of this is applied in the micro-siting criteria section (Section 6) that discusses the criteria used for selecting suitable locations for wind turbine installations taking into account social and environmental conditions. Section seven is important because it summarizes the KPIs and parameters assessed in the previous sections and the report finishes with a summary of conclusions of the work done.

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2. Wind Resource Assessment

Wind energy is a clean and renewable source of power, producing no greenhouse gas emissions or air pollutants during operation. Wind turbines transform the kinetic energy present in the wind into mechanical energy, and finally into electrical energy [17,18]. Based on this, the amount of electricity production depends on the site-specific wind characterization, further described in the following section. Wind characterization parameters

Average wind speed: average wind speeds are commonly used to describe wind conditions; it can be calculated as an arithmetic mean of (usually) 10-minute average values of wind speed measurement at determined height h.

$$\overline{\mathrm{V}}(\mathrm{h}) = \frac{1}{\mathrm{n}} \cdot \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{V}(\mathrm{h})_{10\mathrm{min}}$$

Where: $\overline{\mathrm{V}}(\mathrm{h})$ represents average wind speed at a height h , $\mathrm{V}(\mathrm{h})_{10\mathrm{min}}$ represents measured wind speeds averaged over 10-minutes, n represents the number of measurements.

To describe the wind characterization at a determined area, average wind speed is not very informative without considering other wind characteristics. Although average wind speed can give an idea whether the area is windy or not, for wind energy estimation it is necessary to know how the wind is distributed. Wind distribution contains of two main inputs:

Directional distribution: given by the frequency distribution, in which directions are divided into sectors (usually 12 or 16) and the probability of wind coming from those specific directions is indicated. Figure 1. shows an example in which the wind is blowing from the WNW direction more than 20% of the time, while it almost never blows from the NNE or SSW directions. Directional distribution can also be shown as average wind speed or percentage of energy content by sector.

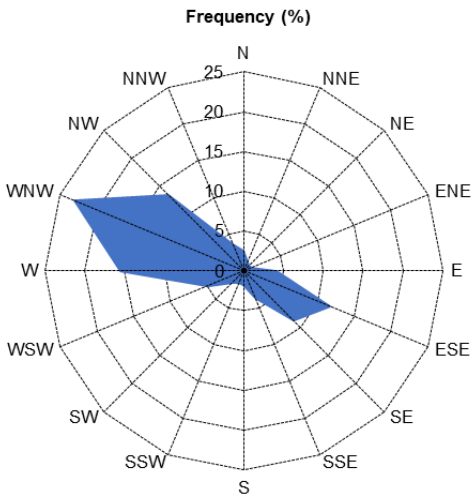

Figure 1: Sample of wind frequency distribution

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Weibull distribution: is the statistical way to describe the wind speed distribution at the site, this distribution (named after the Swedish physicist W. Weibull, who applied it when studying material strength in tension and fatigue in the 1930s) is used to represent wind speed distributions, i.e., the probability of occurrence of different wind speed ranges (named bins) at a specified location. This distribution is mainly defined by two factors: A (scale factor) and k (shape factor), and it can be expressed mathematically as the following:

$$f(V) = \frac{dF(V)}{dV} = \frac{k}{A}\left(\frac{V}{A}\right)^{k-1} e^{-\left(\frac{V}{A}\right)^{k}}$$

Where: V represents the wind speed in m/s, $k > 0$, and $A > 0$ is also expressed in the same unit as wind speed (m/s).

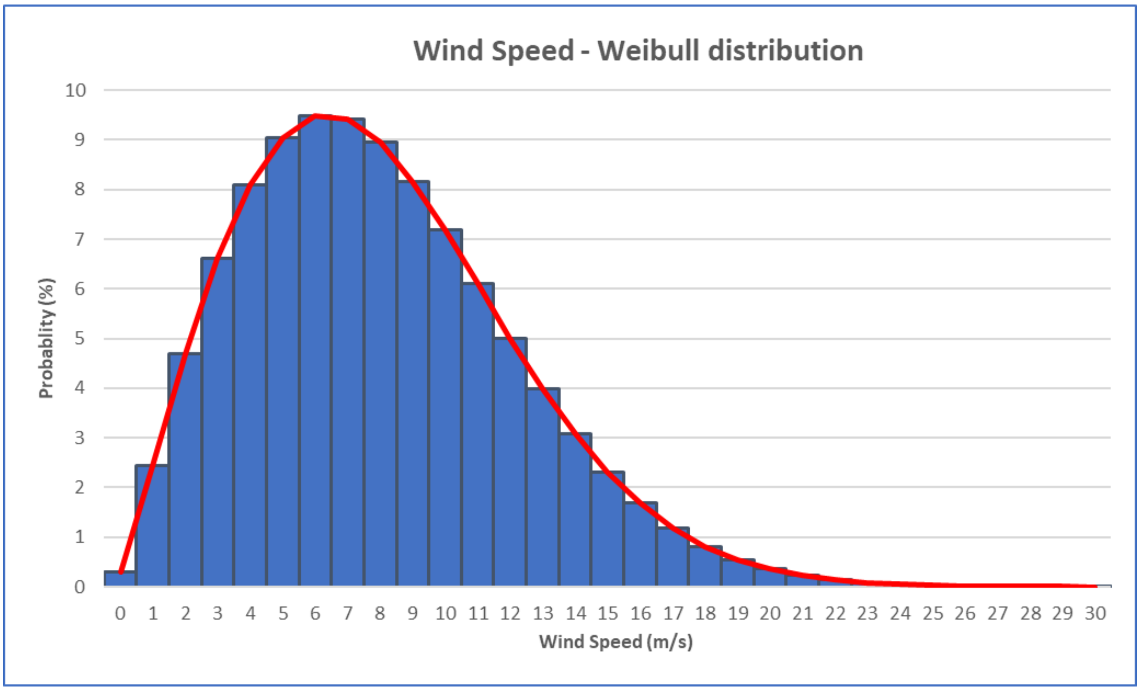

Figure 2: Sample of wind Weibull distribution

Turbulence Intensity (TI): is a parameter that quantifies the variability of wind flow in relation to the average wind speed. It is calculated as the ratio of the standard deviation of the wind speed to the average wind speed. In simpler terms, TI provides a measure of how much the wind speed fluctuates around its average value. A higher TI indicates more variability in the wind flow, while a lower TI suggests a more consistent wind speed.

$$TI = \frac{\sigma}{V}$$

Turbulence intensity decreases with increasing wind speed and TI at 15 m/s is commonly used as reference value.

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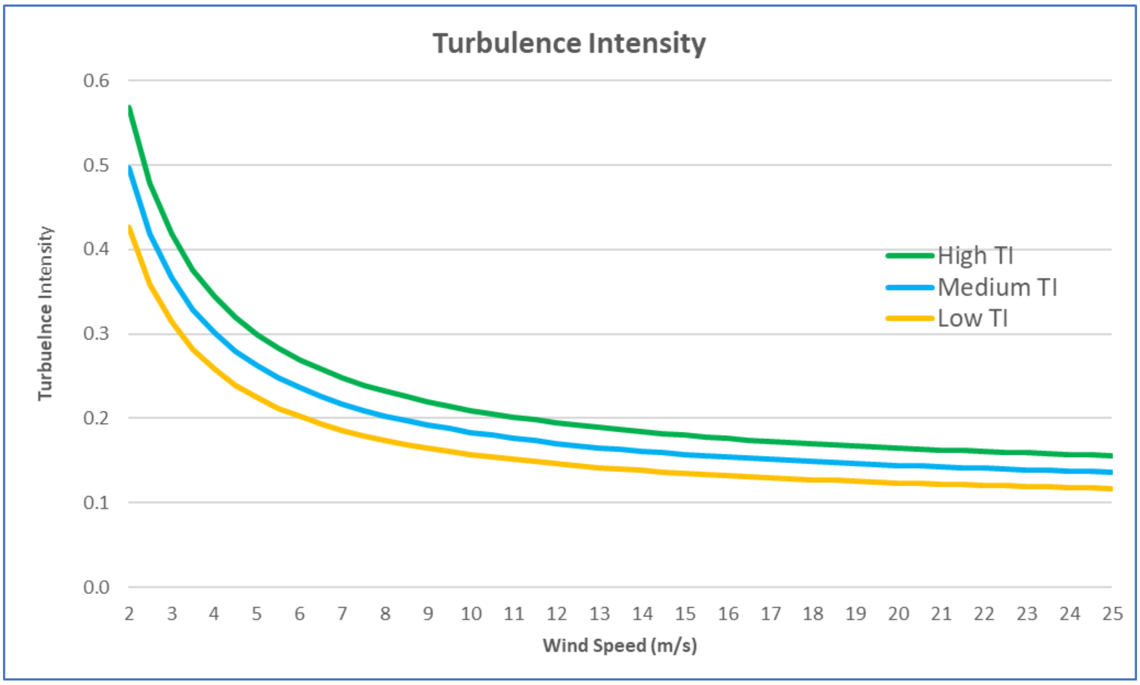

Figure 3: Turbulence intensity as function of average wind speed

Wind Shear (α): Wind shear measures how wind speed changes with height. At higher altitudes, wind can flow more freely because friction from obstacles on earth's surface (such as trees, buildings and mountains) is reduced. The relationship between wind speeds at two different heights is given by the formula below:

$$\frac{\text{Spd H1}}{\text{Spd H2}} = \left(\frac{\text{H1}}{\text{H2}}\right)^{\propto}$$

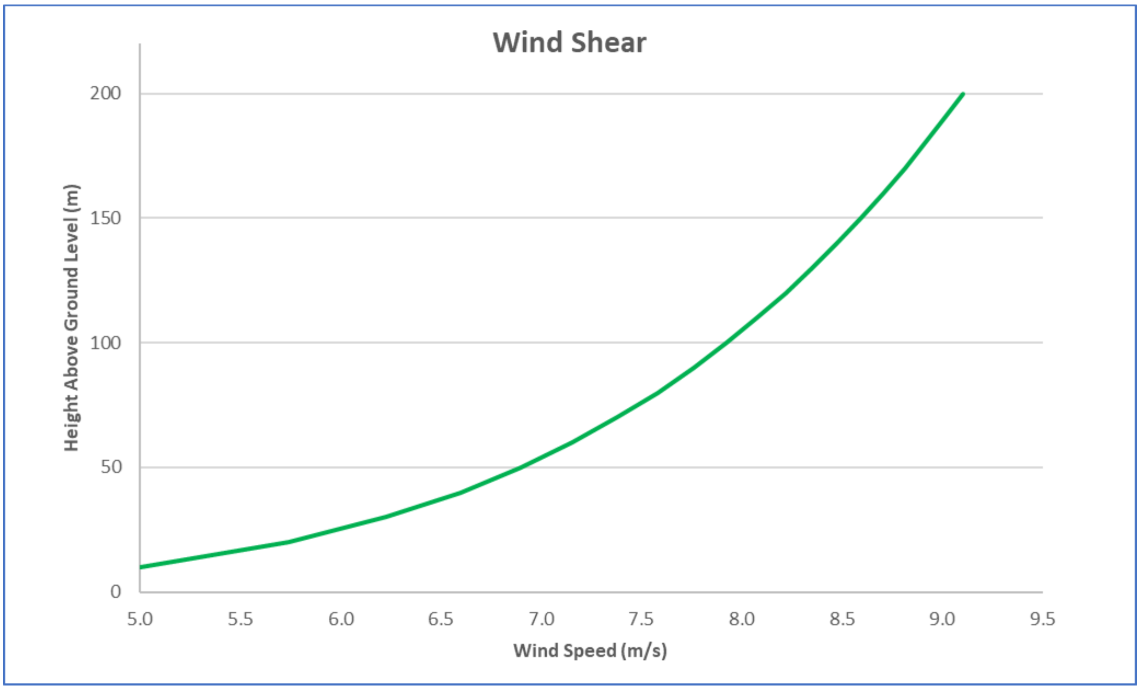

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Figure 4: Wind Speed as function of height

Temperature and other ambient conditions like air pressure and relative humidity will also impact the amount of energy that can be extracted from the wind, and consequently affects the wind potential. Those ambient conditions are usually summarized in air density.

2.1. Energy Assessment

The amount of energy the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed. The kinetic energy of the wind is proportional to those factors.

Air Density: The density of air plays a crucial role in wind energy production. The denser the air, the more mass is present in a given volume, resulting in more kinetic energy being available. The average **wind power density** is given by the following equation:

$$\overline{\mathrm{P}}_{\mathrm{wind}} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i=1}}^{\mathrm{n}}\frac{1}{2}\rho_{10\mathrm{min}}\mathrm{V}_{10\mathrm{min}}^{3}$$

Where: $\overline{\mathrm{P}}_{\mathrm{wind}}$ represents the average wind power density, $\rho_{10\mathrm{min}}$ represents the air density averaged over 10 minutes, $\mathrm{V}_{10\mathrm{min}}$ represents measured wind speeds averaged over 10-minutes, and n nepresents the number of measurements.

Colder air is denser than warmer air, so wind turbines located in colder climates can potentially extract more energy from the wind.

Rotor Area: The rotor area refers to the swept area covered by the rotating blades of a wind turbine. It determines the amount of wind intercepted by the rotor. The larger the rotor area, the more wind energy can be captured. The rotor area increases with the square of the rotor diameter, meaning that doubling the diameter would quadruple the area and potential energy extraction.

Wind Speed: Wind speed is a critical factor in wind energy conversion. According to the principles of Newton's second law, the energy contained in the wind varies with the cube (the third power) of the average wind speed. Therefore, even a small increase in wind speed can result in a significant increase in available energy. For instance, if the wind speed doubles, the energy content of the wind increases by a factor of eight (2^3 = 8). This is because doubling the wind speed not only increases the number of wind slices passing through the rotor per unit time, but each slice carries more energy due to its higher kinetic energy. That t is show in the following equation.

$$Energy = \frac{1}{2}\cdot m\cdot w^2\,; Power = \frac{Energy}{t}; Power = \frac{1}{2}\cdot\frac{m}{t}\cdot w^2;\ Power = \frac{1}{2}\cdot\dot{m}\cdot w^2\,;$$

$$Power = \frac{1}{2}\cdot\rho\cdot A\cdot w^3$$

Where *Power* is the power of the wind measured in W (Watt).

