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.

D4.3: Single multi-variable KPI

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WP 4, T 4.3

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Technical references

Project Acronym	WENDY
Project Title	Single multi-variable KPI
Project Coordinator	CIRCE FOUNDACION CIRCE CENTRO DE INVESTIGACION DE RECURSOS Y CONSUMOS ENERGETICOS jperis@fcirce.es
Project Duration	October 2022 – September 2025 (36 months)

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- PU – Public, fully open
- SEN – Sensitive, limited under the conditions of the Grant Agreement
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- Classified C-UE/EU-C – EU CONFIDENTIAL under the Commission Decision No2015/444
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Disclaimer of warranties

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Executive summary

The following study aims to characterize the impact of a wind installation through a single KPI that considers simultaneously the social, environmental, and techno-economic aspects of the project.

The KPI has been built as a weighted geometric mean of three scores, that evaluate precisely the three dimensions of a wind farm project aforementioned: social, environmental and techno-economic. Each score has been defined with their own methodology, following the insights gained in previous tasks of the WENDY project.

The social score tries to measure the potential acceptance and positive attitude of the community towards a wind farm located nearby. It studies up to six different aspects that have been identified as key drivers of social opposition: visual predominance, effect on tourism, noise, economic acceptance of the project, protection of activities based on nature and biodiversity. Each one of these features is evaluated independently and contributes to the final social score. Also, different social interventions can improve the score in these features.

The environmental score measures the impact that a wind farm has on the biodiversity of the area. The methodology relies heavily on the models for integrated life-cycle assessment on biodiversity developed in deliverable 3.1 of the WENDY project. We calculate the potentially disappeared fraction of species given by the main impacts of an operational wind farm: habitat loss, disturbance, collision, and barrier effects. We normalize this quantity by the installed power of the wind farm and obtain a final environmental score. This calculation relies on the existence of species distribution maps at European level, that we also develop in this project.

Finally, the techno-economic score intents to measure the profitability of a wind installation. The Levelized Cost of Energy, which is defined as the ratio between expenses and generated energy, is commonly used for that purpose. We collect different sources of information related to the costs of a wind farm, including the notable differences between onshore and offshore as well as differences between countries. The energy production can be estimated through the Weibull distribution of wind speed, which we can characterize for any site in Europe, and the power curve of the wind turbine considered.

The evaluation of each one of these three scores, and therefore the final KPI, has been tackled using open access data at a European level. Thus, it is immediately appliable to any location in Europe, and requires very few inputs regarding the technical specifications of the wind farm. These features of the KPI consolidate it as a very fast tool to obtain a first evaluation of the impact on a wind farm, that can then be complemented with more in-depth impact assessments.

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1. Introduction

1.1. Motivation and context

The main objective of this work is to develop a holistic assessment system for in-depth analysis of cumulative social, technical, and ecological impacts of a wind farm (WF), that could facilitate the identification of future areas of deployment.

To achieve that goal, we develop a single multi-variable key performance index (KPI) to define the general well-being of a wind farm project, summarized in a single indicator that covers the main variables that have an impact on the environment and communities.

This tool could aid to obtain an early identification of acceptable locations for a WF, without being a replacement for more in-depth assessments of social and environmental impact, or techno-economic viability.

This KPI will be deployed through a web application in the Wendy Knowledge Exchange Platform (KEP). Alongside the social interventions tool and the spatial WENDY toolbox, it belongs to an ecosystem of holistic tools for impact assessment. The tool will allow the user to place a single turbine in the map, specify the model of the turbine and ownership model of the WF, and obtain the value of the KPI associated to that WF project.

1.2. KPI summary and definition

We will develop a single KPI that summarizes the welfare of a WF project considering the predicted social acceptance, the environmental impact and its technical capabilities for energy production and performance.

The KPI will run on a limited set of user inputs:

- The location of the Wind Turbines (WT)
- Some technical specifications of the WF: height of the WTs, rotor diameter, power curve, etc.
- Additional social interventions aimed at improving its social acceptance can be implemented as boolean variables.

This input information about the WF are analyzed in three dimensions:

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- Social: We measure different factors that could provoke local opposition such as noise and visual impacts on nearby localities, tourism in the area, impact on ecological systems, economic implications of the project, etc.
- Environmental: We measure the impact that the WF will have on native species of birds and bats for onshore WFs and marine mammals and seabird for offshore.
- Techno-economic: Given the wind resources of the area, the technical specifications of the turbines and the predicted costs, we compute the Levelized Cost of Energy (LCOE), which gives us a measure of the profitability of the WF.

We summarize these three dimensions into three different scores: *S, E* and *T* (for Social Score, Environmental Score and Techno-economic Score respectively), normalized in the range [0,1] with 1 being the best score possible and 0 being the worst. We obtain the final value of the KPI as a weighted geometric mean of these three scores:

$$KPI = (S^{W_S} \times E^{W_E} \times T^{W_T})^{\frac{1}{W_S+W_E+W_T}} = \exp\left(\frac{W_S \ln S + W_E \ln E + W_T \ln T}{W_S + W_E + W_T}\right)$$

where W_S, W_E and W_T are the weights associated with the Social, Environmental and Techno-economic Scores respectively.

We do not propose value for these weights, instead we keep them as configurable parameters. Thus, they can be tuned to better fit the sensitivity and policies for each region. However, by using a geometric mean, the KPI penalizes heavily having a very low score in one of the three dimensions. In the most extreme scenario, having a score of zero in one of the three dimensions will drop the KPI to zero as well, regarding the weights.

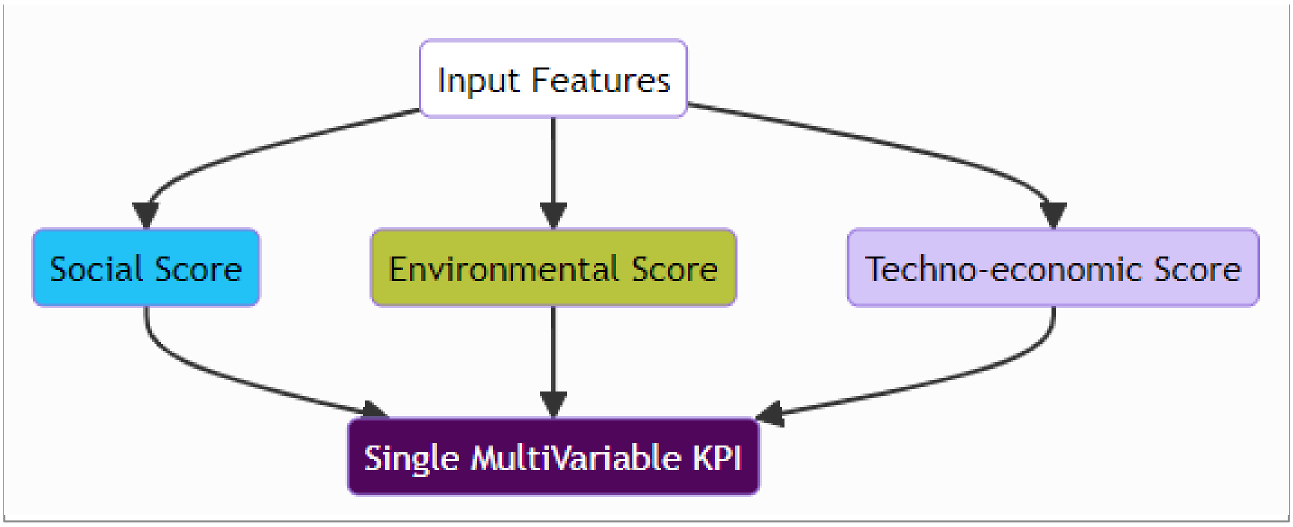

Figure 1: Schematic representation of the KPI

In the following sections we will detail the processes to obtain each one of these three scores.

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2. Social Score

In the social score S we aggregate all possible mechanisms that need to be positively solved in order to obtain a favorable WF project that can count on local support.

During work package 2 of the WENDY project, an extensive study has identified different challenges that wind farms may encounter. [1] Possible interventions that can be applied to reduce them were researched and included in the Social Intervention Acceptance (SAI) tool. [2]

Based on this previous work, we have incorporated the following aspects in the computation of the social score:

- **Visual Acceptance (V):** The local community might be concerned about the appearance of the WTs in the landscape.
- **Tourism Acceptance (T):** The WF could affect the tourism industry of the area, becoming a trigger of local opposition.
- **Noise Acceptance (N):** The low-frequency sound produced by the WT might disturb the neighbors.
- **Project Acceptance (P):** The economic implications of the project and how they are addressed need to be accepted by the community.
- **Nature Activities Protection (A):** It is imperative to protect those local activities that could depend on the nature and be affected by the WF (e.g., farming, fishing)
- **Biodiversity Protection (B):** The local community could oppose the project if the protection of the native flora and fauna is not guaranteed.

For each one of these aspects, $i \in \{V, T, N, P, A, B\}$, we will compute an initial assessment, A_i, in the range [0, 1]. The calculations of these assessments will be mainly based on the location and technical specifications of the WTs. The specific methods to address these aspects are explained in later sections.

Once we have the initial assessments of the social aspects, we can introduce different interventions to improve them. For each aspect i we assign an array of possible interventions $I_{i,j}$ where each element can take two values:

- 0 if the intervention j is not present.
- $V_{i,j}$ if the intervention j is present.

The values $V_{i,j}$ measure the impact that the intervention j will have on improving the social feature i. $V_{i,j}$ (and therefore $I_{i,j}$) will be in the range [0, 1], with 0 meaning they have no effect over the feature, and 1 meaning that the presence of that feature will automatically transform the associated aspect to its maximum value of 1. Thus, the final assessment of the social aspect A_i^* will be a function of the initial assessment, A_i, and the array of interventions $\vec{I_i}$:

$$A_i^* = f\left(A_i, \vec{I_i}\right)$$

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We introduce the interventions in the calculation of the final assessment by adding iteratively a fraction of the gap we have until reaching the perfect score of 1. The fraction we add is precisely $I_{i,j}$.
For instance, in the case of only one possible intervention ($I_{i,1}$), the final assessment A_i^* would be:

$$A_i^* = A_i + (1 - A_i)I_{i,1}$$

We have an initial assessment A_i in the range [0,1] and the remaining gap until the perfect score of 1 is $(1 - A_i)$. We add a fraction $I_{i,1}$ of that gap to the assessment of that feature.

If we add a second intervention, we add it over the result of the first one, so $A_i + (1 - A_i)I_{i,1}$ will take the place of the 'initial' assessment and we add a fraction $I_{i,2}$ of the remaining gap. We keep iterating this process until all the interventions are accounted for. It can be proved that this process does not depend on the order we are introducing the interventions.

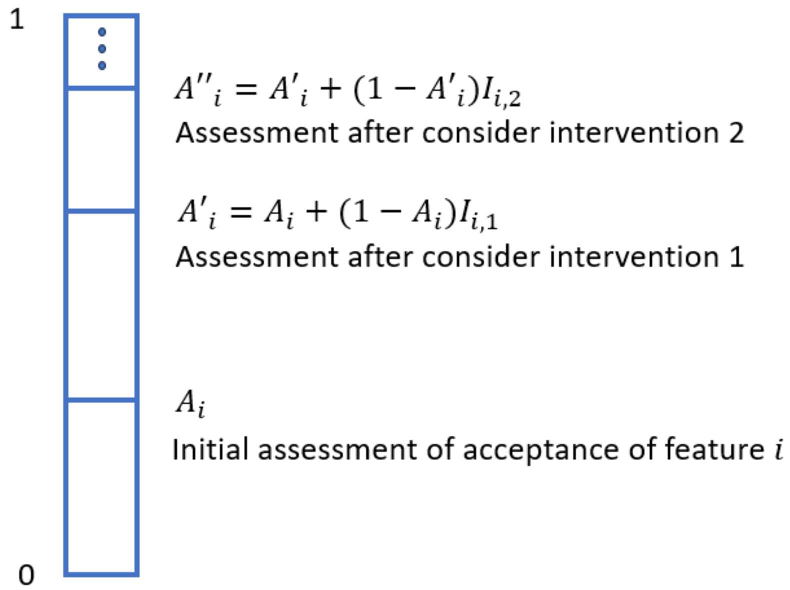

Figure 2: Schematic representation of improvements on a social feature due to interventions.

If the values associated with the interventions remain strictly below 1, the social feature will asymptotically approach the value of 1, as we add new social interventions.

The values assigned to the different social interventions play a key role in the resulting SKPI, as they can completely overturn an initial negative evaluation. Only in very few instances have we found a bibliographical reference based on which we can assign a default value of the intervention. When we are not able to find a better reference, we establish a default value of 0.5. These values remain to be tuned using expert consensus opinion, surveys and/or future studies.

Once we have all the final assessments for each social aspect, the final score will be a weighted geometric mean:

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$$S = \left(\prod_i (A_i^*)^{w_i}\right)^{\frac{1}{\sum_i w_i}}$$

where w_i are the weights considered for each social aspect. These weights also remain to be tuned in the future. For the moment, we assume the same weight for each social feature.

In the following sections, we will explain into detail the calculation of the initial assessment of each social aspect and the possible interventions that can modify them.