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P is the density of dry air = 1.225 measured in kg/m^3 (kilogrammes per cubic metre, at average atmospheric pressure at sea level at 15° C).

w is the velocity of the wind measured in m/s (metres per second).

A is the area of the rotor (metres square).

The graph shows how the available power variates with the wind speed at 1.225kg/m^3

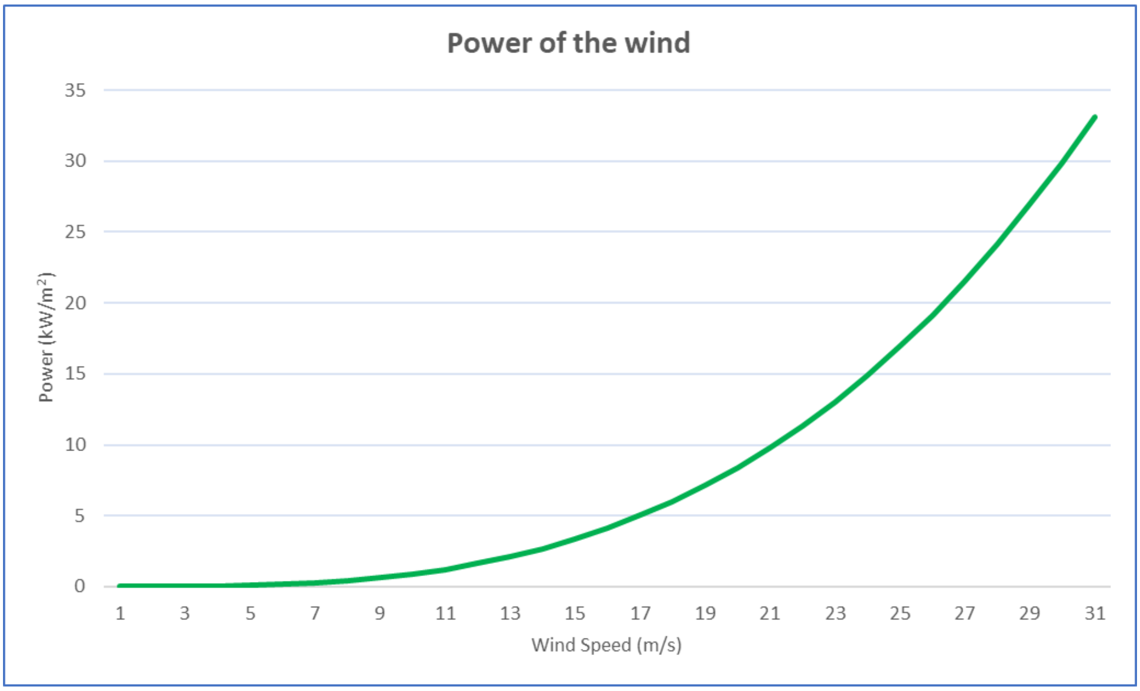

Figure 5: Power of the wind as function of wind speed

3. Technical Assessment

3.1. Wind turbine characteristics

Main characteristics of a wind turbine that influence wind energy production are:

Rotor diameter. Energy can only be extracted from wind that is perpendicular to the rotor blades and that flows over them, so there is a direct link between rotor diameter and the amount of energy that can be extracted. The rotor diameter defines the swept area from which wind energy can be extracted. It should be noted that it has been demonstrated that no turbine can capture more than 59.3% of the kinetic energy in wind, this is known as Betz's law.

Hub height: This refers to the height of the turbine's hub. The height of the hub plays a significant role in wind energy generation, as the wind speed increases with height. This relationship between wind

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speed and height is explained by the wind shear formula, as detailed in Section 2.1. Therefore, a higher hub height can lead to increased wind speeds and potentially greater energy production.

Power curve: It describes the average power output at different wind speeds normalized to standardized conditions, especially regarding air density and turbulence. Different phases in the life cycle of a wind turbine use different power curves. During project development, calculated power curves for a specific planned turbine type are used. During the operation phase, power curves based on measurements are used to compare the actual operation performance of the wind turbine to the intended performance described by the reference power curve. Based on this derated operation, losses during downtime can be calculated. It should be noted that the procedure for determining the power curve is complex and many uncertainties must be considered; the application of different methods for data filtering and power curve modeling can lead to significant differences in the results.

Thrust Coefficients curve (Ct): is a dimensionless parameter that quantifies the axial force exerted by the wind on a wind turbine's rotor. This parameter is crucial in estimating the wake effect and its associated losses. The wake effect occurs when a turbine operates, creating a wind deficit behind the rotor. This deficit can reduce the wind speed and, consequently, the production of turbines situated in this area. Understanding and accounting for this effect is essential for optimizing wind farm layouts and turbine efficiency.

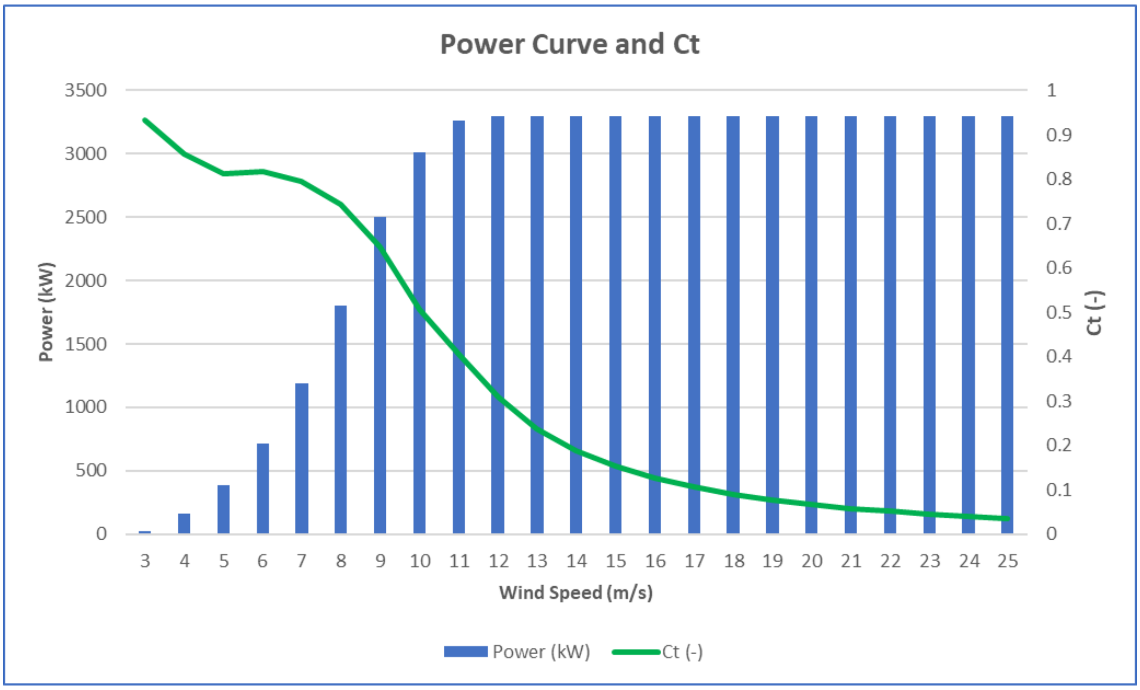

Figure 6: Sample of Power and Ct curves

3.2. Boundary conditions

When selecting sites for wind farms, there are several key factors influencing site selection.

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Accessibility and Topography: Wind farm sites should ideally have easy access for the installation and maintenance of large equipment. A gentle or flat terrain is preferable, as rugged or hilly landscapes can pose challenges during construction, maintenance activities, and affect to the life of the turbine.

Soil Conditions: The soil should be suitable for constructing wind turbine foundations. Hard rock formations may require more effort and resources for foundation construction, while overly soft or unstable ground may not provide the necessary stability. It's important to find firm ground that can support the weight of the turbines.

Water Seepage and Swampy Ground: Sites with water seepage or swampy ground can make foundation construction challenging. In such cases, specialized piloting systems, similar to those used in offshore wind farms, may be required to ensure stable foundations.

Land Rental Cost: The price of land rental should be taken into account to ensure it aligns with the project's economic feasibility. If the wind farm can share land with agriculture or livestock farming, it may help reduce rental costs and provide additional income opportunities.

Environmental Considerations: Wind farms should be located away from protected areas and areas of high ecological value to minimize potential impacts on the environment. It's essential to consider the presence of wildlife, particularly resident and migratory birds and bats (onshore) and marine mammals and ensure the turbines' placement does not significantly affect their habitats or movement corridors.

Local Authorities and Community Acceptance: Installing wind turbines in areas of great cultural and/or natural heritage interest may raise concerns among local authorities and communities. There may be social opposition due to perceived visual or environmental impacts and health issues like noise or flickering. Engaging with local authorities and conducting thorough environmental impact assessments can help address these concerns and facilitate community acceptance.

By carefully considering these factors and engaging in thorough site assessments and consultations, wind farm developers can identify suitable locations that balance economic viability, environmental sustainability, and local acceptance.

4. Economics Assessment

Wind farm projects are important economic investments which require financing and a critical evaluation of the economic aspects.

Along the development and exploitation of a wind farm we can distinguish different costs that can be grouped depending on the phase of the project. Incomes will be those from the produced energy sale.

4.1. Expenses

When planning a wind farm, different sources of expenditures are faced along the complete cycle. The Development Expenditure (**DEVEX**) refers to the costs during the projection phase, including

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prospecting, design, measurements, permissions, engineering costs and similar. Its contribution to the total costs of the project is low compared to other phases. The Capital Expenditure (**CAPEX**) will include the installation and capital costs. Once the wind farm is erected and turbines running the Maintenance and Operation Costs (**OPEX**) must be considered for the lifetime of the wind farm. Other additional costs to be included in the economic feasibility of a wind farm are the **financial costs**.

Since DEVEX is low compared to other costs throughout the project lifetime, those will be ignored in the subsequent detailed description of the costs.

CAPEX:

Capital Expenditure, is the investment in capital or fixed assets made by a company to acquire, maintain, or improve its non-current assets. This can include investments in property, plants, buildings, technology, or equipment. The turbine's price is the main contribution to CAPEX, but also other costs must be faced during this phase.

Turbines prices have decreased in the last years due to greater competition between manufacturers, the increased size of turbines and technology improvements. However, an increase in the material, transportation and other supply chain costs has reduced this trend in the last two years. Further, for onshore wind farms, the terrain complexity can have a great impact on the CAPEX. Wind turbine components have huge dimensions and transportation of pieces to the site requires a road survey to ensure that the site is accessible. Transportation specifications are provided by the manufacturer where the dimensions of the tracks and transport requirements (maximum slopes, curvature, road dimensions) are outlined. In complex terrain the costs of the civil works can increase considerably, heightening the CAPEX and making the project less profitable.

Apart from access to the site, **terrain complexity** must be taken into account at the time of designing the layout. It is not only the civil works for foundations of the turbine, but also that to erect the turbine platform to store the components and the crane for mounting. The dimensions and characteristics of those platforms are also provided by the manufacturer, and sometimes require great extension of flat terrain. Preparing those areas in complex terrain can require important civil works, increasing the costs and, consequently, CAPEX.

For offshore wind farms, the seabed depth or **bathymetry** impacts the CAPEX, since it determines foundation types. Foundations can be classified as fixed and floating. Fixed foundations will be used to depths up to approximately 60 m. For deeper waters, floating foundations can be used,

Since CAPEX includes also other infrastructures needed for energy transformation and transportation, the **distance to the electrical substation** will also impact the costs, while at the same time affecting the energy production due to electrical losses.

OPEX

Operational expenditure (OPEX) of wind turbines adds up to approximately 20 to 35% of their life-cycle cost; a correct choice of maintenance and predictive maintenance strategies for the turbine components and their optimal implementation are essential to reduce the OPEX [19].

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Minor failures are the primary cause of unscheduled repairs, this way, continuous damage analysis must be carried out to reduce down time and increase wind turbine lifetime [20]. Other costs like land rent, insurance and taxes are paid over the lifetime of the installation and the restauration cost of the plant must be considered in the OPEX.

4.2. Revenues

The revenues or incomes along the project lifetime will come from the energy sold. It must be noted that the revenue is not fixed in most cases. The income will depend on the country, and inside the same country, it will depend on the prizes set in auctions or in Power Purchase Agreement (PPA).

4.3. Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy is defined as the relation of all costs (CAPEX and OPEX) described above compared to electricity generation for a project along the entire lifetime, discounted back to a common year:

$$\mathrm{LCOE} = \mathrm{Costs}/\mathrm{Energy\ Production}$$

LCOE is expressed in €/MWh and it can be interpreted as the price of electricity for which the revenues equal the expenses of the project through the lifetime. LCOE can then be used as an indicator of the price of electricity to set its economic suitability.

Offshore wind-power generation presents many engineering challenges including limited guidelines for analysis and design of foundation/support structures, inadequate logistics for construction, and comparatively expensive operation and maintenance costs. This results in an approximately 50% higher LCOE compared to onshore wind-power generation [21]. In Europe, this factor is lower due to the maturity of the offshore wind market.

LCOE calculations and values by country and their specific topics are out of the scope of the report, but as indicative, LCOE in Europe, based on data of 2021 [22], can be estimated around 40 €/MWh for onshore wind farms and approximately 60 €/MWh for offshore.

5. Production estimates

5.1. Production sensitivity to different parameters

Production estimates for a wind farm is the expected annual energy production given in MWh/yr. Since the wind is variable from one year to another, this production estimates are averages expected for the entire wind farm lifetime, using usually a reference period of 20 or 25 years.

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Sometimes, these production estimates are expressed as **Full Load Hours (FLH)**, equivalent to the number of hours in a year that the turbine would be producing at rated power. It is calculated as the production estimates divided by the installed power, and it is expressed in hours per year (hrs/yr).

The **Capacity Factor (CF)** is the number of FLH divided by number of hours in a year and would be equivalent to the percentage of the year that the turbine would be producing at rated power.

Energy production at the wind farm will depend mainly on the wind conditions at projected site and the selected turbine. The simplest way to understand the production estimates and how those two main inputs are combined is shown in Figure 7. For a representative one-year period, frequency at every wind speed bin (in hours/year) is multiplied by the power curve (in kW). Annual production in KWy/yr will be the sum or integral of this operation in the turbine operation wind speeds range (in this case between 3 and 25 m/s):

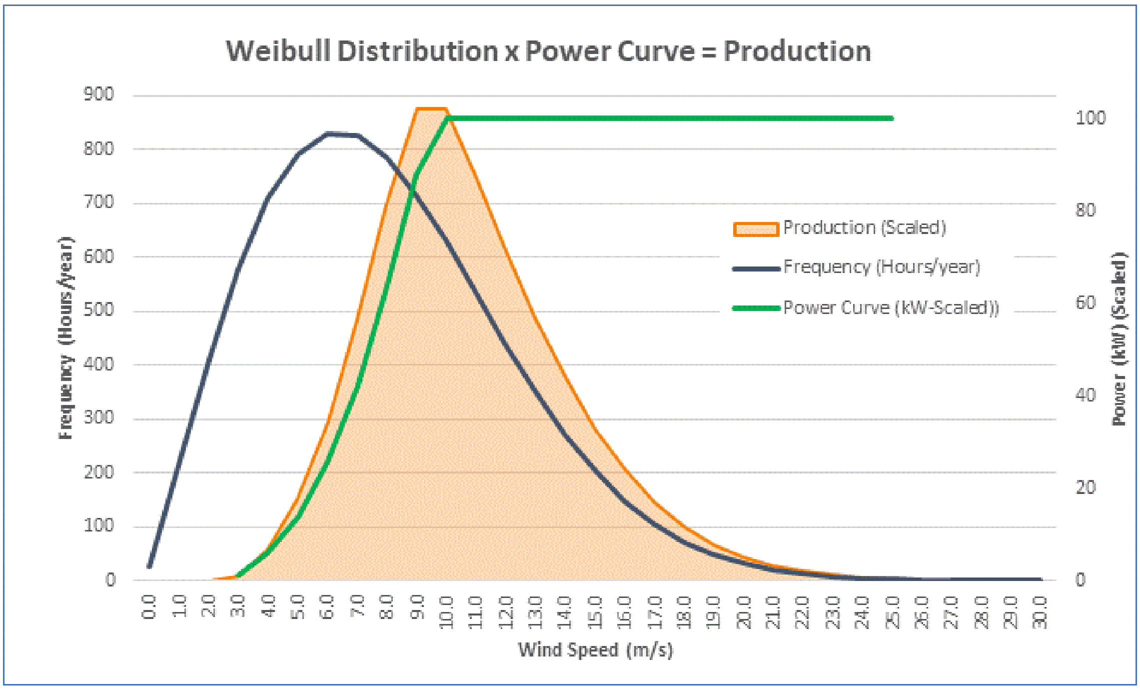

Figure 7: Basis on energy production estimates

Estimating the energy production at a wind farm is not simple although the approach is the same that shown above. For real wind farms, wind data is usually measured at a meteorological mast, and needs to be extrapolated to turbine location and hub height, considering the terrain characteristics. Additionally, turbines inside a wind farm are generating **wakes**, influencing one another and reducing wind speed and production. Also, **ambient conditions** are important for energy estimates, mainly the air density but also the risk of icing or high temperatures.

Turbines are designed to perform under determined conditions, and situations outside those design limits can lead to some **production losses** that need to be considered. Any additional restriction (e.g., social-ecological constraints, production losses due to **curtailment**).
Other production losses that have to be taken into account and considered in the general wind and site industry are also listed in this report, section 5.2.

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A sensitivity analysis has been conducted on several of these parameters to assess their impact. This analysis allows us to understand how changes in a single variable can affect the overall output. The variables examined in this sensitivity analysis include Average Wind Speed, Weibull Distribution, Turbulence Intensity, and Wind Shear.

Average wind speed

Average wind speed is the main input considered at the time of selecting an area where a wind farm is planned. There is no fixed value to establish the minimum wind speed at which a wind farm can be profitable. This is mainly due to the fact that not all turbine models produce the same output at a given wind speed.

A sensitive analysis has been carried out for five different power curves (turbine models). This power curve are shown in the following figures.

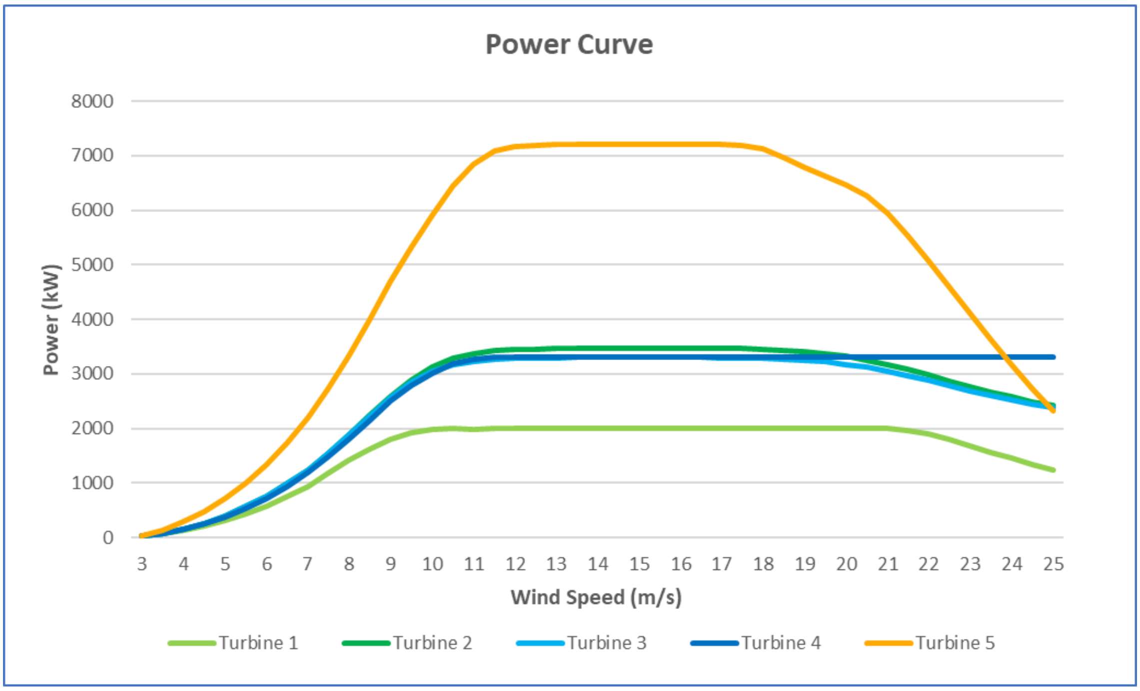

Figure 8: Power curves for five different turbine models

Each of these curves has been evaluated with different free wind speeds at hub height, considering the same shape of the Weibull distribution (k-parameter=2.0), the result of this analysis is shown in Figure 9:

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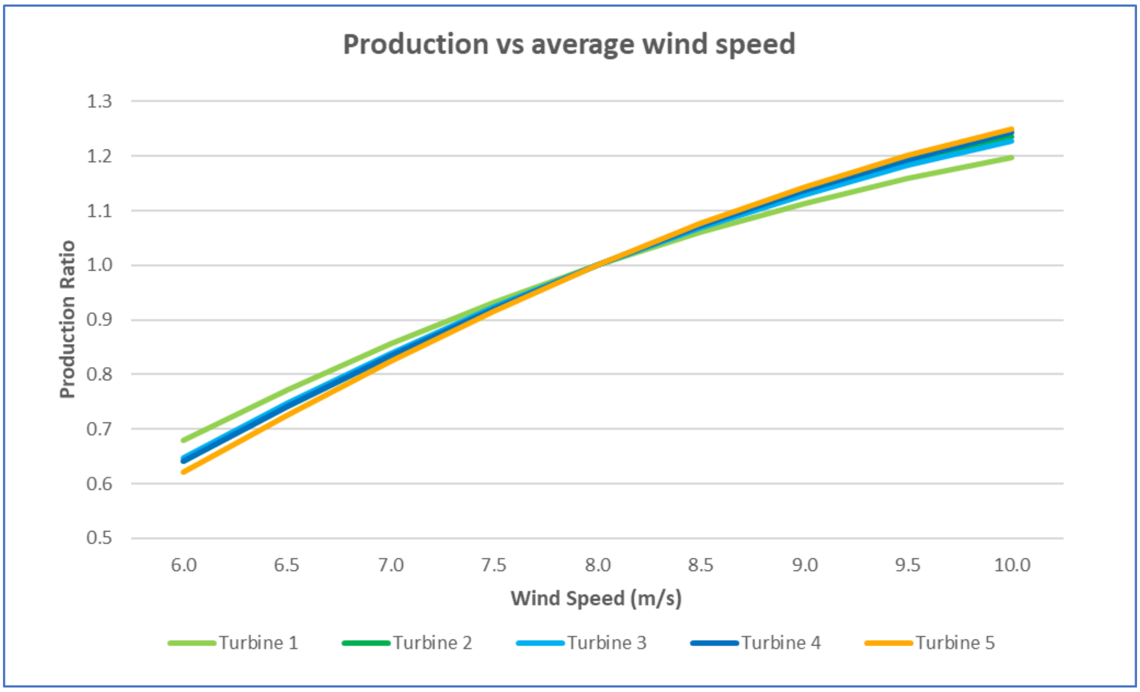

Figure 9: Production change vs. wind speed for five different turbine models

Figure 9 illustrates that certain turbines are more suitable for specific wind speeds. For instance, Turbine 1 is optimal for low wind speeds, while Turbine 5 is better suited for high wind speeds. If we consider a reference wind speed of 8 m/s, a variation of +-25% in wind speed can lead to a change in the production ratio to values close to 0.6 and 1.25. This implies that the change in production can range between -40% and +25%. Therefore, understanding these variations is crucial for maximizing the efficiency of wind energy production.

Figure 10 [23], based on the New European Wind Atlas [24–26] illustrates the variation of average wind speed at 100m across Europe. This variation directly influences energy production and plays a crucial role in selecting the most suitable wind turbine, as depicted in Figure 9.

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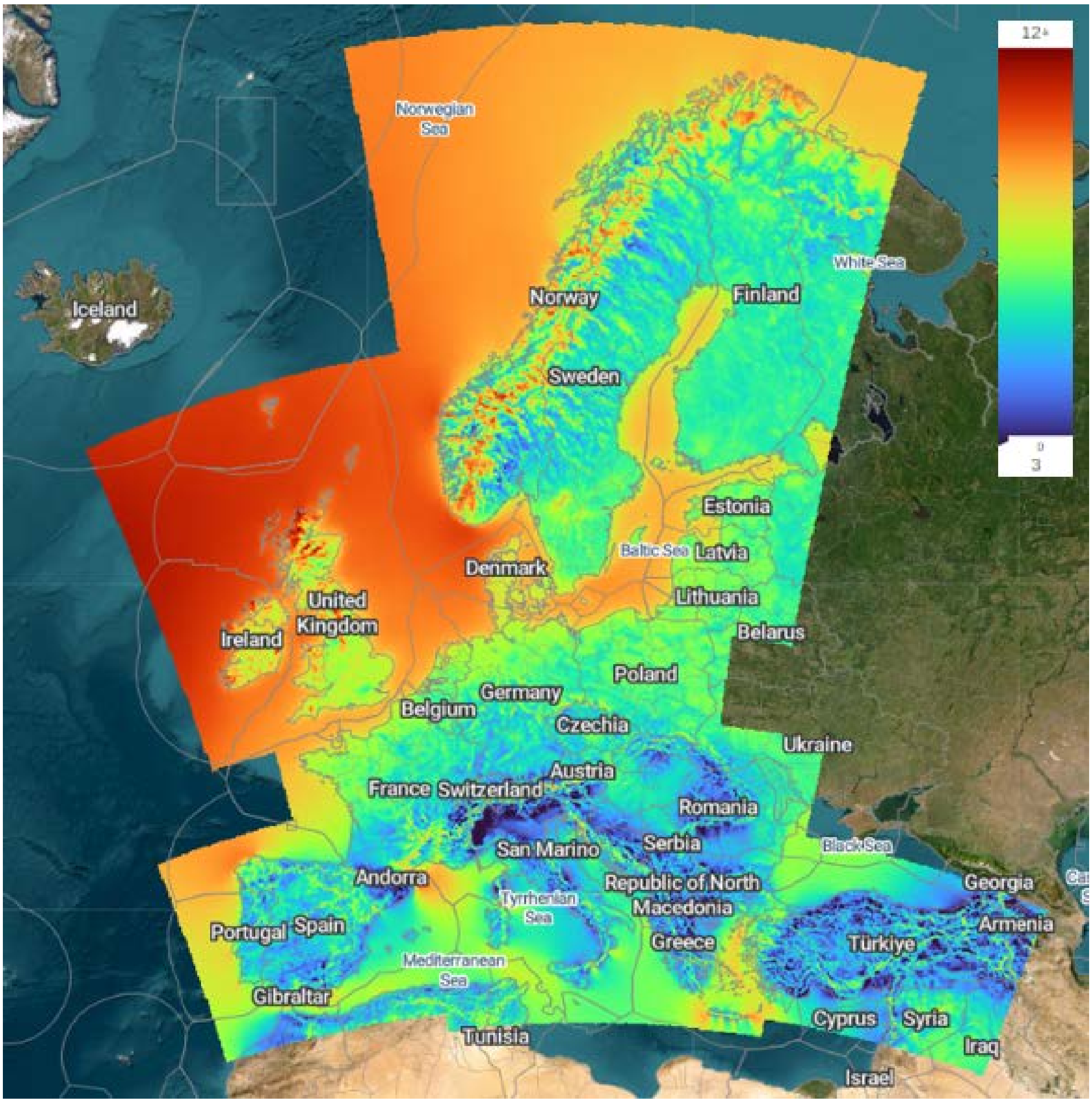

Figure 10: Average wind speed in m/s at 100 m. Source: New European Wind Atlas.

Weibull distribution

To estimate energy production, it's crucial that the Weibull distribution accurately represents the long-term conditions at the site. If we assume that this distribution describes the annual conditions, we can obtain a preliminary estimation of production by considering this distribution in conjunction with the power curve.

Energy production can vary depending on the distribution of wind speeds. The impact of wind distribution on production is illustrated with an example. Consider two different distributions, both with the same average wind speed, but with a shape factor that differs by a factor of three. These two Weibull distributions, shown in different shapes, result in different energy production as depicted in Figure 11.