2.1. Visual Acceptance

2.1.1. Initial assessment

One possible risk that could motivate a strong reaction against a WF is the visual impact they cause on the landscape. A basic approach to assess the visual impact is through the visual angle [3] with the top of the wind turbine as:

$$\beta = \tan^{-1}\left(\frac{h}{L}\right)$$

where h is the height of the wind turbine and L is the distance to the observer, that we will locate on the closest populated area to the WF.

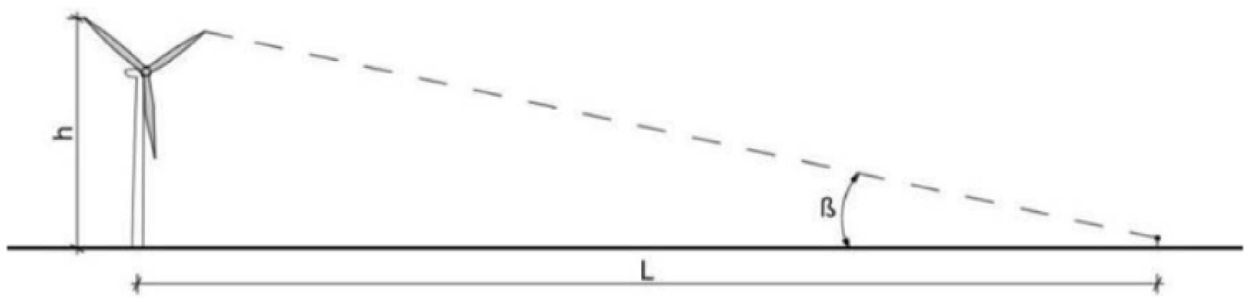

Figure 3: Definition of the β angle, taken from Abromas et al. [3]

In the same reference by Abromas et al. [3] it is assessed that:

- Up to an angle of 0.5º the visual impact is not significant.
- The WT becomes potentially visible between 0.5º and 2.5º
- From 2.5º, they become visually predominant.

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Following that progression, we modelize the visual impact using a sigmoid with maximum slope at 2.5º:

$$\text{Visual Impact } = \frac{\exp(\beta - \beta_0)}{1 + \exp(\beta - \beta_0)}$$

with $\beta_0 = 2.5º$

We transform the Visual Impact to the feature Visual Acceptance by taking 1 – Visual Impact. Thus, the initial assessment for visual acceptance will be:

$$A_V = 1 - \text{Visual Impact } = 1 - \frac{\exp(\beta - \beta_0)}{1 + \exp(\beta - \beta_0)}$$

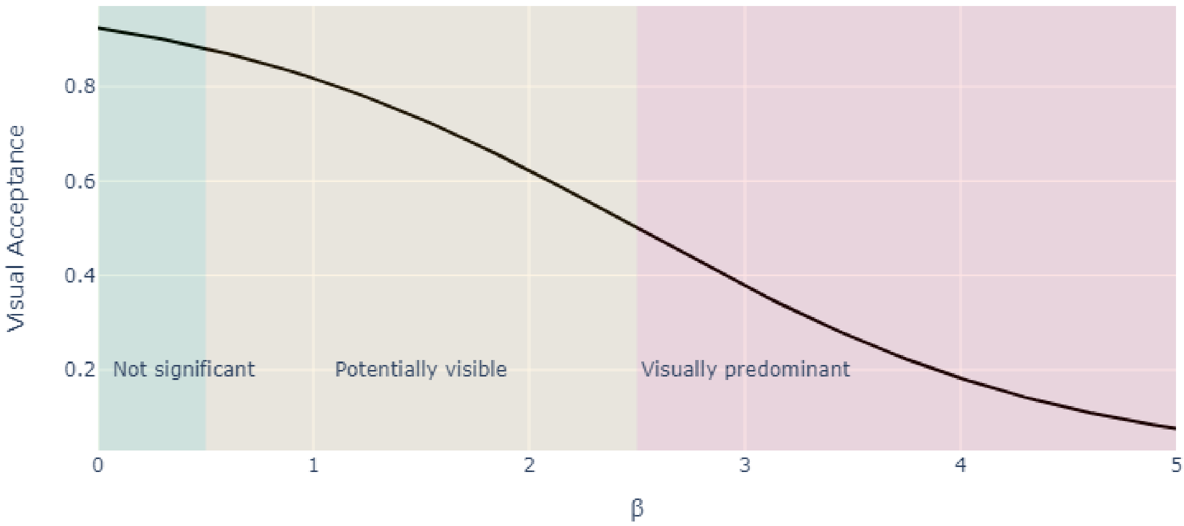

Figure 4: Visual Acceptance vs angle β

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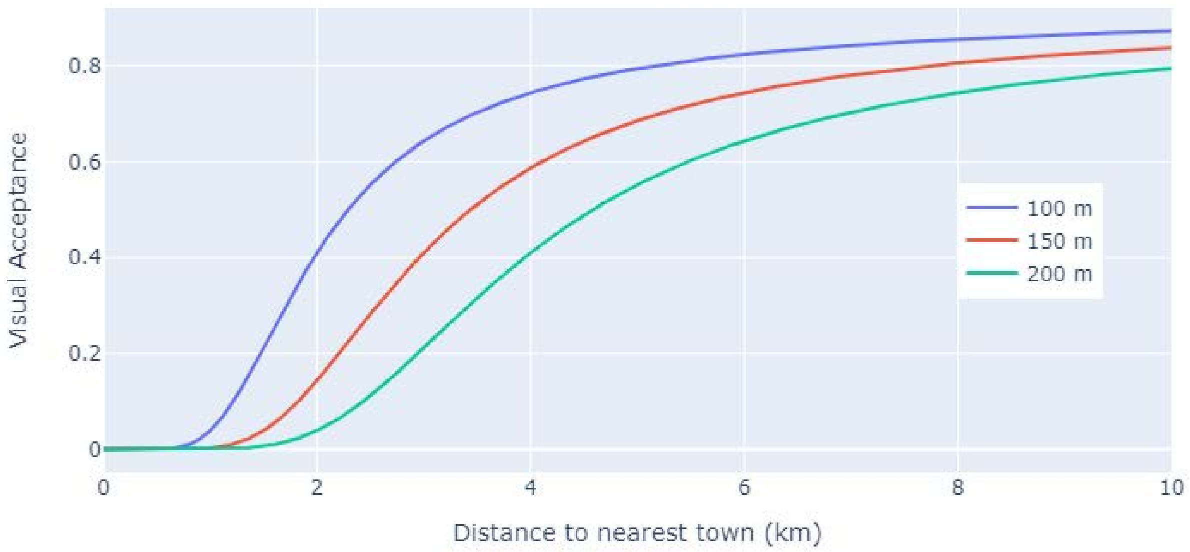

Figure 5: Visual Acceptance vs Distance for different WT heights.

Thus, the inputs we need to define this feature value are:

- Distance to the nearest town.
- Height of the WT.

The height of the WT is a technical specification that must be introduced by the user. We will obtain the distance to the closest populated zone through a query to OpenStreetMap [4], that receives as input the coordinates of the WF (this process will be explained in detail in the Data Processing Section).
We consider the geographic mean point of the WTs as the location of the WF, and we will always select the maximum height of the turbines considered.

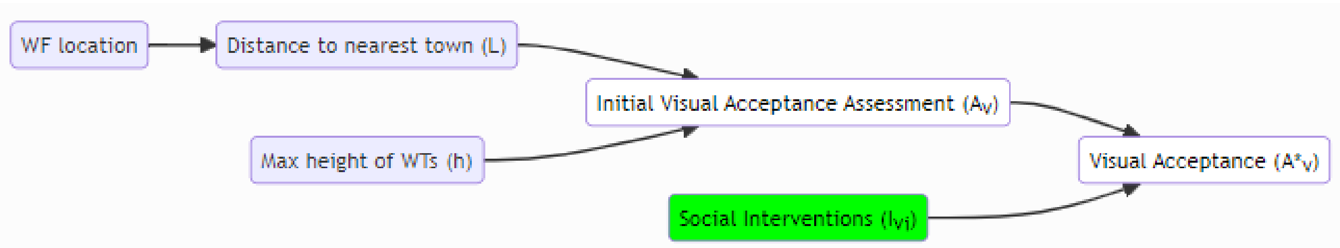

Figure 6: Schematic representation of the workflow to obtain the visual acceptance.

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2.1.2. Social interventions

As explained before; to obtain the actual final value of the visual acceptance (or any social feature), we add the social interventions. The possible interventions that we consider for this feature are:

- **Visual Impact Assessment**: Quantify visual impact by conducting visual impact assessment (VIA) using visual mapping, photography, simulation. Each land/seascape can be divided into visual units which can then be evaluated for diversity, distinctiveness, visual absorptive capacity. Set visual quality objectives to maintain scenic quality.
- **Sponsored Visits**: Developer sponsored visits to an existing wind farm (boat tour for offshore) for the local community members. This can alleviate some apprehensions, concerns about visual impact and dispel some common myths. Similarly, school trips can be organized for children.
- **Visualization Dome**: Use the simulation method of 'Visualization Dome', that has been designed to better communicate the economic, political, spatial, ecological, and social benefits of wind power plants and the associated risks to local communities.
- **Counterbalance Visual Impact**: Funding an alternative like an aesthetically pleasing physical improvement to an existing public space or create a new public space.

The following table specifies the values of $V_{V,j}$ that are assigned to each intervention j when computing the Visual Acceptance.

Table 1: Social interventions related to visual acceptance.

	Value $V_{V,j}$	Reference
Visual Impact Assessment	0.5	Default
Sponsored Visits	0.5	Default
Visualization Dome	0.57	Gawlikowska et al. [5]
Counterbalance Visual Impact	0.5	Default

2.2. Tourism Acceptance

2.2.1. Initial Assessment

Near relevant tourism sites, concerns could be raised regarding a loss in tourism activities in the area due to the proximity of a WF and its visual effect on landscape quality. [6]

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Thus, we can also use the visual impact function to measure this risk as we have done for the Visual Acceptance but locating the observer at the closest touristic site instead of the closest populated area. We can obtain the closest touristic site with a query to OpenStreetMap [4]. This search will include a wide range of location of interest: buildings such as museums or galleries, pernocting sites as hotels and apartments, wilderness areas that might attract excursionists, etc.

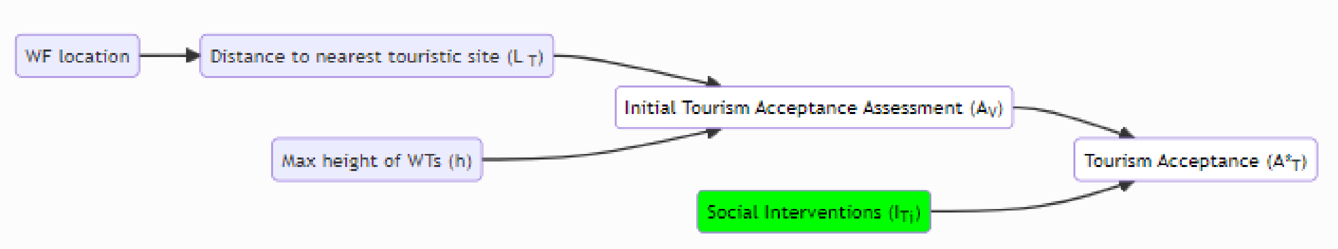

Figure 7: Schematic representation of workflow to obtain tourism acceptance.

2.2.2. Social Interventions

The social interventions that can modify Tourism Acceptance A_T differ from the interventions mentioned for Visual Acceptance:

- **T&R Impact Assessment**: Produce Tourism and Recreation (T&R) Impact Assessment to measure potential impact on tourism and recreational activities, before (baseline) and after construction of a WF, as also a longer-term impact monitoring.
- **Project as tourist destination**: The wind farm can be projected as a tourist destination in itself for those seeking educational and environmental experiences.
- **Consult Seasonal Residents**: Include tourists and seasonal residents, along with the permanent local residents in public outreach.
- **Consult Local Community**: Siting of WF in tourist, cultural, heritage sites should be done sensitively and in keeping with the suggestions of the local community.
- **Maritime Recreational Activities**: Offshore wind farms can be potential sites for developing artificial reefs, other maritime recreational activities and for coastal tourism.

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Table 2: Social interventions related to tourism acceptance.

	Value $V_{T,j}$	Reference
T&R Impact Assessment	0.5	Default
Project as tourist destination	0.5	Default
Consult Seasonal Residents	0.5	Default
Consult Local Community	0.5	Default
Maritime Recreational Activities	0.5	Default

2.3. Noise Acceptance

2.3.1. Initial assessment

Noise disturbance is always a major concern regarding a WF installation.

Similarly to visual impact, the noise that will reach the population will mostly depend on the distance. We assume a simple formula developed by the Swedish Environmental Protection Agency [7]:

$$L_p = L_w - 8 - 20\log(r) - \alpha r$$

where α is the absorption coefficient, r is the distance and L_w is the sound level at source.

The absorption coefficient depends on the frequency of the sound, the temperature, and the relative humidity. At 10ºC and a relative humidity in the range of 20-80%, for low frequency sounds (of about 100 Hz, similar to the range of a WT), the absorption coefficient could be of about 0.5 dB/km, which is the value we will consider. A possible extension of this work would be to extend the calculation using the meteorological conditions of the area.