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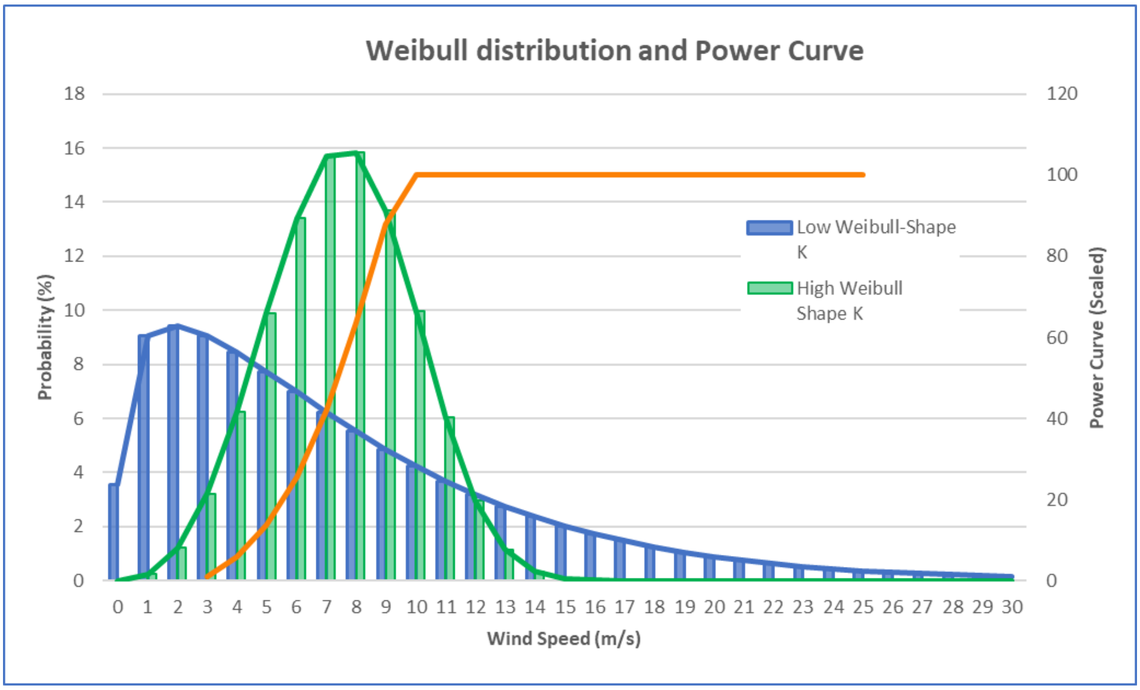

Figure 11: Production change vs Weibull k parameter for the same average wind speed

The energy production derived from these different Weibull distributions, when applied to the same power curve, is presented numerically and shows a difference of 30% (see Figure 12). This implies that a 3% change in the shape of the distribution can result in a 30% change in power output. This highlights the importance of accurately characterizing wind speed distributions when estimating wind energy production.

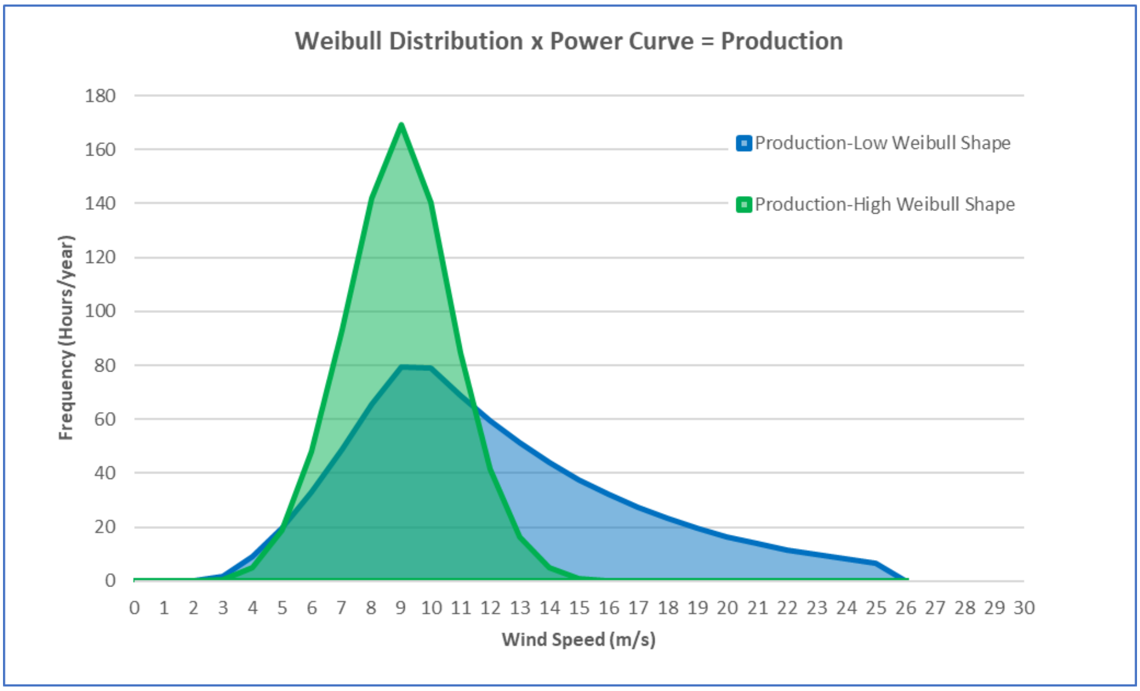

Figure 12: Production change vs Weibull k parameter for the same average wind speed

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Figure 13 aids in understanding the impact of distribution shape on energy production. It illustrates how production fluctuates based on changes in the shape of the distribution. This analysis was performed considering an average wind speed of 7.5 m/s across all study cases. The 'Y' axis represents the percentage variation, with the value of k=2 serving as the reference point.

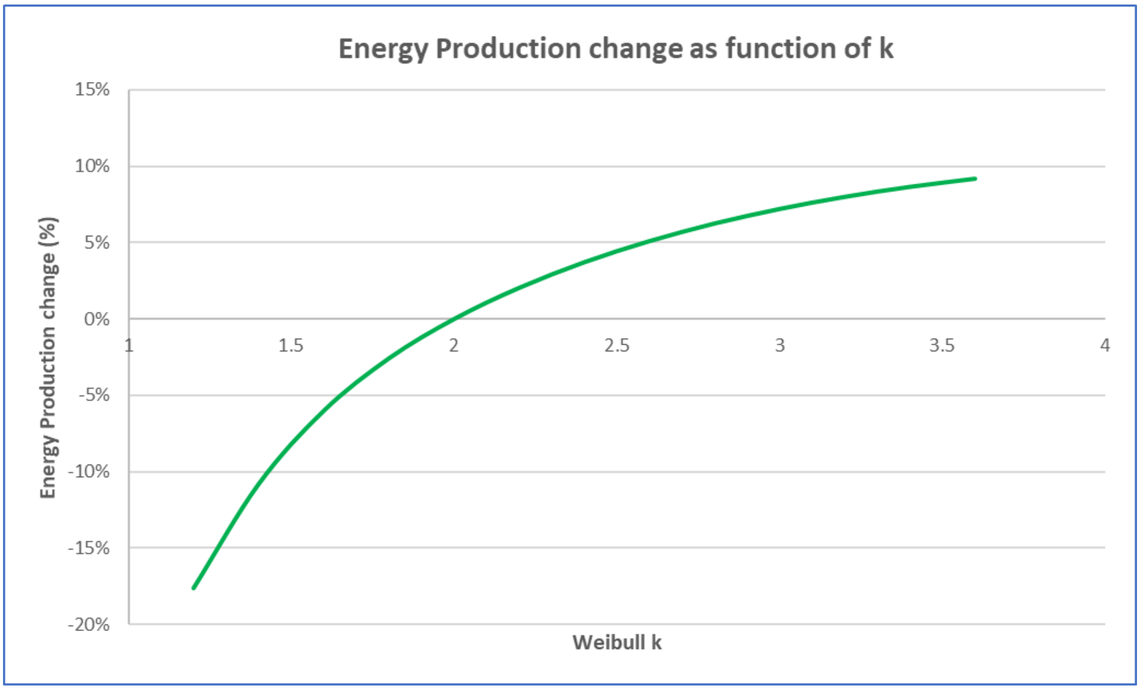

Figure 13: Energy production as function of Weibull k parameter for the same average wind speed

Figure 14 showcases the variation in the 'k' values derived from the Global Atlas for Siting Parameters [27,28]. Generally, lower 'k' values can be expected in regions such as Norway and Mediterranean countries. In contrast, Central Europe tends to exhibit higher 'k' values, indicating more energetic wind distributions. This figure has been generated with WindPRO application tool [29]

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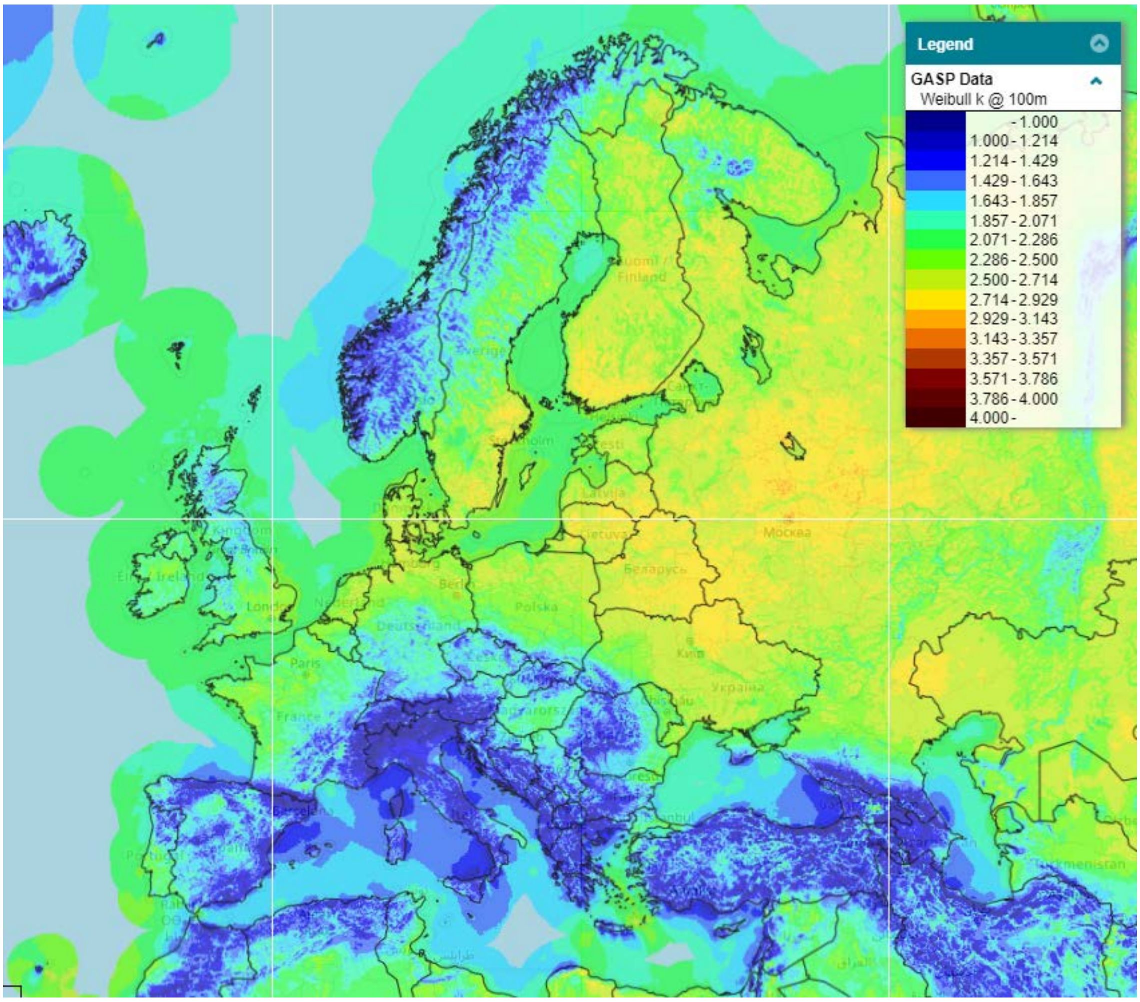

Figure 14: Weibull k parameter. Source: Global Atlas for Siting Parameters

Turbulence Intensity

Turbulence intensity affects final production and suitability of selected wind turbine as follows:

- Power curves: Manufacturers provide power curves for specific turbulence intensity values or ranges. These curves have minor variations. Power curves associated with high turbulence intensity show an increase at wind speeds below 8m/s and over 22m/s. However, at medium wind speeds, these curves tend to decrease. Working with low turbulence intensity is the opposite; the power is higher at medium wind speed (see Figure 15). Considering the wind distribution and the power curve variation, the energy output of the power curves will be higher with lower turbulence intensity.