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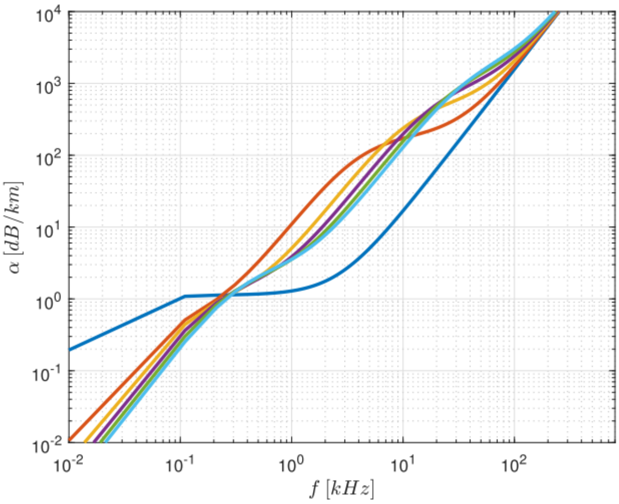

FIGURE 1.2. Value of the atmospheric absorption coefficient at different frequencies evaluated for five different levels of relative humidity, r_h, for a constant temperature of 10°C and pressure of 1 atm. Blue: $r_h = 0\%$, red: $r_h = 20\%$, yellow: $r_h = 40\%$, purple: $r_h = 60\%$, green: $r_h = 80\%$ and cyan: $r_h = 100\%$.

Figure 8: Absorption coefficient values [7].

The value of L_w is a technical specification of the WT that we will need to introduce as an input. It is usually around 100 dB [8]. Using the formula, we can obtain the noise level as a function of the distance:

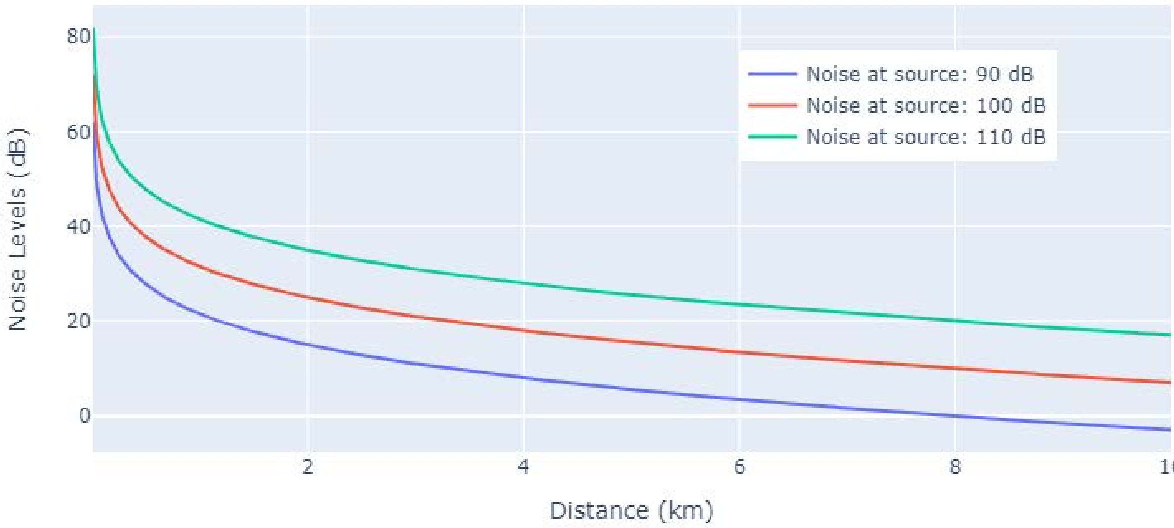

Figure 9: Noise level vs. distance for three different levels of noise generated at source.

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In the case of having multiple sources (i.e. multiple turbines), we calculate the different noise levels ($L_1, L_2, \dots$) for each one, with the distance always referring to the same geographical point (i.e. the closest populated area). Then, we add the levels using the following formula [9]:

$$L_p = 10 \times \log_{10}\left(10^{L_1/10} + 10^{L_2/10} + \cdots\right)$$

We transform the sound levels into a measure of noise acceptance using the following sigmoid formula:

$$A_N = 1 - \frac{\exp\left(k\left(L_p - L_{p0}\right)\right)}{1 + \exp\left(k\left(L_p - L_{p0}\right)\right)}$$

We place L_{p0} at 35 dB (meaning that at 35 dB the noise acceptance is 0.5) and a $k = 0.2$. Using this value for k, at 20dB (the level of a ticking watch) the noise acceptance will be 0.95, while at 50 dB (the level of moderate rainfall, which is clearly audible) it will be around 0.05. These values make quantitatively sense, as below 25 dB there are no sleep disturbance (see figure below by Radun et al. [10]), so assuming a negligible risk is coherent while above 50 dB the impact on health is evident and has to be addressed, thus the nearly zero value for noise acceptance that will lower considerably the social score.

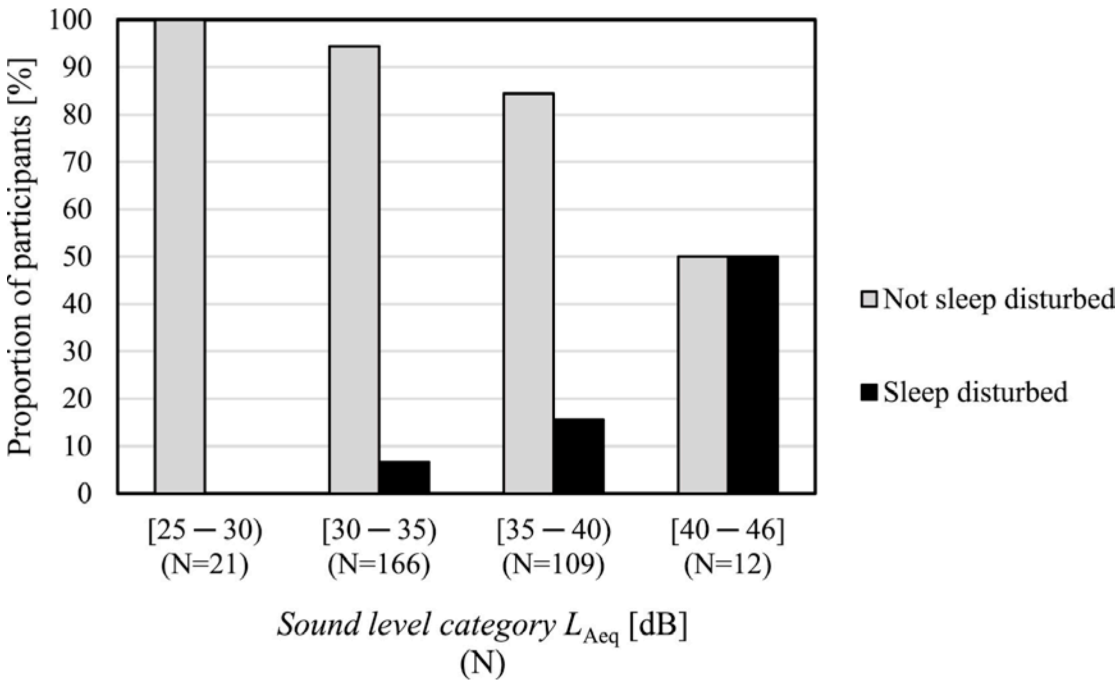

Figure 10: Sleep disturbance caused at various noise levels [10]

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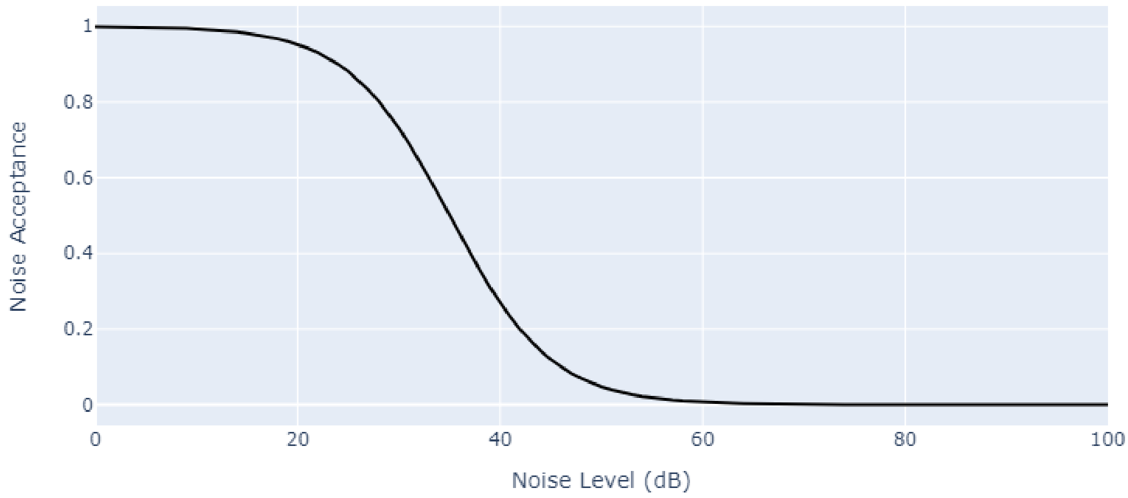

Figure 11: Noise Acceptance as a function of the sound level.

We can finally obtain the noise acceptance as a function of the distance to the closest populated area:

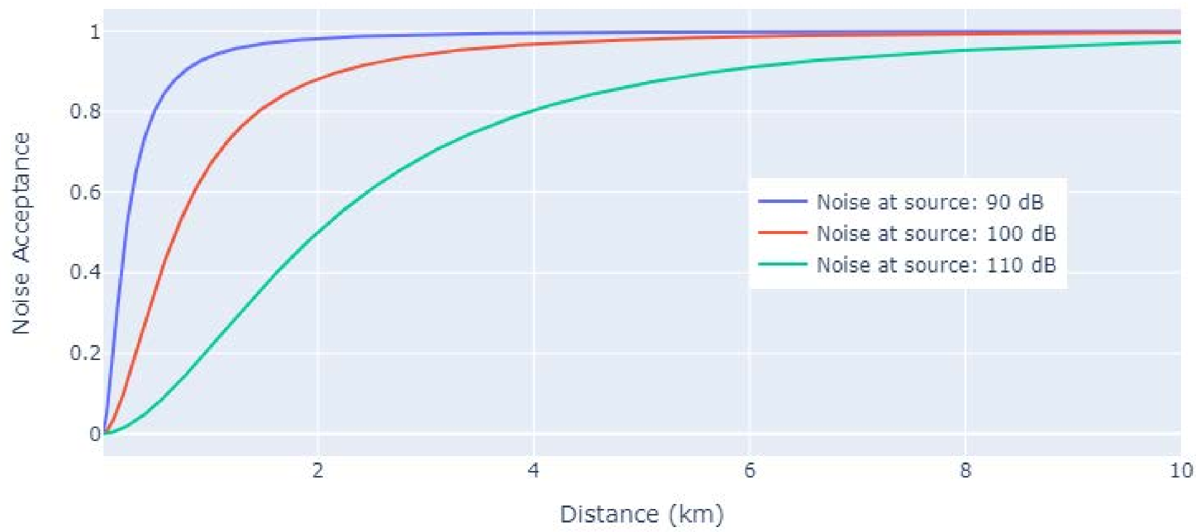

Figure 12: Noise Acceptance vs. distance for three different levels of noise at source.

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The sound level at source is a technical specification of the turbine that we will need to know in order to compute this social feature. The distance to the closest populated location is taken as we did for Visual Acceptance.

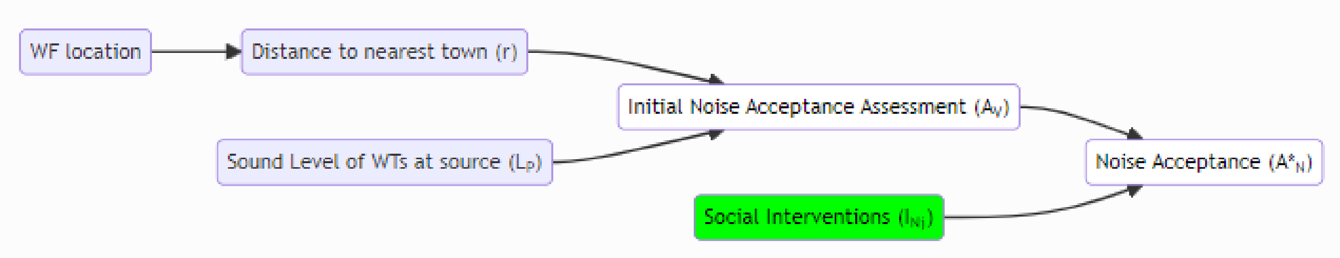

Figure 13: Schematic representation of workflow to obtain noise acceptance.

2.3.2. Social interventions

The social interventions that can raise Noise Acceptance are:

- **Noise Impact Assessment**: WT noise measurement should include both objective (sound pressure levels, distance to WTs, number of visible turbines, wind direction, weather conditions) and subjective measures (attitude towards WT, noise sensitivity, perceptions about wind project). Developers and planners would benefit by using the noise-annoyance-stress (NAS) scale.
- **Noise Information**: Inclusive and participatory planning process, with transparency about both positive and negative effects of WTs (e.g., noise, visual impact). Provide residents clear, factual information about wind power and the WT building process to counter psychological bias.
- **Noise Demonstration Kit**: Develop a noise-demonstration kit so that the local community members can be given an audio demonstration of WT noise under varying conditions, through special headsets.
- **Visualization Dome**: Also used for Visual Acceptance
- **Noise Damping Panels**: Install noise-damping panels to increase insulation against infrasound.

Table 3: Social interventions related to noise acceptance.

	Value $V_{N,j}$	Reference
Noise Impact Assessment	0.5	Default
Noise Information	0.5	Default
Noise Demonstration Kit	0.5	Default

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Visualization Dome	0.57	Gawlikowska et al. [5]
Noise Damping Panels	0.5	Default

2.4. Project Acceptance

2.4.1. Initial assessment

Independently of possible specific objective impacts as the previously discussed, we could have a different predisposition in the community to embrace a wind farm project based on their own biases and beliefs. For instance, it is well known that age reduces the acceptance [11]. Specifically, opposition raises abruptly among individuals older than 60 years old [11].

Thus, we calculate an initial predisposition to the project using as input the percentage of senior population in the community. We extract this information from Eurostat [12], using the data of the NUTS-3 region where the wind farm is located. The initial predisposition is given by:

$$\text{Initial Predisposition} = 1 - \frac{\exp\big(k(x - x_0)\big)}{1 + \exp\big(k(x - x_0)\big)}$$

with x being the percentage of senior population and fixing the sigmoid parameters at $x_0 = 25\%$ and $k = 0.20$.

Besides, social ownership models might enjoy a level of acceptance by default in comparison with corporate or even hybrid models. Thus, we multiply this initial predisposition by 1 in the case of a social model, 0.70 in the case of hybrid and 0.41 to corporate. We have chosen for the acceptance of corporate ownerships being a 41% with respect of the social model based on the estimation that 41% of people don't trust energy suppliers [13].

$$A_P = \text{Initial Predisposition} \times \text{Economic Factor}$$

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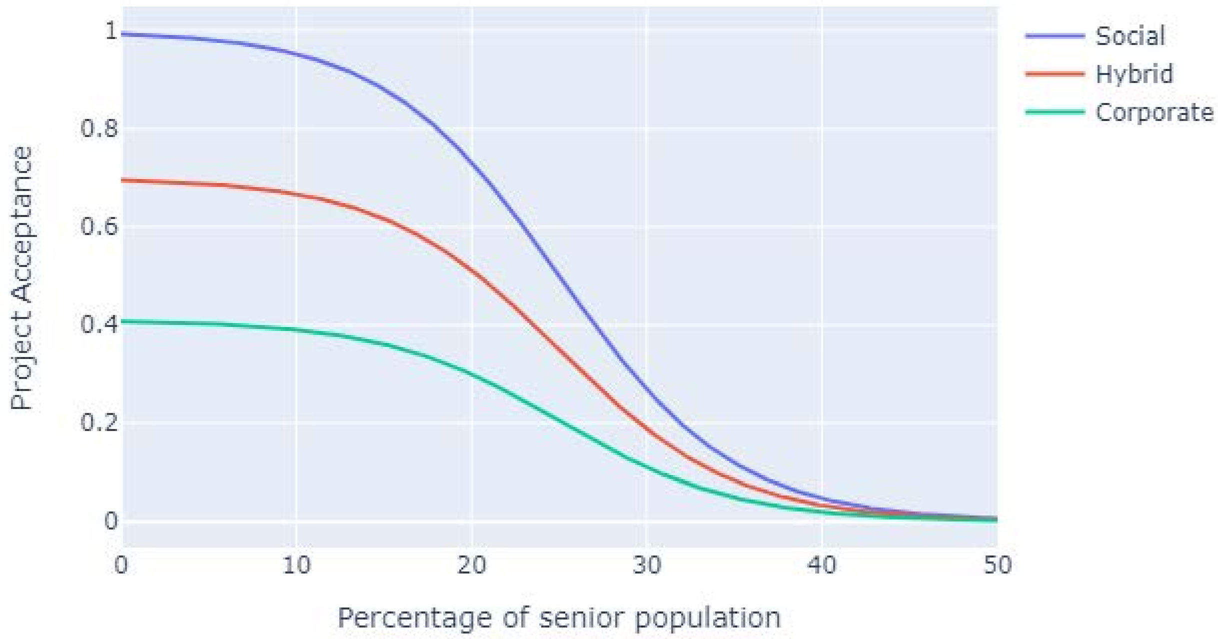

Figure 14: Initial Assessment of Project Acceptance vs Percentage of Senior Population

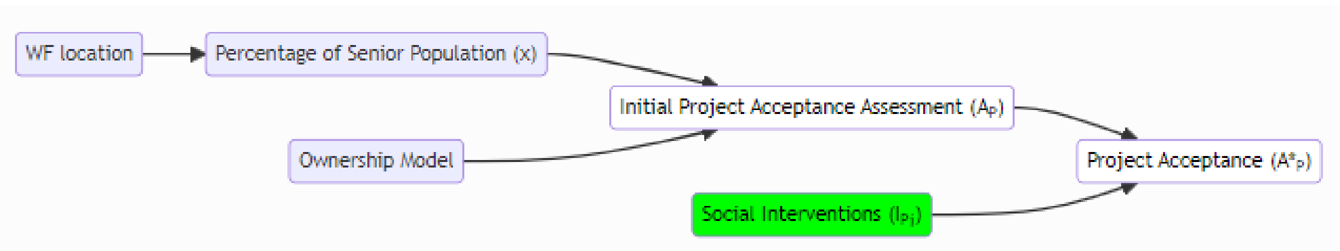

Figure 15: Schematic representation of workflow to obtain Project Acceptance.

2.4.2. Social interventions

There are several social interventions designed to outreach the public and engage the community that can improve substantially this initial assessment:

- **Information about electricity infrastructure**: Share information about the electricity infrastructure and whether the generated electricity would benefit the local community.

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- **Future Energy Plans**: Discuss the country/region's current and future energy plans to highlight the need and motivation to move to wind energy (WE). Both positive and negative aspects of WE should be discussed transparently.
- **Public Reports**: Produce regular publicly available monitoring reports on the project and its socio-economic impacts at the local, regional level.
- **Community Engagement Plan**: Creation of a Community Engagement Plan (CEP), that outlines engagement activities, key stakeholders, engagement strategies and monitoring, timetable, …
- **Consult Community Needs**: Local citizens should be consulted and be allowed to participate in designing of community benefits/compensation schemes to align them with their needs.
- **Local Liaison Officer**: Appoint a 'local community liaison officer' to engage with community throughout the project life-cycle.
- **Survey Impacts**: Survey community views of development impacts at key stages in the project lifecycle, including focus on key impacted groups.
- **Local Jobs and Training Opportunities**: Plan for local job creation and estimate direct and indirect jobs created. Local rms can be employed for planning, construction and maintenance services, regional/local banks and regional/local energy supply companies can be employed. Additionally, can contribute towards new educational and training opportunities.
- **Institutionalize Community Benefits**: It is suggested that community compensation measures be institutionalized, be more prescriptive instead of being ad-hoc and voluntary, as this will help build trust and remove the negative connotations associated with such compensation. Such institutionalization should also allow for discussion between communities and developers regarding the type and amount of compensation.
- **Community Development Fund**: Establish a long term/annual community development fund (CDF), administered by the local community, to finance local development projects.

Table 4: Social interventions related to project acceptance.

	Value $V_{P,j}$	Reference
Information about infrastructure	0.5	Default
Future Energy Plans	0.5	Default
Public Reports	0.5	Default
Community Engagement Plan	0.5	Default
Consult Community Needs	0.83	Gebreslassie et al. [14]
Local Liaison Officer	0.5	Default
Survey Impacts	0.5	Default
Local Jobs and Training Opportunities	0.5	Default
Institutionalize Community Benefits	0.5	Default
Community Development Fund	0.5	Default

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2.5. Nature Activities Protection

2.5.1. Initial Assessment

In communities where livelihoods are dependent on nature (e.g. farming, fishing), there is an additional source of potential discontent as people perceive that their lifestyles are put in danger.

This feature assesses that risk, by using as an input the percentage of land used in agricultural and rural activities in the vicinity of a WF. We can compute this value through a query to OpenStreetMap [4], using a bounding box around the WF location with a distance to the corner of 4km.

Once we have this input, we define the Nature Activities Protection with a linear function that reaches 0 at 40% (which is approximately the percentage of cultivation land in Europe) [15]

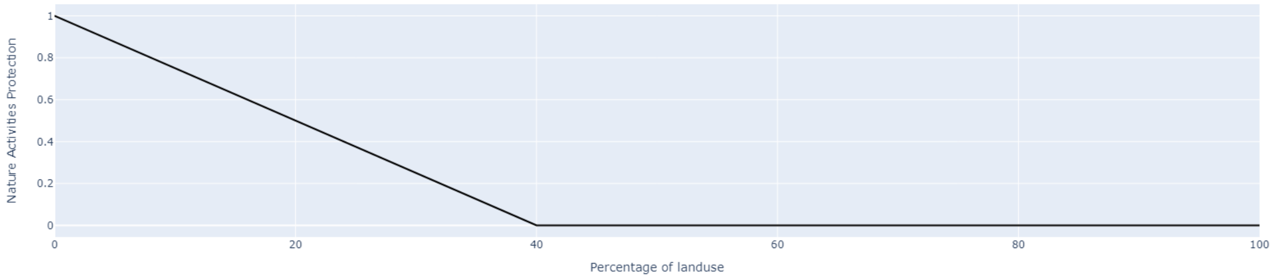

Figure 16: Initial Assessment of Nature Activities Protection vs Percentage of Landuse

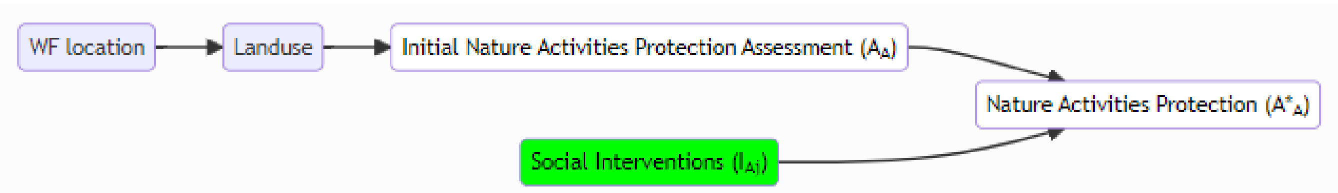

Figure 17: Schematic representation of workflow to obtain Nature Activities Protection

This assessment for Nature Activities Protection is only valid for onshore WFs. In the offshore case we will ignore this feature. A possible extension to incorporate offshore WFs would be to replicate this approach using fishing activities instead.

2.5.2. Social interventions

For this feature we only consider one possible intervention:

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- **Support economic nature-dependent activities:** Strengthen the benefits in communities where livelihoods depend on nature (e.g. farming, fishing), support such livelihoods and offer land-tenure security.

Table 5: Social interventions related to nature activities protection.

	Value $V_{A,j}$	Reference
Support economic nature-dependent activities	0.5	Default

2.6. Biodiversity Protection

2.6.1. Initial assessment

Local opposition, specially from ecologist groups could arise in areas with a particularly rich biodiversity in terms of birds and bats species (or marine mammals in the case of offshore).

We can obtain global raster maps with a 10 km^2 resolution with the number of species of birds and bats from Biodiversity Mapping [16]. We will analyze separately the number of bird and bats species, and then combine them into a unique Biodiversity Protection assessment for onshore WFs. In the case of offshore, we consider seabirds and marine mammals.

In the case of birds, we found the following distribution for bird richness (i.e. the number of bird species) at each different grid cell across Europe:

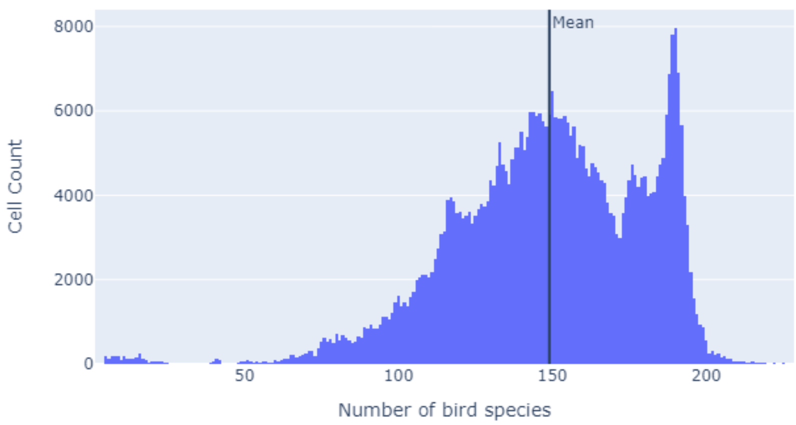

Figure 18: Distribution of number of bird species in 10 km x 10 km grid cells across Europe.

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Then, using the number of bird species as an input, we assign a bird protection score as:

$$\text{Bird Score } = \frac{1}{1 + \exp\left(k_{\text{birds}}\left(n_{\text{birds}} - n_{0,\text{birds}}\right)\right)}$$

with n_{birds} being the number of bird species in the vicinity of the WF and setting the parameters as $n_{0,\text{birds}} = 175$ and $k_{\text{birds}} = 0.04$.