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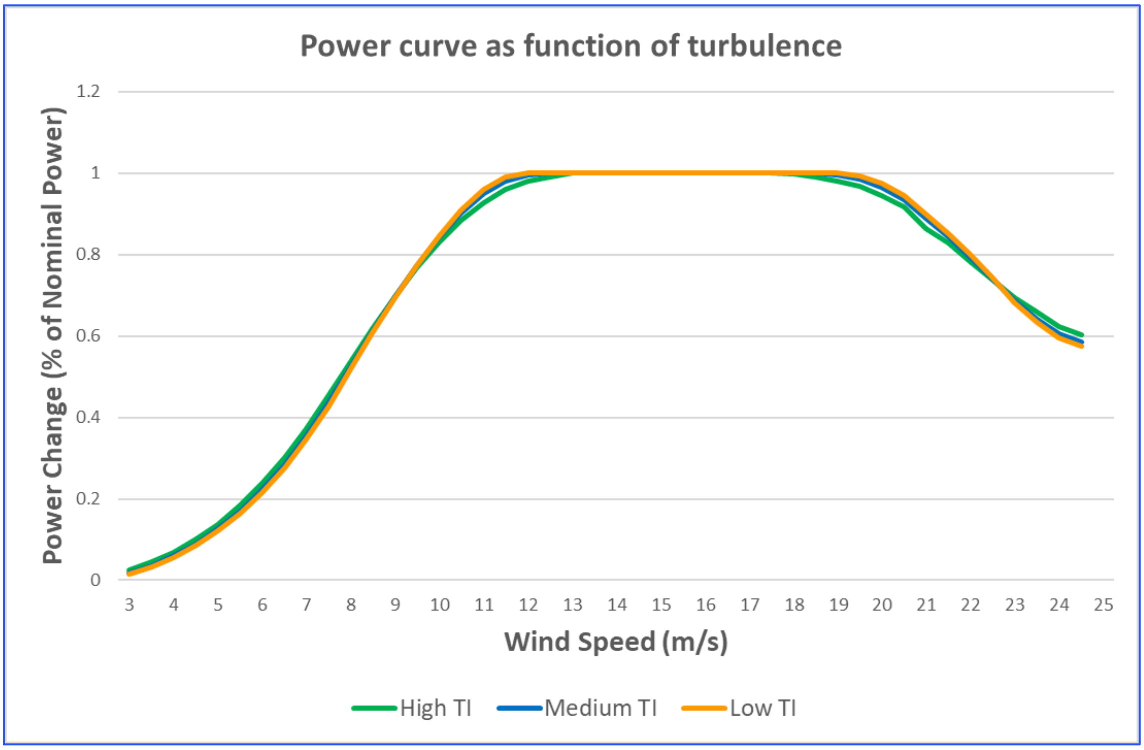

Figure 15. Power curves at different turbulence intensity

- Wake effect: The turbulence intesity influences the wake effects. The wake effect is a loss that applies directly to the energy output. In a turbulent flow, the wind mixes early, and the wake effect of the turbine reaches shorter distances behind it. In other words, higher turbulence generates a lower wake effect on the downwind turbine for the same distance between turbines. The influence of turbulence intensity on wake losses has been tested for two wind farms:

  For the onshore wind farms, the wakes generated at a reference turbulence intensity of 10% have been considered as a reference. With this consideration, the wake losses are estimated to change according to the following expression:

  WakeLosses(%) =ReferenceWakeLossesForTI10%*(1-2.1x(TI-0.10))

  In the case of offshore wind farms, wakes generated at a turbulence intensity of 8% have been considered as a reference, and wake losses are estimated to vary according to the following expression:

  WakeLosses(%) =ReferenceWakeLossesForTI8%*(1-4.3x(TI-0.08))

  The results of the wake losses estimated by these formulas are shown in the following figure: where it can be seen that offshore wind farms have a more significant wake effect, i.e., for the same distance between turbines, they have higher losses than onshore wind farms, to compensate for this effect the distances between wind turbines are increased.

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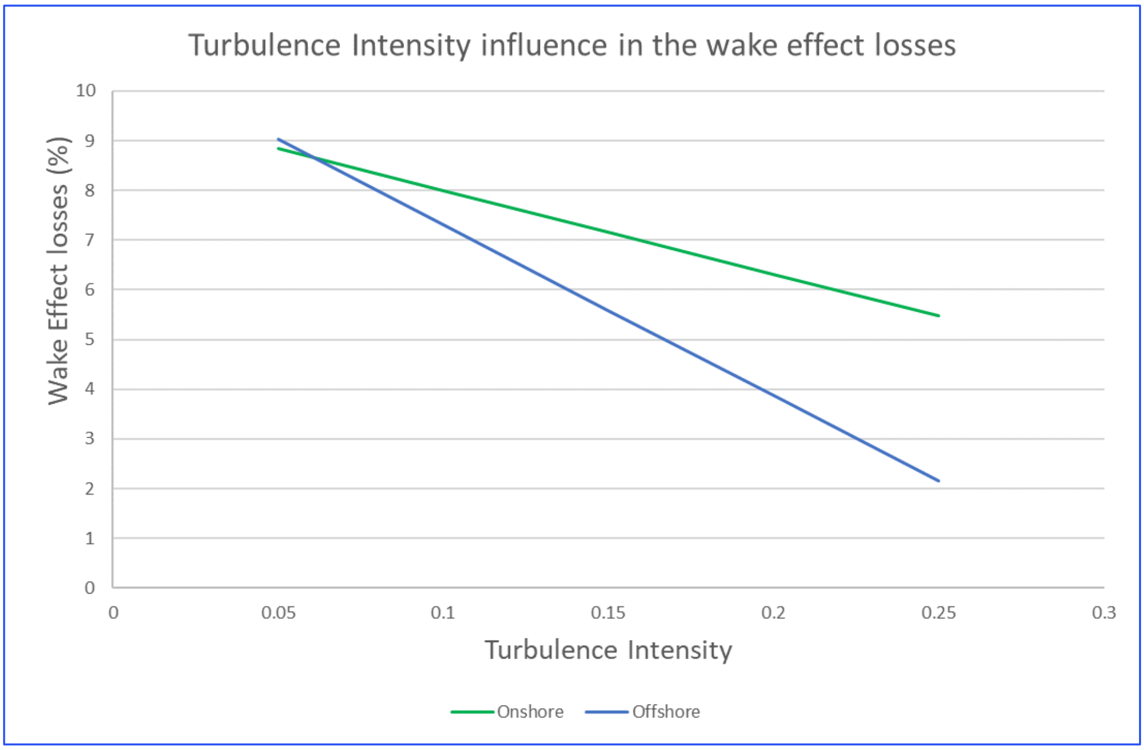

Figure 16: Production losses change vs turbulence intensity variation.

- loads and stresses: The loads and stresses on turbine components will depend on turbulence intensity, either considering the turbine structural integrity or the loads increase due to wake effects. Loads will be checked by the manufacturer.

Wind Shear

Wind shear, as defined in Section 2.1, also significantly influences energy production. For a given hub height, a high wind shear indicates a substantial increase in wind speed, which can considerably boost the estimated production. Conversely, low wind shear suggests that the wind speed does not increase significantly with height. As a result, in areas with low wind shears, increasing hub heights may not be as effective since the higher cost of turbines may not be offset by the gain in production.

The following graph shows how wind speed changes at different heights as function of the wind shear. In the graph wind speed at 100 m has been considered as constant at 7.0 m/s, showing that for wind shear 0.26 wind speed at 150 m is 8% higher than for wind shear 0.08.

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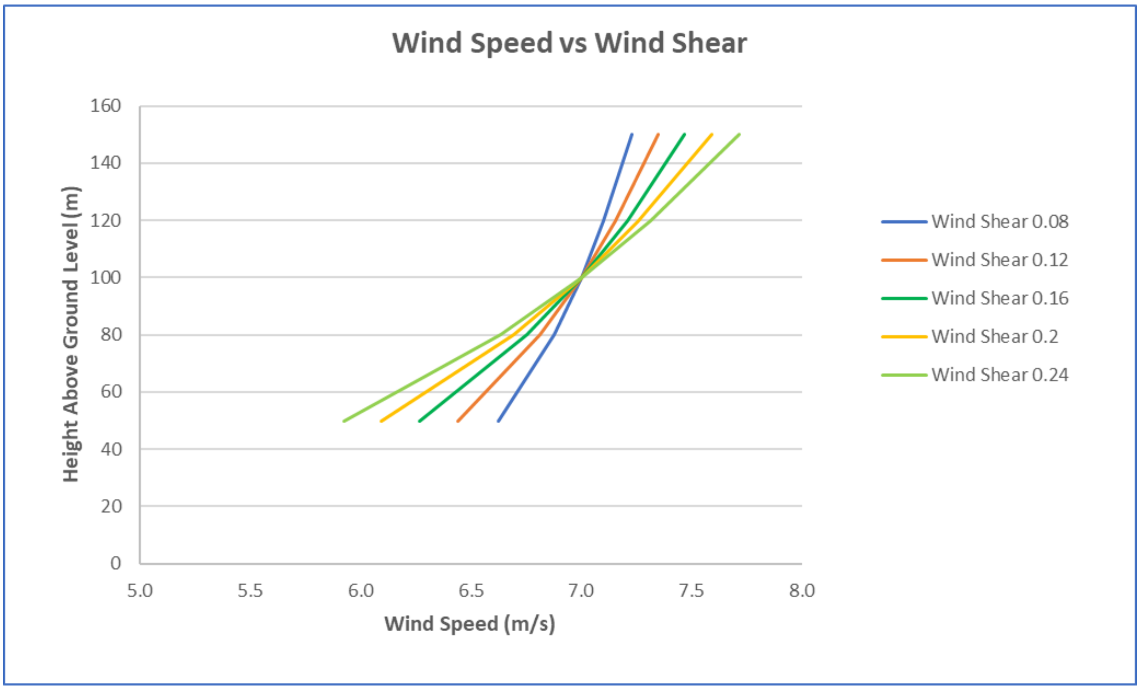

Figure 17: Change of wind speed with height for different wind shear values.

Ambient conditions

The ambient conditions also impact the energy estimates, which are described mainly by the **air density**, that at the same time is function of other parameters.

Air density: The energy produced by a wind turbine is influenced by air density. Given a constant average wind speed, higher air density results in greater energy production compared to lower air density. To account for this effect in energy calculations, manufacturers typically provide different power curves for varying air densities.

The graph below illustrates the percentage difference in power values for a wind turbine at different wind speeds, with various air densities represented by different colours. The percentage difference is calculated using the standard air density (1.225 kg/m3) as a reference point.

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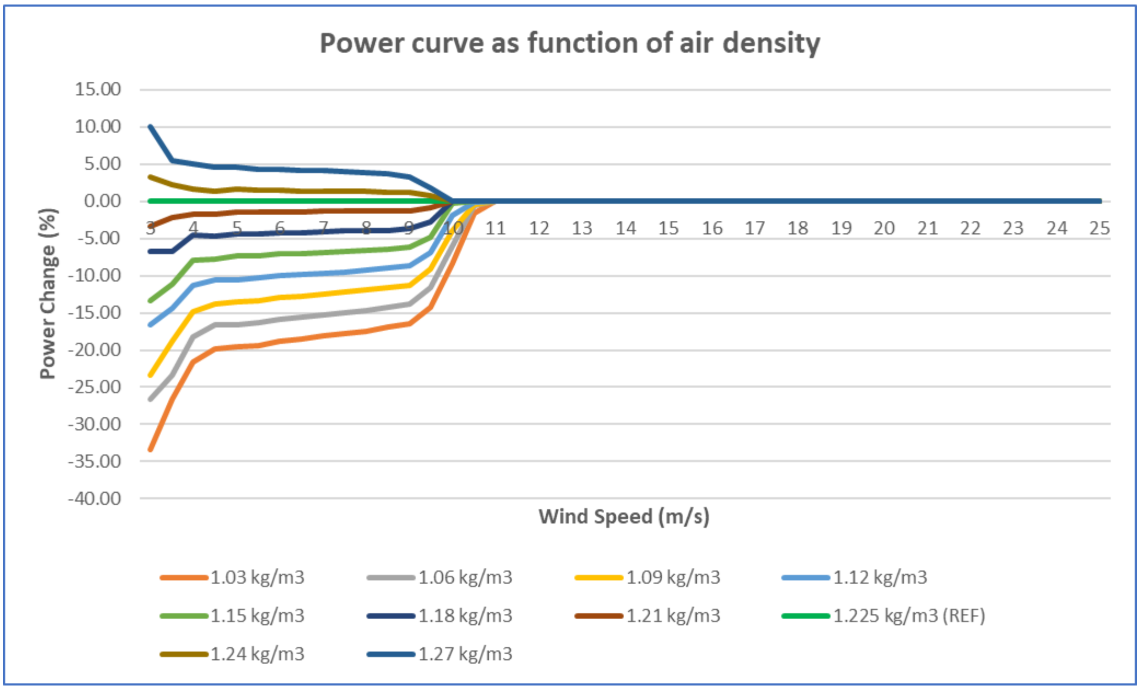

Figure 18: Change of power curve as function of air density.

At the same time, air density is a function of **air pressure**, **temperature,** and **relative humidity**.

Temperature: In addition to being the most influential factor in air density, the temperature at a site must be analyzed to assess the operational range of the selected wind turbine and the risk of icing and derating.

In locations with low temperatures, ice can accumulate on the blades, reducing their performance and leading to potential production losses. Furthermore, some manufacturers establish deratings or curtailment strategies under specific temperature conditions. In areas with high temperatures, turbines can be derated (decrease the power to compensate the temperature in the components), resulting in less power production than expected based on the standard power curve.

In both scenarios - low and high temperatures - the production losses may not be substantial, but they should nonetheless be taken into account for an accurate energy production estimation.

Pressure: Air density is directly related to air pressure. As the pressure increases, the density of the air also increases. This is because pressure is a measure of the force that the air exerts per unit area, and when this force increases, it compresses the air molecules closer together, leading to an increase in air density. Generally, the air pressure is inversely dependent on earth surface is dependent on the altitude,

Relative humidity: The addition of water vapor to air (increase the humidity) reduces the density of the air. This is because the mass of water vapor is lower than the mass of other gases in the air.

Terrain characterization, complexity, and elevation (onshore): For onshore wind farms, terrain is described by the orography and roughness. The orography will describe the changes in elevation, and the terrain will be classified as flat or complex terrain. The roughness is linked to the land cover and is

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low over water surfaces (offshore) and high in forested areas and cities. Both parameters are considered in wind resource assessments and used to extrapolate measured data at a mast to the turbines' location.

At the time of planning a new onshore wind farm, areas with high terrain roughness, that will indicate the presence of vegetation, trees or buildings must be avoided in order to preserve the environment and maintain a constant wind flow. So, at this stage, only the orography is analyzed.

The only impact on production of the terrain complexity is the fact that usually power curves given by manufacturers are provided for determined terrain conditions; power curves are usually provided for flat terrain where the inflow angle (angle of incidence of wind on the turbine rotor) is lower than certain limit; if the value is exceeded the turbine behavior will be different and the provided power curve not valid.

The inflow angle is the most extended parameter used for terrain complexity around the turbine and it is used to state the climatic conditions of the site so the manufacturer can check the selected turbine suitability.

Terrain complexity will also have an impact on the different phases of the wind project. During the development phase terrain complexity needs to be considered from a viability point of view. Terrain complexity can be evaluated considering the slopes of the terrain in the surroundings.

Bathymetry and waves (offshore): For offshore wind farms the depth of the sea will be considered. The bathymetry impacts the suitability of the offshore wind farm as it will determine the type of foundation to be used and ultimately the costs. Another important restriction in offshore wind farms is the electricity evacuation infrastructures.

The influence of the waves in offshore wind farms has not been deeply studied up to date and further investigations are being carried out. Although investigations have been focused on small and isolated wind turbines, some preliminary conclusions show that models including the waves predict higher production and longer wake lengths if waves and wind are travelling in the same direction [30].