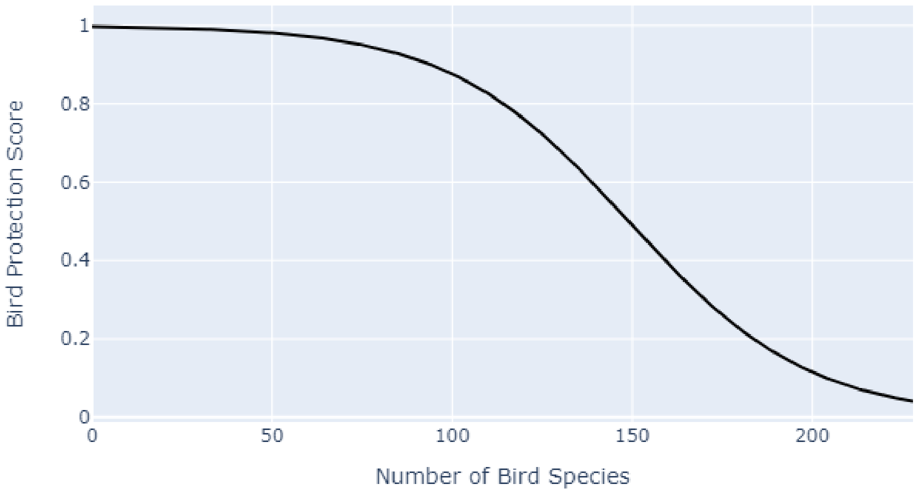

Figure 19: Bird Protection Score vs Number of Bird Species near a WF.

We repeat the same procedures for bats. The distribution of bat richness is:

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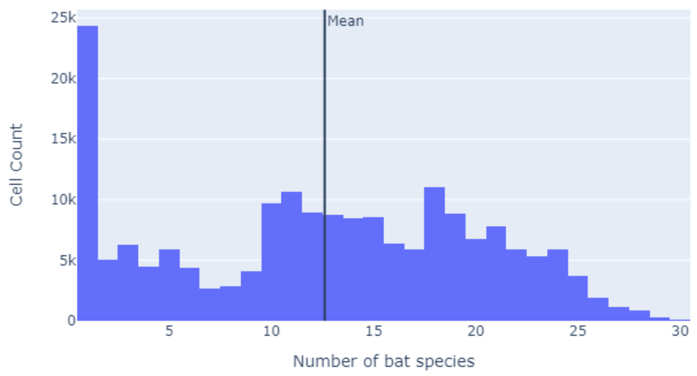

Figure 20: Distribution of bat species in 10 km x 10 km grid cells across Europe.

and we can apply an analogous formula to obtain the Bat Protection Score:

$$\text{Bat Score} = \frac{1}{1 + \exp\left(k_{\text{bats}}\left(n_{\text{bats}} - n_{0,\text{bats}}\right)\right)}$$

where $n_{0,\text{bats}} = 15$ and $k_{\text{bats}} = 0.3$, giving the following shape:

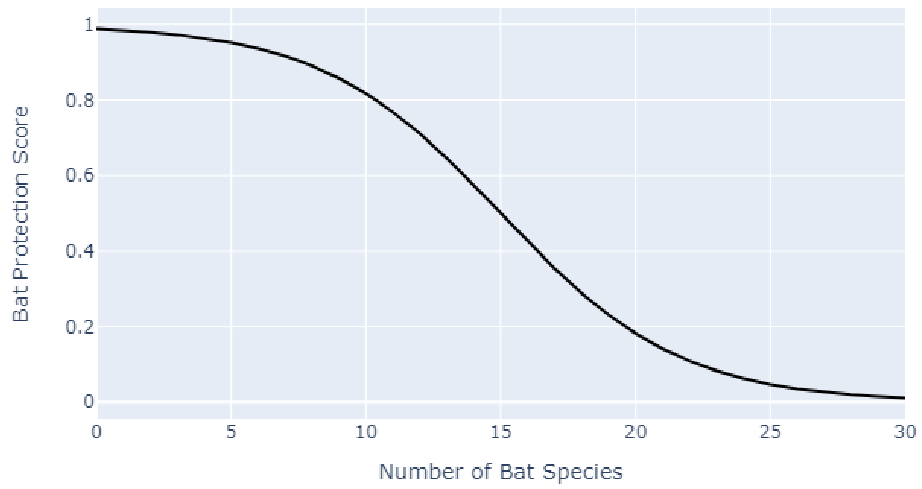

Figure 21: Bat Protection Score vs Number of Bat Species near a WF.

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The final initial assessment of biodiversity protection, A_B, is given by the product of both:

$$A_B = \text{Bird Score} \times \text{Bat Score}$$

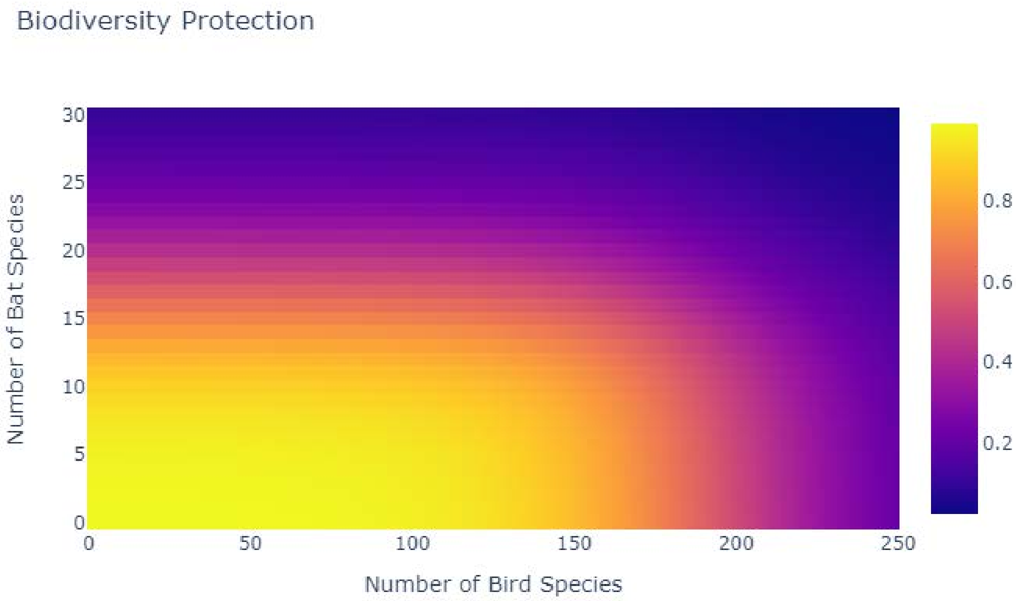

Figure 22: Heatmap of A_B (onshore) for different numbers of species of birds and bats.

Thus, the inputs required for the initial assessment of biodiversity protection are the number of bird species and the number of bat species. We obtain these values by drawing a circle of 10km around the WF and computing the average species richness from the maps from Biodiversity Mapping [16].

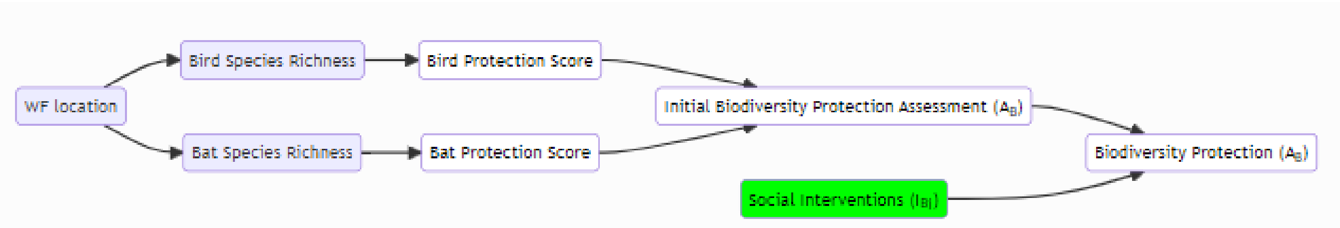

Figure 23: Schematic representation of workflow to obtain biodiversity protection (onshore).

For offshore, we replicate the same procedure but replacing birds and bats by marine mammals and seabirds:

$$A_B = \text{Marine Mammal Score} \times \text{Seabird Score}$$

with:

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$$\text{Marine Mammal Score} = \frac{1}{1+\exp\left(k_{\text{marine mammals}}\left(n_{\text{marine mammals}} - n_{0,\text{marine mammals}}\right)\right)}$$

being $n_{\text{marine mammals}}$ the number of marine mammal species in the area, $n_{0,\text{marine mammals}} = 12$ and $k_{\text{marine mammals}} = 0.4$, and:

$$\text{Seabird Score} = \frac{1}{1+\exp\left(k_{\text{seabirds}}\left(n_{\text{seabirds}} - n_{0,\text{seabirds}}\right)\right)}$$

being n_{seabirds} the number of seabird species in the area, $n_{0,\text{seabirds}} = 9$ and $k_{\text{seabirds}} = 0.5$, which give us the following heatmap for biodiversity protection in the offshore case:

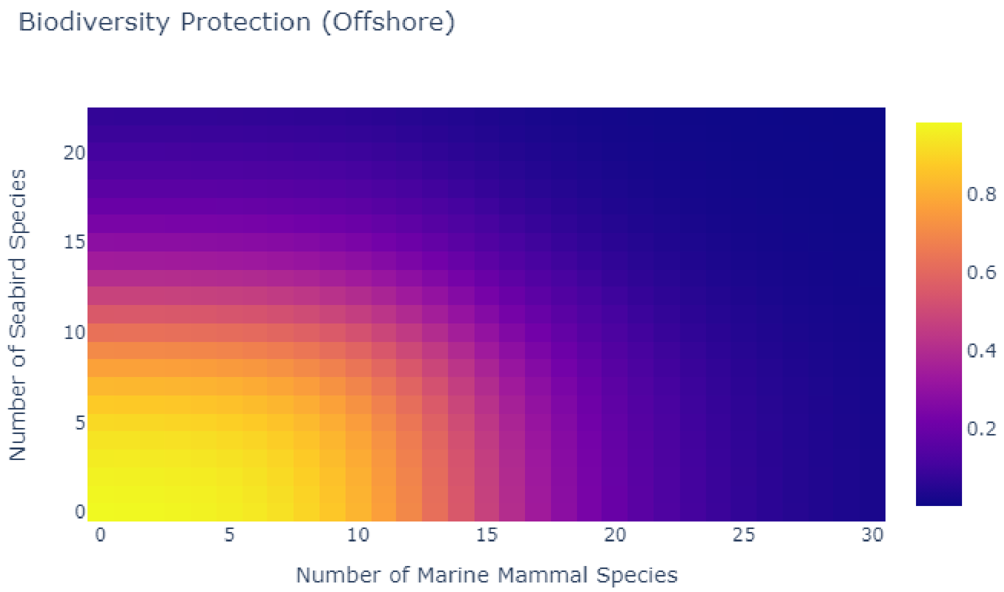

Figure 24: Heatmap of A_B (offshore) for numbers of species of marine mammals and seabirds.

2.6.2. Social Interventions

Several interventions can be implemented to protect the avifauna and thus mitigating social opposition:

- **Sensitivity Mapping Assessments**: Conduct sensitivity mapping assessments to determine baseline number of birds/bats during an annual cycle.
- **Air Bubble Curtain Technique**: Use noise mitigation measures like the air bubble curtain technique, in combination with other measures like Hydro Sound Damper, Cofferdam.

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- **Buffer Zones**: Create buffer zones around wildlife specific regions (forests, swamps, caves)
- **Avoid Sensitive Periods**: Time construction to avoid sensitive periods (roosting, migration, breeding).
- **On-site ecologist**: Employ an on-site ecologist during construction.
- **Remote Sensing**: Use remote sensing (e.g. radar, thermal animal detection system, TADS) to monitor bird/bat fatalities.
- **Redevelop vegetation**: Redeveloping vegetation in areas surrounding WTs, using locally indigenous plants.

Table 6: Social interventions related to biodiversity protection.

	Value $V_{B,j}$	Reference
Sensitivity Mapping Assessments	0.5	Default
Air Bubble Curtain Technique	0.5	Default
Buffer Zones	0.5	Default
Avoid Sensitive Periods	0.5	Default
On-site ecologist	0.5	Default
Remote Sensing	0.5	Default
Redevelop vegetation	0.5	Default

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3. Environmental Score

3.1. Definition

A conceptual framework to integrate biodiversity and ecosystem service assessments (ESA) into a life-cycle assessments was established in WENDY Deliverable 3.1 [17], both for onshore and offshore wind energy.

We capitalize on that knowledge in the definition of the environmental score, which aims to measure the impact to biodiversity caused by the wind farm during the operational phase.

For biodiversity, endpoint impacts quantify the changes in (often the loss of) species richness and thus refer to the intrinsic value of biodiversity. This is usually quantified as the potentially disappeared fraction (PDF) of species, which describe the loss of species richness following impacts which cause the loss of suitable habitat [18].

PDF is a relative measure of the potential loss of species richness from a reduction in the area available at a given cell i ($A_{\text{new},\,i} = A_{\text{original},\,i} - A_{\text{lost},\,i}$) using the classical species-area relationships (SAR) [19].

We distinguish four impact pathways from which we can obtain a loss in species richness:

- Habitat Loss (H)
- Disturbance (D)
- Collisions (C)
- Barrier Effects (B)

Let a wind farm f have wind turbines $w = (1, \dots, l_f)$. For each impact pathway X in functional group of species k, each turbine w will occupy a zone with area $A(X)_{\text{lost},\,k,f,w}$ in the shape of a circle with center in the coordinates of the turbine. The total area lost for the entire farm $A(X)_{\text{lost},\,k,f}$ will be the area of the union of circles for the different turbines. The area lost at a particular cell i, $A(X)_{\text{lost},\,k,f,i}$ will be the intersection of the total area lost for the entire farm and the cell. Then, the PDF for the group of species k at cell i can be estimated as:

$$\text{PDF}(X)_{k,f,i} = \frac{S_{k,i}\left(1 - \left(\frac{A_{\text{original},\,i} - A(X)_{\text{lost},\,k,f,i}}{A_{\text{original},\,i}}\right)^{z}\right)}{\sum_{i=1}^{n} S_{k,i}}$$

where the exponent z is taken to be 0.21 (95% CI = [0.19, 0.22]) or 0.26 (95% CI = [0.24, 0.27]), the continental-scale SAR estimate for, respectively, birds and mammals in Eurasia [20] and $X \in \{H, D, C, B\}$ indicating the pathway mechanism. $S_{k,i}$ indicates the richness at cell i of species group k, which would be taken as:

- The sum of species probability distribution maps for all species in group k, for pathways H, D and C.

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- The sum of species connectivity maps for all species in group k, for pathway B.

We can find details on how to build these species richness maps in the Data Processing section of this report.

The final PDF for a wind farm f at group k is the sum of the cell-wise PDFs:

$$\mathrm{PDF}(X)_{k,f} = \sum_i \mathrm{PDF}(X)_{k,f,i}$$

,to obtain the final PDF for pathway X we sum across all functional groups:

$$\mathrm{PDF}(X)_f = \sum_k \mathrm{PDF}(X)_{k,f}$$

and to obtain the final PDF of the farm, we sum across the impact pathways:

$$\mathrm{PDF}_f = \sum_X \mathrm{PDF}(X)_f$$

PDF_f quantifies the total impact of a wind farm f on the functional groups of species included in the analysis. For computational purposes, as the maps we include contain the whole continent of Europe, instead of using the sum of all cells' raster values in the denominator of the $\mathrm{PDF}(X)_{k,f,i}$ definition, we use the average. This simply results in a multiplication by the number of cells (n) in the final result:

$$\mathrm{PDF}_f^* = n \times \mathrm{PDF}_f$$

We normalize the PDF^* by the installed power in the farm P_f, thus obtaining a measure of biodiversity impact per installed MW.

Finally, we need to transform this measure of biodiversity impact, into our final environmental score that lies in the range [0,1]. We will detail later how we obtain the function to do this transformation:

$$\text{Environmental Score} = \mathrm{f}\left({\mathrm{PDF}_f^*}/{P_f}\right)$$

We have limited the environmental score to the impact in biodiversity, without including the ecosystem services. The framework to assess the impact in ecosystem services has been developed in deliverable 3.1 of WENDY project [17]. It requires that the stakeholders map the site first, thus surpassing the scope of the multivariable KPI that was constrained to a fast indicator that is immediately applicable to any location in Europe with a minimal set of inputs.

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3.2. Impact Pathways

In the following subsections we will detail the calculations of the different impact pathways considered for the definition of the environmental score.

3.2.1. Habitat Loss

Habitat loss for birds and bats onshore is determined by the area required for the foundation of a turbine and the surrounding infrastructure, which increases with the power capacity of the turbine [21]. The directly impacted area (permanent changes) has been found to be 0.003 km^2/MW (95% CI = [0.0026, 0.0033]) [22]. The area lost to each wind turbine can then be given as:

$$A(H)_{\text{lost},k,f,w} = a_{EP} EP_w$$

where a_{EP} is precisely this value for direct impact (0.003 km^2/MW) and EP_w is the electric power of wind turbine w [21].

In the case of offshore wind turbines, we should consider here the area of the foundation. There exist many different types of foundation for offshore wind turbines (monopile, gravity based, etc.), but as a first approximation we consider the same relation with the MW capacity used onshore.

3.2.2. Disturbance

In addition to the habitat loss, a species may be deterred from using a larger area surrounding each wind turbine due to disturbance effects. The strength of this effect may vary between species. We quantify the avoidance effect by the disturbance distance (d) for each functional group (in km). This disturbance distance can be obtained from the literature for birds and bats, and will be estimated based on the effect of the noise emitted from the wind turbines for marine mammals.

3.2.2.1. Disturbance onshore

For birds onshore and offshore, flight initiation distance obtained from the literature were used as a measure of the disturbance distance for each functional group (all sources are provided in the full data set by May et al. [21]). For bats we find disturbance distances at Leroux et al. [23].

In any case, the area lost to each wind turbine due to disturbance is given by:

$$A(D)_{\text{lost},k,f,w} = \pi \left(D_k d_{k,\max} \right)^2$$

Here, $d_{k,\max}$ is the maximum disturbance distance in meters and D_k is the disturbance factor.

These are the parameters considered for birds:

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Table 7: Disturbance related parameters for each functional group of birds

Functional Group	D_k	$d_{k,\max}$ (m)	Order reference
Corvids	0.109	120	Passeriformes
Gallinaceous birds	0.089	500	Charadriiformes
Gulls	0.089	500	Charadriiformes
Herbivorous songbirds	0.109	120	Passeriformes
Insectivorous songbirds	0.109	120	Passeriformes
Non-passerines	0.557	38	Coraciiformes
Owls	0.284	55	Strigiformes
Polyphagous songbirds	0.109	120	Passeriformes
Raptors	0.189	476	Accipitriformes
Seabirds	0.089	500	Charadriiformes
Waders	0.089	500	Charadriiformes
Waterbirds	0.307	108	Gruiformes
Waterfowl	0.151	500	Anseriformes

These values are obtained from the supplementary material from May et al. [21], considering the most common taxonomic order within the species of a functional group.

For bats, according to Leroux et al. [23], we consider a disturbance distance (i.e. the product of D_k and $d_{k,\max}$) of 100 meters for Short-Range and Long-Range Echolocators, and 43 meters for Mid-Range Echolocators.

3.2.2.2. Disturbance offshore

For marine mammals, disturbance is caused by the underwater noise generated by operating wind turbines. We select a disturbance radius (in km) with the formula:

$$d = 0.1 \times 10^{\frac{L(p)+W(f)-\text{threshold}}{\kappa}}$$

The threshold in this formula is selected at 120 dB as defined by the National Oceanic Atmospheric Administration (NOAA) [24].

$L(p)$ is the sound pressure emitted by a turbine of power p given by [25]:

$$L(p) = \delta + \alpha \log_{10}\left(\frac{l}{100m}\right) + \beta \log_{10}\left(\frac{w}{10m/s}\right) + \gamma \log_{10}\left(\frac{p}{1MW}\right)$$

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with $\delta = 109, \alpha = -23.7, \beta = 18.5$ and $\gamma = 13.6$. l is the distance to the source that will be initially fixed at 100 meters, and w is the wind speed, fixed at 10 m/s.

$W(f)$ is the weighting auditory frequency function given by [26]:

$$W(f) = C + 10\log_{10}\left(\frac{\left(f/f_1\right)^{2a}}{\left(1+\left(f/f_1\right)^2\right)^a\left(1+\left(f/f_2\right)^2\right)^b}\right)$$

where the parameters C, f_1, f_2, a and b depends on the functional group, according to the following table:

Table 8: Disturbance related parameters for marine mammals' functional groups

Functional Group	f_1	f_2	a	b	C(dB)
LF	0.20	19	1.0	2.0	0.13
HF	8.80	110	1.6	2.0	1.20
VHF	12.00	140	1.8	2.0	1.36
PCW	1.90	30	1.0	2.0	0.75
OCW	0.94	25	2.0	2.0	0.64

We evaluate the weight of the frequency for a fixed value of 0.400 kHz that is audible for most marine mammals. Finally, the parameter κ is set at 23.7 as found by Tougard et al. [25]

3.2.3. Collision

Species of birds and bats which utilize the area within the rotor swept zone around each wind turbine have a risk for collision both onshore and offshore. Species-specific estimates of Poisson-distributed collision rates with lower and upper 95% credible intervals were collected from Table S4 by Thaxter et al. [27]. The collision rates for all species where then used to estimate the probability of at least one collision occurring per year (R_k) by $R_k = 1 - e^{-\text{rate}_k}$ where rate_k is the average collision rate for group k. The area lost to each wind turbine for collision effects can then be given as:

$$A(C)_{\text{lost}, k,f,w} = R_k \pi r_{f,w}^2$$

where $r_{f,w}^2$ is one-half the rotor diameter (in km) [21]

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For offshore turbines we only consider the functional groups of birds associated with marine biodiversity.

Table 9: Collision rates for functional groups of birds and bats.

Functional Group	rate_k
Corvids	0.056
Gallinaceous birds	0.042
Gulls	0.069
Herbivorous songbirds	0.032
Insectivorous songbirds	0.039
Non-passerines	0.039
Owls	0.035
Polyphagous songbirds	0.042
Raptors	0.099
Seabirds	0.048
Waders	0.043
Waterbirds	0.039
Waterfowl	0.031
SRE	0.105
MRE	1.016
LRE	0.508

Collision rates for each species of bird have been obtained from May et al. [21] and averaged for each functional group. Data on bats were collected from Thaxter et al. [27], also at a species-level, and then averaged over the functional groups we are considering.

3.2.4. Barrier Effect

Wind farms may cause a barrier effect, resulting in an increase in travel distance for migrating animals that avoid going through the disturbed area [28]. Barrier effects are quantified using the method developed in May et al. [29], where the increase in energetic expenditure is proportional to the disturbance caused by building a wind turbine at a given site. The total energy requirement for migration (M_k) in group k is quantified based on the energetic requirement (a_k) per km travelled and the distance travelled per season (l_k) multiplied by 2 to account for spring and autumn migration, $M_k = 2a_k l_k$. The

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area of impact for each wind turbine is equal to the disturbance area multiplied by the total energy requirement for migration [29]:

$$A(B)_{\text{lost},\,k,f,w} = M_k A(D)_{\text{lost},k,f,w}$$

This area is evaluated over the connectivity maps instead of the species richness maps when calculating the associated PDF.

Somveille et al. [30] calculated a formula of the energy requirement per km as a function of the mass:

$$a = 6.07 \times 10^{-5} m^{-0.01}$$

where m is the body mass in kg.

For bats we can obtain an analogous formula:

$$a = 1.79 \times 10^{-4} m^{0.013}$$

Data on mass can be obtained for birds in Tobias et al. [31] and for bats in Froidevaux et al. [32] while data on migration distances can be obtained from Vincze et al. [33] and Froidevaux et al. [32]. Averaged over the functional groups we are considering; we obtain these values:

Table 10: Mass and migration distance for bats and birds' functional groups

Functional Group	Mass (kg)	Migration Distance (km)
Corvids	0.201	3726
Gallinaceous birds	2.416	186
Gulls	0.611	2445
Herbivorous songbirds	0.026	1752
Insectivorous songbirds	0.017	3443
Non-passerines	0.143	2053
Owls	0.431	1521
Polyphagous songbirds	0.040	3165
Raptors	1.977	4322
Seabirds	0.822	1675
Waders	0.159	6086
Waterbirds	1.929	3204
Waterfowl	1.702	3704

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SRE	0.011	294
MRE	0.006	840
LRE	0.018	1136

In the case of offshore, we have the following formula for whales (functional groups LF, HF and VHF):

$$a = 5.67 \times 10^{-5} m^{-0.997}$$

and the following formula for seals (that we apply to the functional groups PCW and OCW):

$$a = 1.51 \times 10^{-4} m^{-0.997}$$

For marine mammals we find the mass of each species from the PanTHERIA database [34], that we average for each functional group as usual. For migration distances we set approximate values based on some representative species: 11000 km for cetaceans (LF, HF and VHF), 3100 km for seals (PCW) [35] and 54 km for OCW [36].

Table 11: Mass and migration distance for marine mammals' functional groups.

Functional Group	Mass (kg)	Migration Distance (km)
LF	26299	11000
HF	89	11000
VHF	242	11000
PCW	213	3100
OCW	89	54

3.3. Final calibration process

As explained earlier, we obtain the normalized PDF $\left(x = {}^{\text{PDF}_f^*}/_{P_f}\right)$ as a measure of the environmental impact. Unfortunately, we cannot use that quantity directly as our environmental score, as we need it to be in the range [0,1] with 1 being the perfect environmentally friendly WF and 0 being the worst possible scenario.

To study the best way to translate the normalized PDF into an environmental score, we study the distribution of values for the normalized PDF obtained in a random sample of points across Europe where we locate a 5 MW turbine. We explain the procedure in the Data Processing section.

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Then, we propose a mapping function with a sigmoid-like shape that is able to fit the cumulative distribution obtained in our random sample.

For onshore WFs we will have the following environmental score:

$$E = \frac{1}{1 + \exp\left(k(x - x_0)\right)}$$

with $x_0 = 0.061$ and $k = 65$. The following figure shows the environmental score as a function of the normalized PDF for onshore WFs alongside the CDF of the random sampled points, to evaluate the goodness of the fit.