5.2. Production losses

While section 5.1 described all parameters impacting the production estimates of a wind farm and the expected losses, this paragraph discusses the production losses in detail.

General production losses

Main production losses that will have to be considered are:

- Electrical losses due to transformation and transportation of the energy, that will be function of the distance to the electrical substation.
- Availability of turbines and grid.
- Power performance, degradation and dirt on blades.

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Site specific losses

As described in previous paragraphs some losses are site-specific and ultimately influence the expected production:

- Extreme temperatures: turbines are designed to run and produce inside a determined range of temperatures.
- High temperature derating, mainly at sites at high elevation.
- Icing.

Blockage effect

Wakes effects of turbines have been studied in the past and defined as produced through downwind, behind the turbine. Recent investigations are being carried out analyzing the effects of turbine upwind, concluding that there is a reduction of wind speed also in front of the turbine causing the named blockage effect.
Production losses due to blockage effects depends strongly on the turbines' location and dimensions, a kind of turbines population density, and is revealed to be more important for onshore wind farms and for low wind speed sites. Maximum production losses due to blockage effect are estimated to be 3-5% as concluded in some investigations and can be usually neglected for wind farms with capacity lower than 50 MW or layouts with a single row [31].

Curtailments

In some cases, turbines within a wind farm can be subject to different operational conditions. Main causes of curtailment at turbines are described below:

Distance between wind turbines: As a standard, turbines within a wind farm will be located with a distance of 3 rotor diameters to each other. However, in some cases this distance can be reduced, for example, for a layout in one single line and clearly directional wind. In such cases manufacturers can impose some restrictions on turbines, usually known as Wind Sector Management, and those should be stopped at wind speeds above a determined value for some specific directions. In addition, some strategy could be imposed by the manufacturers in order to warranty the wind turbine integrity in the case that specific loads exceed the design ones.

Production losses due to Wind Sector Management are usually low, mainly due to the fact that directions where distance is short have too low energy content.

Noise restrictions: Environmental noise is a great health concern in Europe as, according to the World Health Organization (WHO), prolonged exposure to noise can lead to illnesses [32]. The noise regulations vary from one country to another. Established admissible noise levels depending on the use of the buildings, the impact on the species and daytime.

For offshore wind farms, noise is usually less restrictive, but also can have an impact on fishes and marine mammals as sounds propagates farther through water.

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Noise produced by turbines comes from different sources, with the predominant contribution coming from the rotor and blades. The noise emitted is given by the manufacturer and could exceed limits allowed if there are some sensitive noise areas close by.

The manufacturer usually provides noise curves as noise at 10 m height for different hub heights, although in some cases, the noise curve provided is a hub height. The following graph shows noise levels at different distances and a height of 1.5 m above ground level from a 114 m hub height wind turbine working in a mode noise of 105.0 dB (measured at 10 m). The noise at the turbine's foundation is around 55 dB, and the noise decreases as far away as the wind turbine.

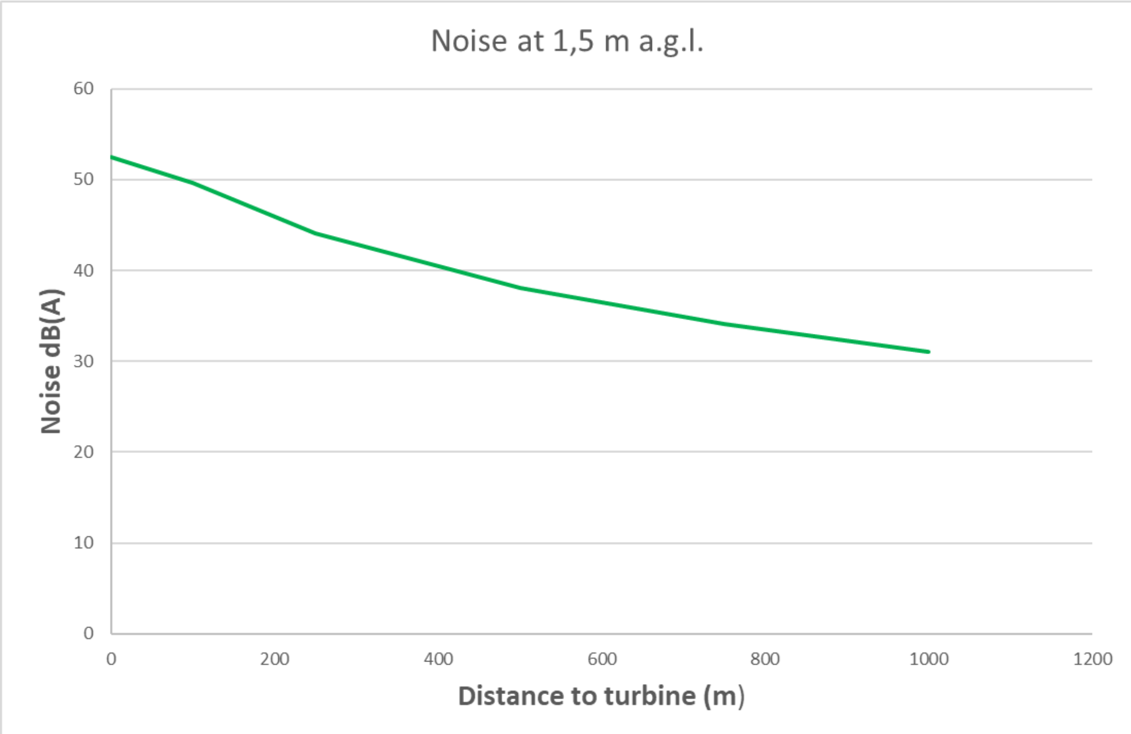

Figure 19: Noise level as function of distance to turbine.

Some countries and regions have their own rules regarding the distance from turbines to buildings and farms. As a general rule, a minimum distance of 500 m to isolated buildings and 1 km to villages and cities should be kept, although this distance will depend on the turbine size and emitted noise.

To reduce noise at turbines, manufacturers present different solutions. The simplest one is an add-on to the blades, that reduces noise without affecting the power curve and thus the energy production.

For different turbines there also exist different Noise Modes, but with different power curves; noise is reduced by acting in the turbine control, and production is lower.

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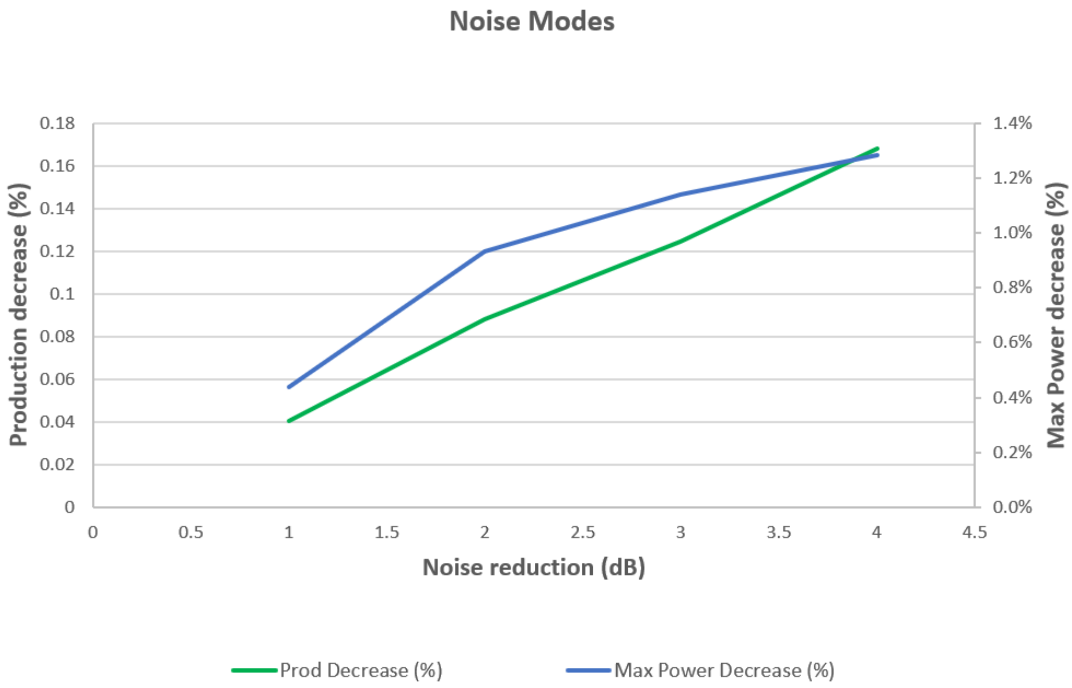

Figure 20: Maximum power and production noise example for different Noise Modes.

If these solutions are not enough to mitigate noise exceedances, turbines should be stopped. Different Noise Modes and Shut Down of turbines can be programmed for some specific wind directions, wind speed daytimes and seasons, in order to minimize production loses.

Flickering: The rotating rotor of a wind turbine generates shadows that can be annoying. This is called flickering and usually is calculated as the number of hours per year. The main health concern associated with shadow flicker is the risk of seizures in those people with photosensitive epilepsy.

Studies above [32] show the relationship between photoinduced seizures (i.e., photosensitive epilepsy) and wind turbine flickering. These studies suggested that flickers from turbines that interrupt or reflect sunlight at frequencies >3Hz pose a potential risk of inducing photosensitive seizures in 1.7 people per 100,000 of the photosensitive population. This translates to a maximum rotation speed of 60 rpm for turbines with three blades. Modern turbines commonly have a rotor speed well below this threshold [32]. Although flickering from wind turbines is unlikely to lead to a risk of photoinduced epilepsy, there has been little research on how it could increase the annoyance factor for those living near turbines.

To avoid flickering and shadows and their corresponding disturbance curtailment strategy could be needed.

Birds and Bats: Birds and bats are known to be affected by wind farms. While wind energy is generally considered a clean and renewable energy source, it is important to address potential environmental impacts associated with its implementation, including the effects on bird and bat populations, as it is illustrated in deliverable D3.1 of Wendy project.

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Birds can be at risk of colliding with wind turbines, particularly large soaring species and migratory birds. The rotating blades of wind turbines can be a hazard for birds, especially if the turbines are located along migratory routes, on ridges or in areas with high bird density. Collision-related fatalities can occur when birds fly into the spinning blades, towers, or associated infrastructure.

Bats are also at risk of collisions with wind turbines, but the reasons differ from those of birds. Bats are more susceptible to collisions as they may be attracted to the blades due to attraction of insects to the turbines. It is also hypothesized that bats misinterpret the blade's structure to be water and want to drink from it. In addition to collisions, evidence suggests that the change in air pressure caused by the rotating blades can affect bats' internal organs, leading to mortality or injury (i.e., barotrauma).

Wind farm developers and operators employ various strategies to mitigate the impact on these animals. Environmental impact assessments are conducted before wind farms are constructed to identify high-risk areas for collisions [33,34]. However, recent studies show that pre-construction surveys are often underestimating actual bat fatalities [35]. This information helps in selecting suitable locations for wind farms. Additional measures include:

- *Monitoring and research*: Ongoing monitoring programs are conducted to assess the impact on bird and bat populations and identify further measures for mitigation.
- *Turbine placement:* Wind turbines are placed away from known migration routes, ridges, bird/bat habitats, and areas with high bird or bat activity.
- *Radar systems*: Some wind farms use advanced avian radar systems to detect and record movements and adjust turbine operations accordingly. Some of these systems are explained in the deliverable D3.3.
- *Lighting*: Appropriate lighting techniques are used to reduce the attraction of birds to the turbines during nighttime.
- *Acoustic deterrents*: Acoustic deterrents, such as speakers emitting specific sounds, can help keep birds away from wind turbines. Ultrasonic sound devices can be installed to emit high-frequency sounds that deter bats from approaching wind turbines.
- *Operational curtailment*: Wind turbines can be programmed to reduce or shut down their operations during periods of high activity, such as during their migratory season or when weather conditions are conducive to bird or bat presence.
- *Blade feathering*: Turbine blades can be pitched to minimize their rotation speed during peak activity periods.

There are studies focusing on wind farm impacts on birds and bats [36,37]. One of the studies reveals that the average number of avian fatalities due to collisions with wind turbines is approximately 2.19 birds per turbine per year, and bat mortality at the wind turbines was nearly three times higher than bird mortality.

Spring and Autumn are often associated with a higher risk due to factors such as seasonal migration and behavioral patterns. In the spring, the display behavior increases, while in the autumn, juveniles leave the nest. Migration can occur at various altitudes, ranging from just above sea or ground level to several kilometers above. However, it is most likely to occur from sea level up to several hundred meters above.

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The presence of birds and bats not only affects the operation of the wind farms but also influences the development and building time, producing delays. For example, construction works are restricted during the bird breeding periods.

Although less knowledge on fatality patterns exists offshore, curtailment has been promoted also here, for instance during periods of peak migration. These are usually identified using avian radar systems or migration intensities derived from meteorological radar systems. There exists little knowledge on the impact and options for curtailment for bats in offshore wind farms, although bats are known to frequent these.

Social constraints: Achieving complete social acceptance may not always be possible. However, by considering the concerns and perspectives of local communities, implementing effective communication strategies, and addressing environmental and economic considerations, augment social acceptance of wind farm projects.

The social acceptance of wind farms can vary depending on various factors such as local community engagement, environmental concerns, aesthetic considerations, and economic impacts. Here are some key points related to social acceptance, more detail can be review in the deliverables WP2:

- *Community Engagement*: The level of community involvement and engagement in the planning and development process of wind farms is crucial for social acceptance. Early and transparent communication, public consultations, and addressing community concerns can help build trust and understanding among local residents.
- *Economic Benefits*: Wind farms can bring economic benefits to local communities. They can create jobs during the construction and operation phases, stimulate local businesses, and provide a source of tax revenue for local governments. Highlighting these benefits can contribute to greater social acceptance.
- *Environmental Considerations*: Wind energy is generally seen as a clean and renewable energy source, which can help reduce greenhouse gas emissions and combat climate change. Communicating the environmental benefits of wind farms, such as reduced reliance on fossil fuels and improved air quality, can enhance social acceptance among individuals concerned about environmental issues.
- *Aesthetics and Visual Impact*: The visual impact of wind farms is often a subject of debate. Some people appreciate the graceful sight of wind turbines, while others may find them visually intrusive. Careful planning, including siting wind farms away from highly populated areas and sensitive landscapes, can help address aesthetic concerns and minimize visual impact.
- *Benefits for Local Communities*: Engaging local communities and providing them with direct benefits from wind farm projects can contribute to social acceptance. This can be done through community ownership models, revenue sharing agreements, or community development funds that support local initiatives, infrastructure projects, or educational programs.
- *Education and Awareness*: Educating the public about wind energy and its benefits, dispelling myths or misinformation, and promoting a better understanding of technology can help foster

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social acceptance. Public awareness campaigns, educational programs, and information sharing can play a significant role in shaping public perception.

Perception of wind farm developers by the public is rightly receiving more attention [6], and it has been shown that developers who ignore local knowledge are likely to alienate communities [7], leading to possible problems between the community and the wind farm owners.

Grid constraints: Due to the sudden increase of renewable installations, there is a chance that the electrical infrastructure cannot absorb all the clean energy produced and the consequent risk of the installation shutting down when the grid is overloaded.

6. Micrositing criteria

Micro-siting is a process involving the meticulous selection and positioning of individual wind turbines within a wind farm. This procedure is crucial for obtaining optimal energy output levels, improving operational efficiency, and minimizing negative environmental and societal impacts. Micro-siting involves a multidisciplinary approach, involving aspects such as wind characterization and resource assessment, terrain analysis, environmental and societal considerations, and economic feasibility.

This section deeps into the various factors that play a pivotal role in the micro-siting process, with the aim of shedding light on the crucial considerations and methodologies employed to ensure optimal positioning of wind turbines. It also touches upon the challenges and intricacies inherent in micro-siting, such as the dynamic and unpredictable nature of wind resources, the delicate task of balancing energy production with environmental and societal considerations, and the restrictions imposed by land availability and regulatory frameworks.

The section starts with the introduction of innovative strategies in the field of micro-siting (Sections 6.1 & 6.2). This is succeeded by an in-depth exploration of the various elements that shape the micro-siting process (Section 6.3). The discourse concludes with a set of recommendations for future micro-siting initiatives, emphasizing the promotion of sustainability, enhancement of energy efficiency, and cultivation of social acceptance (Section 6.4).

6.1. Turbine selection

Turbine selection is out of the scope of this report, and only a brief introduction to parameters to take into account is described.

Turbines are designed under specific conditions and are deemed suitable for installation within these parameters to guarantee their structural integrity throughout their lifespan. In accordance with IEC 61400-1:2019 [38], turbines are categorized into groups as shown in Table 1. They are classified into Classes I, II, III, or S based on the maximum average wind speed (Vave) or extreme wind speed (Vref, the expected maximum 10-minute wind speed for a reference period of 50 years). With respect to turbulence intensity, turbines fall into classes A+, A, B, and C.

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Wind Turbine Class		I	II	III	S
Vave	(m/s)	10	8.5	7.5	Values specified by the designer
Vref	(m/s)	50	42.5	37.5	
	Tropical (m/s)	57	57	57	
Vref, T	(m/s)	57			
Iref (-)	A+	0.18			
	A	0.16			
	B	0.14			
	C	0.12			

Table 1: Turbines classification based on IEC 61400-1.

Consequently, turbine type and hub height should be selected based on its IEC Class as provided by the manufacturer. Nevertheless, turbine manufacturers tend to give some flexibility to those limits and check the turbine loads at the specific project to confirm its suitability. In case of exceedance, the manufacturer can propose some operational strategy/curtailment.
As part of the turbine selection, hub height must be defined. At his point wind shear should be consider. Class III turbines offer more steady hourly generation profiles and higher full load hours, but in some locations the increased cost is not worthwhile, or wind gusts become a limiting factor [23].

6.2. Layout structure

Turbines will be located perpendicular to main wind direction, and as a standard in the wind industry distance between turbines is 3 rotor diameters in the same line and 5 rotor diameters between lines (see Figure 20). With increasing turbines sizes, it is observed that distance between lines is increasing up to 3 rotor diameters between turbines in a line and 7 rotor diameters between lines. It must be noted that this is not a fixed rule, and of course final distance between turbines will depend on many other factors as the number of turbines and/or lines, wind directionality, and other parameters influencing the wind flow inside the wind farm.

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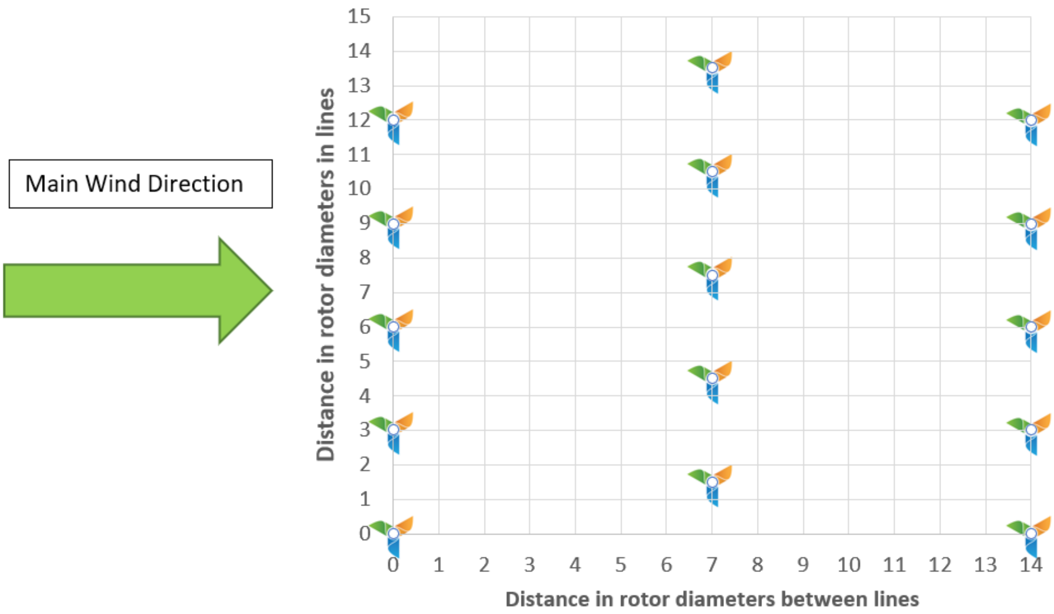

Figure 21: Standard distribution of turbines in the layout

To simplify the positioning of the turbines, from this point onwards, distance to keep between wind turbines will be defined as ellipses, with minor and major axis as a function of the rotor diameter.

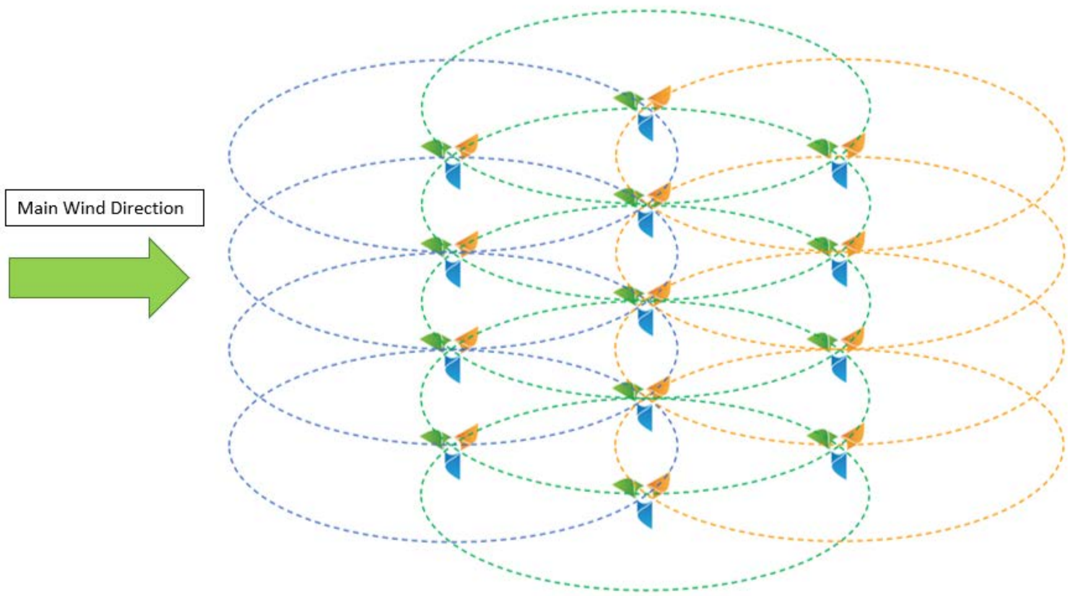

Figure 22: Distance between wind turbines

Directional distribution

Directional distribution will show the main wind direction. The most frequent input is the frequency distribution, showing the percentage of time the wind is coming from a determined direction. But not

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always the sector with highest frequency is the one with highest wind speed. To take into account both contributions to production, the energy distribution can be used.

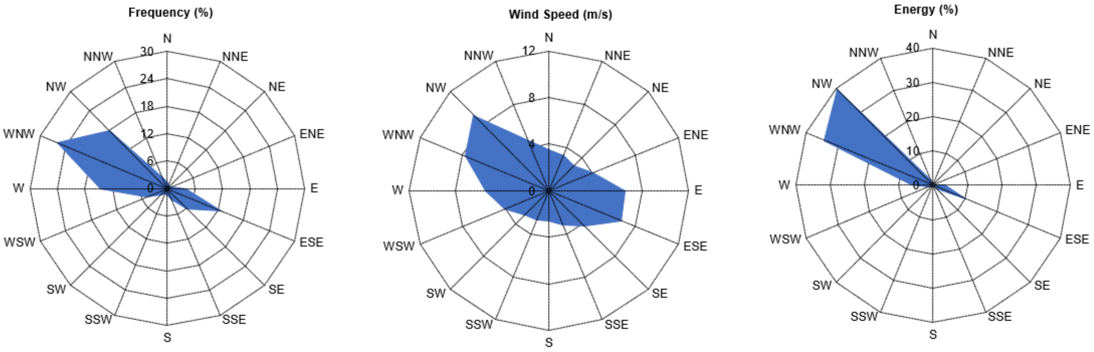

Figure 23: Directional wind distribution

To exemplify, figure 20 indicates that the most frequent wind direction is WNW, but direction with highest wind speed is NW, resulting in a clear main direction WNW-NW. However, the main direction is not always so obvious, since wind can be coming from two opposite wind directions, or distribution can be more open, with wind coming from almost all directions with same frequency and/or wind speed. Therefore, three different types of directional distributions are distinguished:

1.- Unidirectional wind distribution, when wind blows from one single main direction or opposite wind directions (for example North and South or East and West, figure 21).

2.- Bidirectional wind distribution: two main directions not opposite one each other (figure 22)

3.- Multidirectional wind distribution: not clear predominant direction (figure 23)

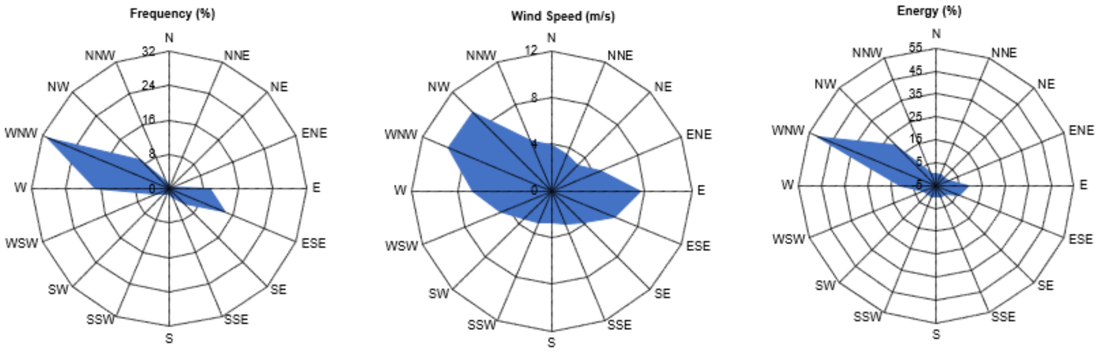

Figure 24: Unidirectional wind distribution

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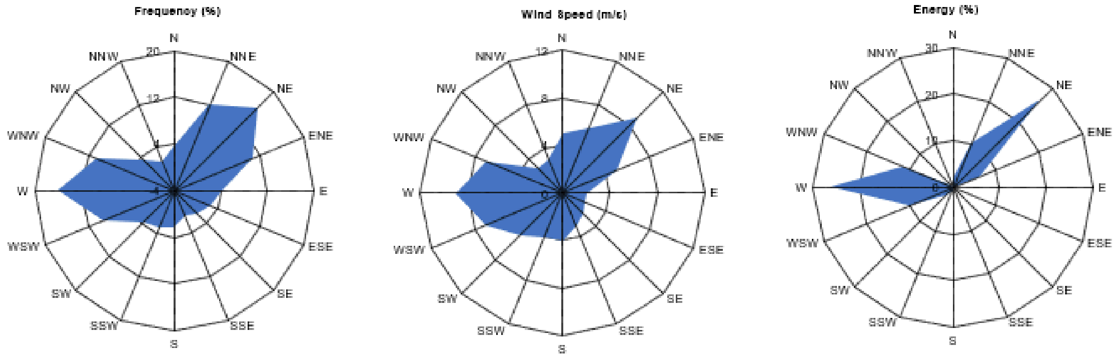

Figure 25: Bidirectional wind distribution

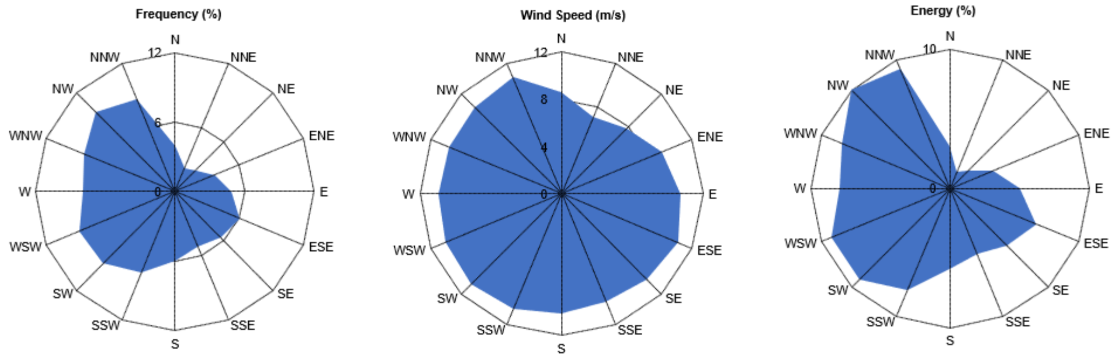

Figure 26: Multidirectional wind distribution

For an unidirectional distribution, turbines can be aligned in the standard layout (fig. 18/19), since the main direction is clear and wake losses can be easily reduced with a good layout orientation.