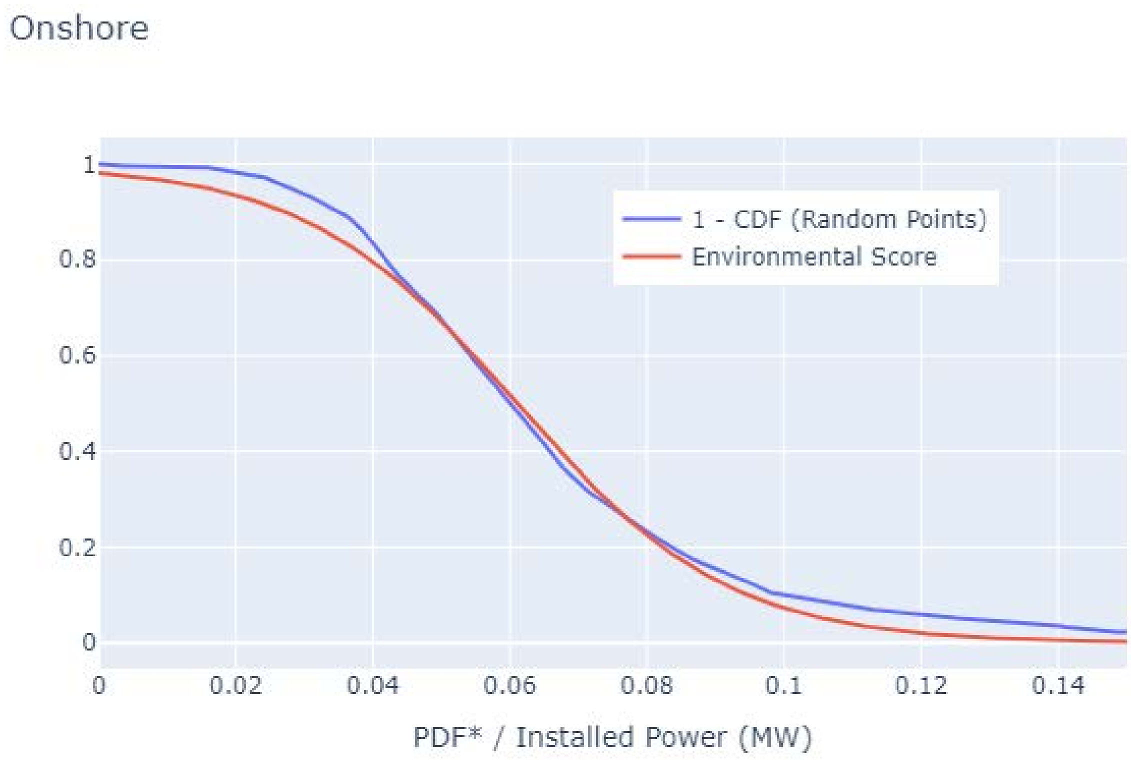

Figure 25: Environmental Score vs normalized PDF for onshore WFs

For offshore WFs we have the following formula:

$$E = \frac{2}{1 + \exp(kx)}$$

with $k = 4000$.

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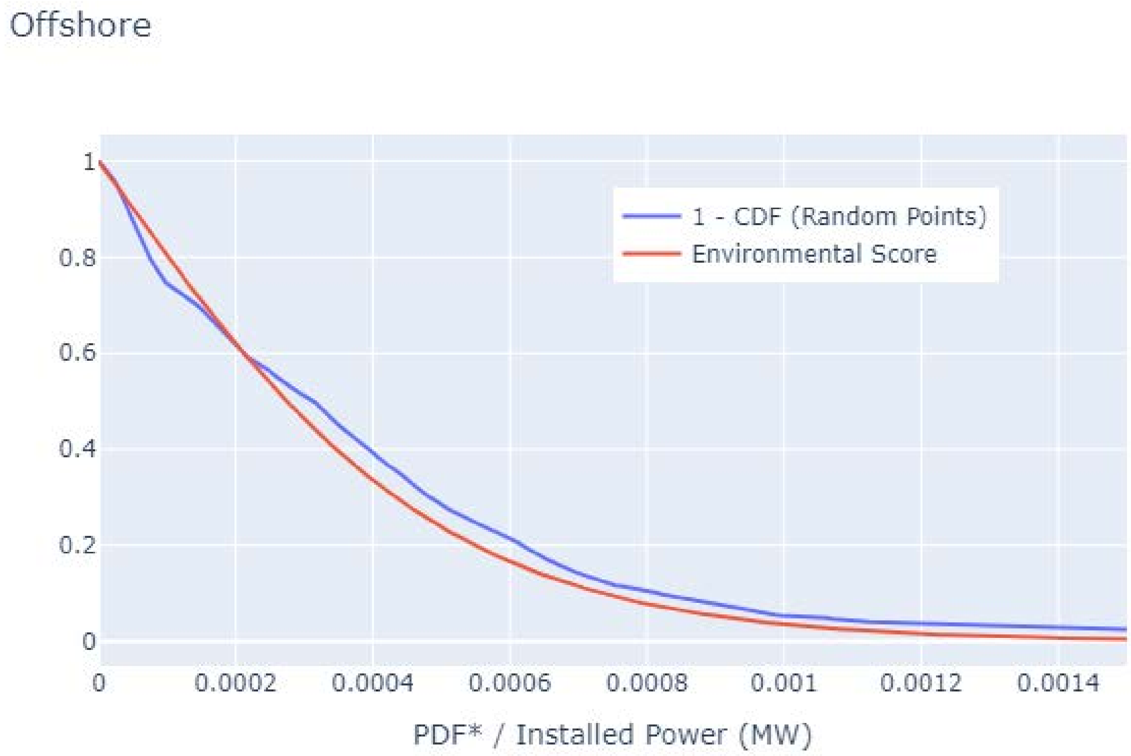

Figure 26: Environmental Score vs normalized PDF for offshore WFs

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4. Techno-economic Score

4.1. Introduction

In Wendy Deliverable 3.4 [37], we studied different factor involved in estimations of wind farm output and project's costs.

We will summarize this information into a techno-economic score, that should account for the competitiveness of the WF. The main KPI that is often cited as a convenient summary for that is the LCOE.

$$\mathrm{LCOE} = \frac{\mathrm{CAPEX}_0 + \sum_{t=1}^{n} \frac{\mathrm{OPEX}_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

where CAPEX_0 is the capital expenditure at the beginning of the project, OPEX_t is the operational and maintenance cost at year t, E_t is the energy produced at year t, n is the expected lifetime of the WF in years and r is the annual interest rate.

In summary, the LCOE is the ratio between costs and produced energy. Energy production will depend basically on wind characterization and turbines specifications. Meanwhile, the costs (CAPEX and OPEX) will also depend on the turbines chosen, although it might be affected by other factors: interest rate, land rental, insurance cost, salaries, difficulty of the terrain, etc.

We will obtain a techno-economic score following the following steps:

1. Calculate the expected annual energy production of the wind farm.
2. Calculate the costs (CAPEX and OPEX) and the LCOE.
3. Transform the LCOE into a techno-economic score that lies in the range [0,1].

In the following subsections we will detail how we proceed with each one of these steps.

4.2. Annual Energy Production

We need two different inputs to compute the Annual Energy Production (AEP)

- Wind characterization, that will allow us to obtain the Weibull distribution in the area. We can obtain this information from New European Wind Atlas [38]
- Turbine specifications, more specifically its power curve, that should be a user input.

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The methodology we choose to obtain the AEP consists on using the entire Weibull distribution given by the A and k parameters. We can obtain the values of these parameters at any location using New European Wind Atlas [38] for different heights (we choose the closest height to the wind turbine we are considering). Thus, the probability distribution of wind speed (v) is given by:

$$\Psi(v) = k\frac{v^{k-1}}{A^k}\exp\left(-\left(\frac{v}{A}\right)^k\right)$$

Thus, we can take the production by computing the expected mean power and multiply by the period of time we are considering:

$$E = T \times \int_0^\infty P(v)\ \Psi(v)dv$$

where $P(v)$ is the power curve, i.e. the function that tells us the power generated by the turbine at speed v, and T is the period of time we consider (in this case we are obtaining annual productions, so we take a year, i.e. 8760 hours).

The power curve is typically given with a resolution of 0.5 m/s. Thus, we discretize the previous formula:

$$E = T \times \sum_0^{v_{\max}} P(v)\ \Psi(v)dv$$

We cut the distribution at $v_{\max}$ (typically around 25 m/s, for higher wind speeds the turbines are stopped).

Additionally, we also implement an air density correction. We correct the power curve, so it is interpolated to a different wind speed given by:

$$v' = v\left(\frac{\rho_{\text{site}}}{\rho_{\text{std}}}\right)^{1/3}$$

as suggested in IEC 61400-12. The standard air density is 1.225 $^{kg}/_{m^3}$ and the air density at the location can also be obtained from New European Wind Atlas [38], given the coordinates.

4.3. CAPEX and OPEX

LCOE stands for Levelized Cost of Energy, which means the price that should be assigned to the produced energy to be able to recover the investment spent in the project (TLCC Total Life Cycle Cost). Mathematically:

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$$\text{Total Costs} = \text{CAPEX}_0 + \sum_{t=1}^{n} \frac{\text{OPEX}_t}{(1+r)^t}$$

as we already seen when we introduced the concept of LCOE.

Thus, to proceed with our calculations we need to determine some basic data for the values of CAPEX and OPEX expenditures. For CAPEX we have obtained some values for onshore WFs from the Wind Europe "Financing and investment trends" report of 2022 [39]. For offshore WF we are using a value of 7 million € per MW, from the same source. [39]

Table 12: CAPEX values per installed MW in million euros for onshore WFs in different countries.

Country	CAPEX Costs (€m/MW)
Spain	1.2
Sweden	1.3
Poland	1.3
Croatia	1.2
Romania	1.2
Azerbaijan	1.2
Germany	1.4
Ireland	1.4
France	1.5
Netherlands	1.6
Serbia	1.7

We transform these values to €/kW (multiply them by 1000).

For OPEX, we extract some values for different countries in Europe for onshore and offshore WFs from the IRENA report for renewable Power Generation costs for 2022 [40].

Table 13: OPEX values per kW and year in US Dollars for onshore WFs in different countries.

Country	OPEX Costs (2022 USD/kW/year)
Sweden	36
Ireland	30
Germany	43

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Denmark	30
Norway	36
Spain	26
United Kingdom	37
France	47
Other OECD	36

Table 14: OPEX values per kW and year in US Dollars for offshore WFs in different countries.

Country	OPEX Costs (2022 USD/kW/year)
Belgium	76
Denmark	69
Netherlands	80
Germany	77
United Kingdom	74
France	80
Other OECD	75

This values for OPEX are transformed to €/kW/year, and alongside the CAPEX values will allow us to obtain a measure of the total cost of a WF in €/kW. This measure, multiplied by the installed power will give us the total costs of the WF.

$$\text{Total Costs per kW} = \text{CAPEX}_0 + \sum_{t=1}^{n} \frac{\text{OPEX}_t}{(1+r)^t}$$

$$\text{Total Costs} = \text{Total Costs per kW} \times P$$

where P is the installed power.

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4.4. Social Interventions Costs

The social interventions that we consider in the calculation of the Social Score, will have a cost associated to them.

We have determined some values for the different interventions. These values are based on the paper by Tegen et al. [41]. In this report some ranges of prices are given for different collections of activities in broad categories (e.g. public outreach). We have chosen the maximum limit, scaled per MW and divide the quantity among every related activity equally. Also, we applied a general rule for farmers compensation [42].

Table 15: Cost for the considered social interventions in € per installed MW

Social Intervention	Cost per MW (€)
Visual Impact Assessment	7500
Noise Impact Assessment	7500
T & R Impact Assessment	7500
Sensitivity Mapping Assessment	7500
Project as tourist destination	7500
Consult Seasonal Residents	7500
Consult Local Community	7500
Marine Recreational Activities	7500
Sponsored Visits	5000
Noise Information	5000
Noise Demonstration Kit	5000
Visualization Dome	5000
Information about electricity infrastructure	5000
Future Energy Plans	5000
Public Reports	5000
Community Engagement Plan	5000
Consult Community Needs	5000
Local Liaison Officer	5000
Survey Impacts	5000

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Local Jobs and Training Opportunities	5000
Noise Damping Panels	4000
Air Bubble Curtain Technique	11500
Buffer Zones	11500
Avoid Sensitive Periods	11500
On-site ecologist	11500
Remote Sensing	11500
Counterbalance Visual Impact	4000
Institutionalize Community Benefits	4000
Community Development Fund (CDF)	4000
Support economic nature-dependent activities	4000
Re-develop vegetation	11500

Future research and expert opinion could improve the accuracy of these values. The costs associated to the interventions performed by the WF are added to the total costs we specified before. Thus, improving the Social Score by implementing different interventions has the counterpart of increasing the cost, and thus reduce the Techno-Economic Score.