When the main direction is not distinguishable and/or wind is coming from several directions, wake losses could be considerable in those sectors and can be reduced by increasing distance between wind turbines.

As a conclusion, we can ensure that layout, either its orientation or distance between turbines is dependent on directional distribution. Please note that a bad layout orientation can lead to production losses due to wake effects of around 40%.

Wake losses

Turbines included in certain layout generate wakes and reduce production due to downwind effects. Main factors affecting the wake losses are:

- Distance between wind turbines: Wake losses decrease with distance, so to reduce wake losses turbines should be spaced.
- Turbulence intensity: Wake losses decrease with turbulence intensity.
- Turbine Ct Curve: Thrust coefficient is given by the manufacturer. Explain it in section 3.1.

Although change in production losses is very dependent on turbulence intensity and wind directions, the figure 24 can give an idea on the change in wake effects when increasing or decreasing the distance

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between turbines in a row or between rows, showing that duplicating the distance the production losses due to wake effects can be reduced 40%, changing for example from 10% to 6%.

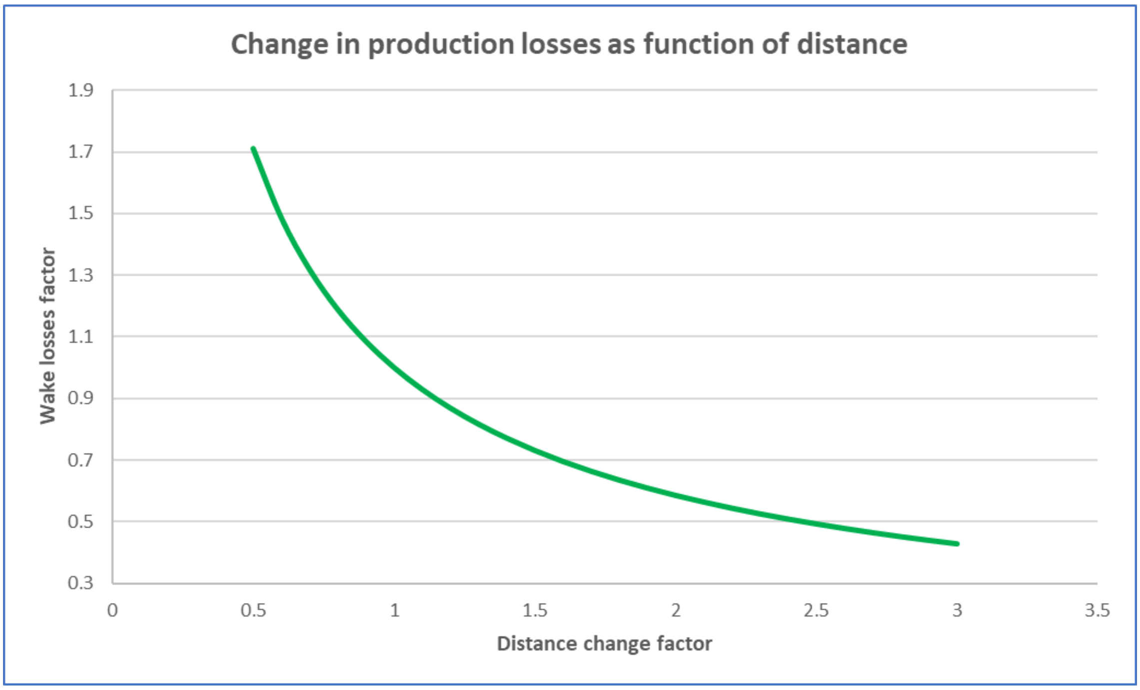

Figure 27: Overview of estimated Wake losses as function of distance

6.3. Layout setup

In conclusion, from the previous paragraphs, the layout will be defined as maximizing the wind farm's energy and building a grid perpendicular to the main direction. Standard layout will be preferably defined, keeping a distance between wind turbines of 3 rotor diameters between turbines in the same line and 7 rotor diameters between lines. Depending on how directional the wind is in the area and the ambient turbulence intensity, those distances will be increased or decreased.

However, it is only sometimes possible to locate turbines in a regular grid, mainly for onshore flat terrain wind farms or offshore, without restriction. When it is impossible, keeping a minimum distance between wind turbines of at least 3 rotor diameters is recommended.

As a general rule, the placement of turbines in protected areas is not permitted. However, some licensing sites have specific considerations for the microsite. These considerations may depend on the country and region. Some examples could be the protection of natural vegetation, irrigation areas, or avoiding regions previously affected by fire, among other considerations.

Local laws change from place to place. These rules determine the distance between wind turbines and inhabited areas. These regulations should be factored into the definition of the micro-site.

The main constraints for offshore wind farm layouts are sue of the area by marine wildlife (fish, marine mammals, seabirds) as well as migratory species (birds, bats) and other areas of ecological interest.

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Maritime shipping lanes, fisheries and aquaculture, and other strategic installations (e.g., oil and gas platforms) and harbors must be considered when designing the layout.

As a rule of thumb, layouts will be designed to keep wake losses below 10%. High wake losses impact not only production estimates but also operational and maintenance costs, as the wake effects increase turbulence and may damage the turbines.

6.4. Mitigation strategies to minimize environmental and social impact.

Besides optimizing micro-siting from a technological perspective, also other factors play a role in optimizing the wind farm layout. These include minimizing social impacts such as noise nuisance, flickering, visual impacts, or cultural heritage sites. From an environmental perspective, turbines can be placed away from areas of high ecological values such as breeding or foraging sites or ridges attracting soaring birds due to orographic updrafts. Such considerations need to be included during the micro-siting procedure.

There are also occasions when the measures adopted in the micro-siting only meet some of the specifications of the construction and operation permit of the wind-power plant. In this case, mitigation measures can be included, which, without eliminating the impact, can significantly reduce it. These reduction measures are generally applied in the operation phase of the project.

Visual Impact:

Generally, the sizes of turbines are on an upward trend, and wind farms are increasingly becoming a common sight in many landscapes. The areas with the highest wind speeds are typically elevated, making wind turbines visible from distances [39]. To mitigate this visibility, potential solutions could include reducing the size or hub height of the turbine or relocating the turbines. Another approach that has been tested is painting the structures in different colors. However, this could potentially make the wind turbines less noticeable to birds and planes [40].

Noise:

As previously mentioned, noise from turbines in operational phase can be reduced by **add-ons** on blades and different operational **Noise Modes**. In case further noise reduction is required, **Wind Sector Management** strategy can be implemented.

For offshore wind farms and during construction, noise can be reduced using **bubble curtains** to minimize impacts on marine mammals and fish. A bubble-curtains A bubble curtain was designed to absorb sound during the installation of offshore wind turbine foundations, consisting of a barrier of compressed air, and can be used in the operation phase in some places. Please also note that in some cases, and onshore wind farms, construction works are restricted at some times of the day and even, to protect fauna, during the breeding periods.

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Flickering:

It is recommended to keep a distance of at least 1 km from turbines to residences, however this distance could be not sufficient if the turbine is on a ridge, where its shadow will extent longer. To avoid flickering and shadows and its corresponding disturbance **curtailment strategy** could be needed.

Turbines' manufacturers are aware of the issue and are incorporating as optional **flicker control systems**. By installing light intensity sensors, the system can determine if the turbine is causing shadow flicker onto inhabited areas and pause the turbine.

Wildlife protection:

Micro-siting can also take into account considerations for wildlife during the design phase. For instance, mapping of areas with enhanced uplift properties. Such areas can consist of land cover enhancing thermal updrafts or topography enhancing orographic updrafts such as ridges [41] .

Detection systems (e.g. radar-based or camera-based shut-down on demand) can be implemented to reduce the risk of birds and bats collision in onshore wind farms, by detecting and predicting the flight path, and shutting down the turbine if needed. These systems can also be implemented in offshore to protect seabirds.

Other camera-based systems may be trying to deter birds from approaching a wind farm, such as noise emission or simulating predators. Some measures aim to improve the visualization of the wind turbine to avoid bird collisions, such as painting the blades.

Bat protection systems (i.e. smart curtailment) are also offered by some manufacturers. Based on the behavior of bats, the system evaluates the environmental conditions and pauses the turbine is needed. The solution can also include bat deterrent systems.

7. Key Performance Indicators

One of the WENDY project goals is fostering the acceptance of renewable wind energy in European communities through a holistic approach including social, environmental, and technical dimensions. Key Performance Indicators (KPIs) are a set of values that will help to reach this goal. In the WENDY project, one single KPI will be set at a later stage to identify the best locations to plan a new wind farm by joining different indicators from the three dimensions.

At this stage of the project different KPIs have been defined from the technical point of view. Those KPIs have been selected from the main parameters that can be impacting the production or the cost and ultimately the LCOE. Several single KPIs are listed but not necessarily all of them will take part in the single multivariable KPI that will be developed in WP4.

Additionally, some micro-siting parameters that consider the social and environmental suitability of a wind farm have been added.

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7.1. Preliminary KPIs – Micrositing criteria

The parameters have been categorized into three dimensions: Technical, Social, and Environmental. The tables below display these parameters. While all of these parameters could initially serve as Key Performance Indicators (KPIs), it's important to note that some may be interdependent. Therefore, in task 4.3, these parameters will be evaluated to analyze their dependencies.

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Table 2: Parameters for micro-siting criteria

Nature	Group	Criteria
Technical	Wind Characterization	Wind Speed
		Weibull Distribution k parameter
		Wind Shear
		Turbulence Intensity
	Ambient conditions	Air density (Temperature, Pressure, Humedity)
	Site conditions	Terrain Complexity (onshore)
		Terrain Roughness (onshore)
		Bathymetry (offshore)
		Distance to substation
Social	Visual	Distances
		Hub heigh
	Noise	Distances
		Operation mode
	Flickering	Location of the turbine
	No permitting	Location of the turbine
	No restricitions	No criteria apply
Environmental	No permitting	Location of the turbine
	Permiting with sensitivity in vegetation or fauna	Location of the turbine
		Compensatory measures
		Protection measurements
	No restricitions	No criteria apply

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7.2. KPIs to be integrated in Multivariable KPI

One of the scopes of the WENDY project is creating a multivariable KPI to integrate all technical, social and environmental KPIs into a single multivariate Key Performance Indicator (mV-KPI). This final mV-KPI will be fed from different tasks carried out along the WENDY project and are still under definition. However, based on the variables studied in this work, main contributions regarding micro-siting will be coming from:

- Wind Characterization, being the main parameter the **average wind speed**.
- Ambient conditions, summarized in the **air density** of the site.
- **Terrain description**, that will categorize depending on the orography complexity and the roughness or land use/characteristics (cf. Hanssen et al. 2020).
- To maximize the social acceptance and minimize impacts to people, visibility or noise propagation (decibel thresholds) or distance to populated areas and/or isolated residences/buildings will be evaluated and preliminary could be scored considering the **density of population** at specific sites.
- For **environmental protection**, the result of the WENDY tool and the locations of protected and sensitive areas in the surroundings will be considered.

Additional information required for the final evaluation of the different KPIs and its integration in a multivariate KPI is needed:

- Type of wind farm: **onshore/offshore**
- **Installed capacity** or number of turbines and its unit power.
- **Distance to substation**.

7.3. KPIs to be integrated in Wendy tool.

The Wendy tool considers several technical Key Performance Indicators (KPIs) or parameters to evaluate wind farm feasibility:

- Average Wind Speed: The average wind speed at the proposed wind farm site is a crucial factor for determining its potential energy production. Higher wind speeds generally result in greater electricity generation.
- Terrain Description: The terrain description provides information about the topography and land characteristics of the site. Factors such as elevation, slopes, and roughness can impact wind flow patterns and turbine performance.
- LCOE (Levelized Cost of Energy): The Levelized Cost of Energy is a metric that calculates the average cost of generating one unit of electricity over the lifetime of the wind farm. It takes into account factors such as construction costs, operational and maintenance expenses, financing, and the expected energy production. The LCOE provides an estimate of the cost per megawatt-hour (MWh) generated by the wind farm and helps assess its economic viability.

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8. Conclusions

The study has analyzed the parameters influencing wind farm production estimates, micro-siting options, and the economic viability, but also social and wildlife friendliness, of the projects. Categorizing these parameters into resource-related, technical-related, and economic-related groups provides a structured approach to understanding their significance.

The characterization of the wind resource in the area is a critical factor influencing production estimates. Factors such as wind speed, direction, turbulence intensity, and wind shear must be analyzed to assess energy yield accurately.

The optimal placement of wind turbines is significantly influenced by environmental, social conditions, and terrain characteristics. Key considerations include the preservation of wildlife, biodiversity conservation, protection of natural vegetation, the harmony between the ecosystem, local inhabitants, and wind farms. Additionally, terrain attributes such as topography, surface roughness, and the presence of obstacles also impact the performance and positioning of turbines.

Evaluating the economic viability of a wind farm involves considering capital costs, operational and maintenance expenses, financing, and the expected energy production. The study examined factors like LCOE and financial indicators to assess project profitability.

Conducting a sensitivity analysis helps identify the parameters that greatly influence turbine location or production. This analysis helps prioritize critical factors and understand their impact on the project's success from a production perspective. Other considerations may affect production output, but may be critical from a licensing perspective (e.g. to minimize social or wildlife related conflicts).

The study examined project losses, specifically curtailment, which refers to non-production due to environmental or social issues. Identifying curtailment and understanding its causes is important for increasing the acceptance of wind farms.

Mitigation strategies have been proposed to minimize project losses, including curtailment. By proactively addressing environmental and social issues, developers can reduce non-production periods and optimize energy generation.

All these considerations could improve the layout configuration, including optimizing turbine placement, spacing, and orientation to maximize energy production, minimize environmental impacts, and address social concerns.

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