4.5. Final LCOE Calculation and Techno-economic Score

Note that both the OPEX and the AEP are introduced in a summatory to account for interest rate over the years. But the calculation of the yearly OPEX and AEP do not evolve in time, thus being a constant in the sum. This simplifies the formulas, and allows us to get rid of the sum:

$$\mathrm{LCOE} = \frac{\left(\mathrm{CAPEX} + \mathrm{OPEX}\,\frac{1+r}{r}\left[1-\left(\frac{1}{1+r}\right)^{n}\right]\right)\times P}{E\,\frac{1+r}{r}\left[1-\left(\frac{1}{1+r}\right)^{n}\right]}$$

Then, we need to transform the LCOE into a Techno-Economic Score in the range [0,1]. To calibrate this transformation, we use a similar procedure to the process we follow to calibrate the Environmental Score.

We will use the same sample of random, where we place 5MW turbines, evaluate the LCOE for each one, and propose a mapping transformation that is able to approximately follow the cumulative distribution function.

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In this case, we will use asymmetric sigmoid functions:

$$\sigma^*(x; x_0, k_{\text{left}}, k_{\text{right}}) = \frac{\exp\left(k(x; x_0, k_{\text{left}}, k_{\text{right}})(x - x_0)\right)}{1 + \exp\left(k(x; x_0, k_{\text{left}}, k_{\text{right}})(x - x_0)\right)}$$

where:

$$k(x; x_0, k_{\text{left}}, k_{\text{right}}) = \begin{cases} k_{\text{left}} & \text{if } x < x_0 \\ k_{\text{right}} & \text{if } x \geq x_0 \end{cases}$$

We use this function to obtain the final Techno-Economic Score as:

$$T = 1 - \sigma^*(x; x_0, k_{\text{left}}, k_{\text{right}})$$

with the following fitted parameters: $x_0 = 0.018$, $k_{\text{left}} = 400$ and $k_{\text{right}} = 125$ for onshore wind farms; and $x_0 = 0.066$, $k_{\text{left}} = 150$ and $k_{\text{right}} = 60$ for onshore wind farms.

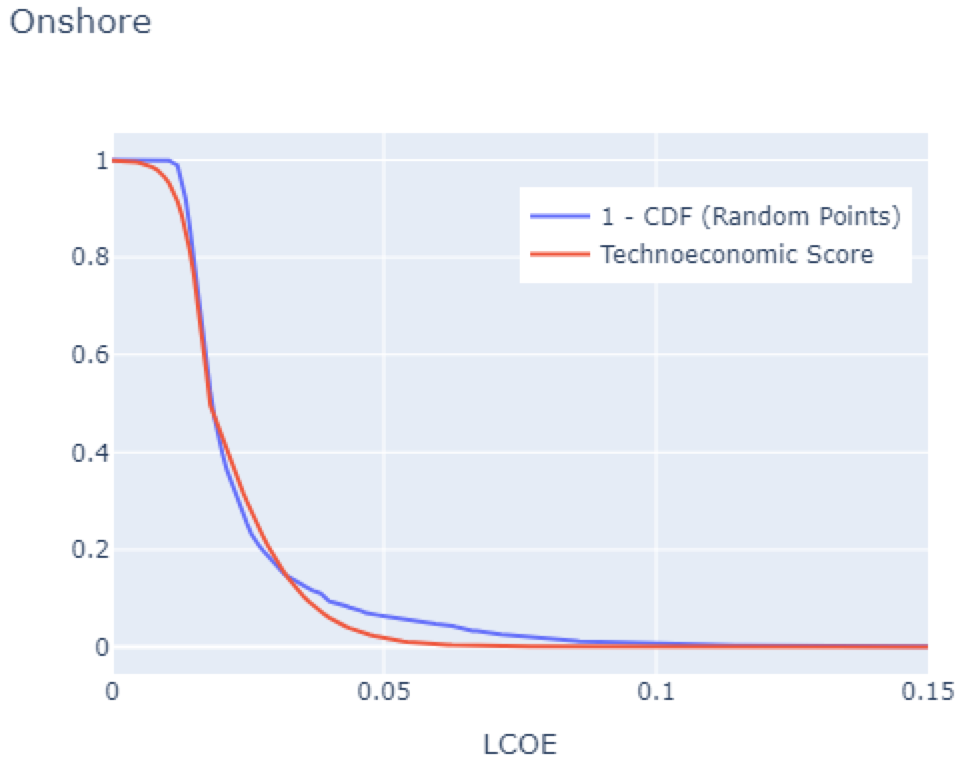

Figure 27: Techno-Economic Score vs normalized PDF for onshore WFs

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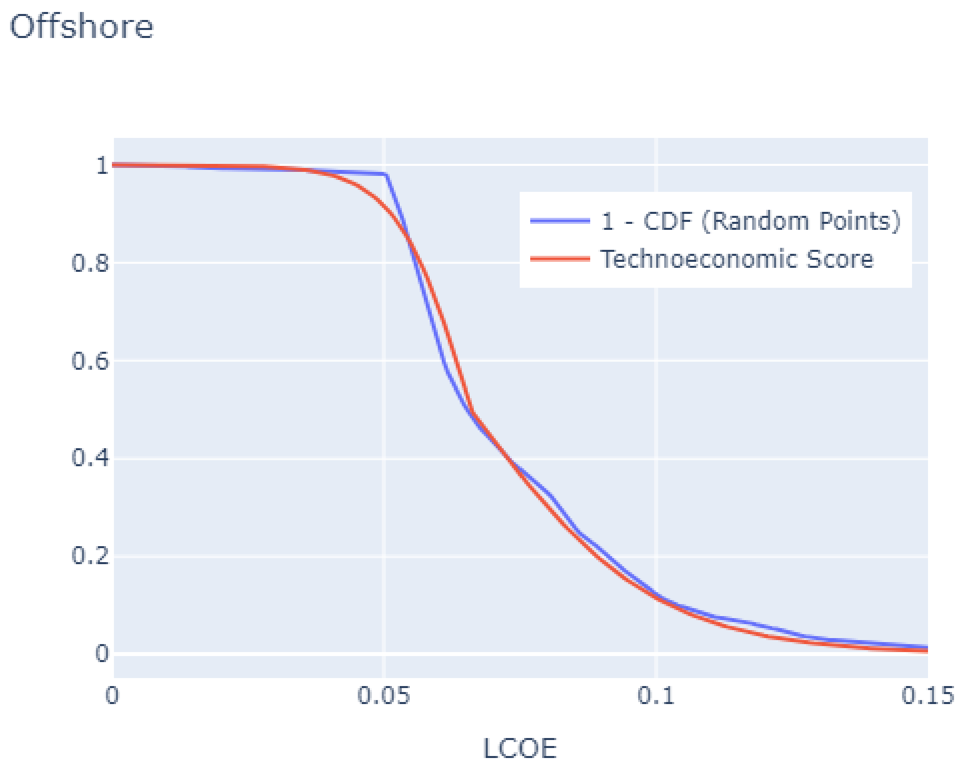

Figure 28: Techno-Economic Score vs normalized PDF for offshore WFs

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5. Data Processing

5.1. Introduction

This KPI relies on the exploitation of different geolocalized data sources. During the previous sections of this report, we have mentioned the different data inputs that we needed to calculate the different ingredients of this multi-variable KPI. As a brief reminder, this is the list of information items that we need to extract:

- Distance from the WF to the closest populated area.
- Distance from the WF to the closest touristic site.
- Percentage of senior population.
- Percentage of agricultural and rural land use.
- Species richness of birds and bats (or seabirds and marine mammals).
- Maps of species distributions.
- Maps of species connectivity.
- The wind Weibull parameters A and k, and the air density at a given elevation.
- CAPEX and OPEX values

Some of these items can be obtained 'live' by sending a query to an API using the WF coordinates as an input. In other cases, we need to prepare raster files maps beforehand and then proceed to get the required zonal or punctual statistics.

Table 16: Main data sources

Data Source	Used for
OpenStreetMap	- Distance to nearest populated area. - Distance to nearest touristic site. - Percentage of land use
Eurostat	- Percentage of senior population
Biodiversity Mapping	- Species richness
GBIF	- Maps of species distribution and connectivity
New European Wind Atlas	- Weibull parameters A and k
IRENA reports	- CAPEX and OPEX

In the following sections we will detail how we use each one of these data sources to extract the precise information we need.

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5.2. OpenStreetMap

OpenStreetMap (OSM) is a collaborative cartographic project that offers detailed and free to use maps around the world.

In this project it has been used to obtain key inputs for the social score, allowing us to analyze the elements surrounding a WF and anticipating possible social interactions.

We have used Overpass Turbo [43], more specifically its Python package, OSMTools [44]. The general use we will make of this package consists of sending queries searching for certain categories of elements within a bounding box with the WF at its center. From the elements extracted we will recollect the specific information we need.

In the next subsections we will detail the exact queries used, and the processes perform to extract the specific information we need.

5.2.1. Distance to closest populated area.

First, we need to define a bounding box around our WF and send a request to OSM to retrieve every populated place in the area.

To identify and categorize the different elements, OSM uses a system of keys and tags. The following table indicates all the different combinations of keys and elements that we are using to identify populated areas:

Table 17: Lists of keys and tags used to identify populated areas.

Key	Tag	Description
place	city	The largest urban settlement or settlements within the territory.
place	borough	A part in a larger city grouped into administrative unit.
place	suburb	A part of a town or city with a well-known name and often a distinct identity.
place	city_block	A named city block, usually surrounded by streets
place	neighbourhood	A smaller named, geographically localised place within a suburb of a larger city or within a town or village
place	plot	A named plot is a tract or parcel of land owned or meant to be owned by some owner.
place	town	An important urban centre, between a village and a city in size.
place	village	A smaller distinct settlement, smaller than a town with few facilities available with people traveling to nearby towns to access these.
place	hamlet	A smaller rural community, typically with fewer than 100-1000 inhabitants, and little infrastructure.

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place	isolated_dwelling	The smallest kind of settlement (1-2 households).
place	farm	An individually named farm.
place	allotments	A separate settlement, which is located outside an officially inhabited locality and has its own addressing.
landuse	residential	Land where people reside; predominantly residential detached (single houses, grouped dwellings), or attached (apartments, flats, units) dwellings.

```
[out:json][timeout:25];
// gather results
(
  nwr["landuse"="residential"]({{bbox}});
  nwr["place"="city"]({{bbox}});
  nwr["place"="borough"]({{bbox}});
  nwr["place"="suburb"]({{bbox}});
  nwr["place"="city_block"]({{bbox}});
  nwr["place"="neighbourhood"]({{bbox}});
  nwr["place"="plot"]({{bbox}});
  nwr["place"="town"]({{bbox}});
  nwr["place"="village"]({{bbox}});
  nwr["place"="hamlet"]({{bbox}});
  nwr["place"="isolated_dwelling"]({{bbox}});
  nwr["place"="farm"]({{bbox}});
  nwr["place"="allotments"]({{bbox}});
);
// print results
out geom;
```

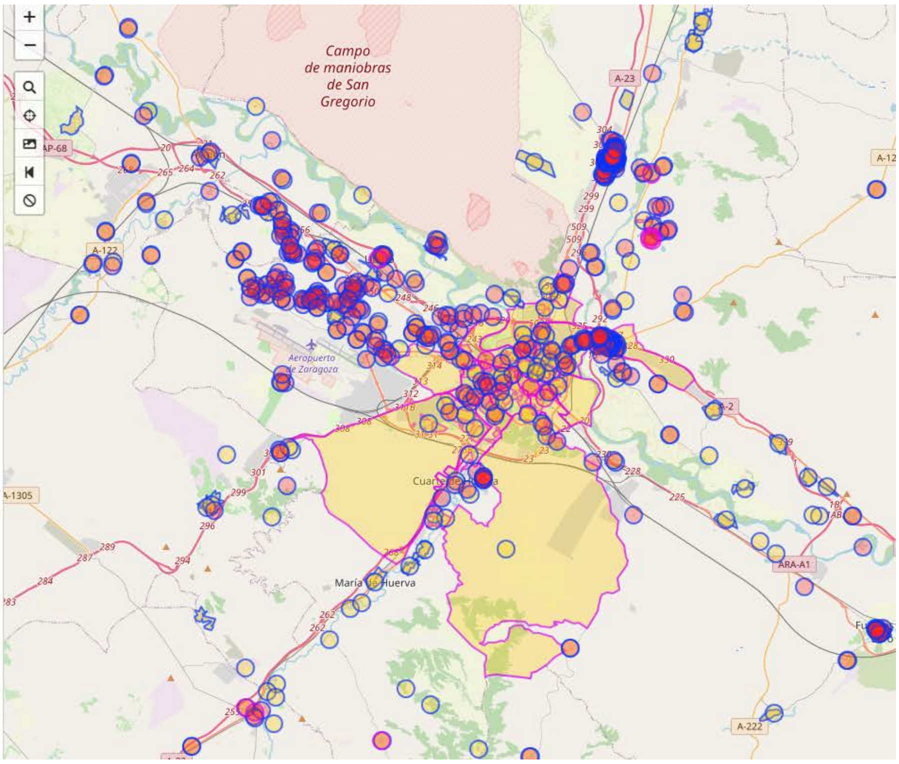

Figure 29: Example of the query to identify populated places in Overpass Turbo

The search should return us a collection of populated places around the WF. If the search returns no results, we repeat the search in a larger bounding box.

We then proceed to calculate the distances to the elements we extracted. We might receive two kinds of elements: nodes (which only contain a latitude and a longitude) or polygons. In the case of polygons, the distance we consider is the minimum distance to the boundary of the polygon.

Finally, we consider the minimum distance from the full list of elements. This is the distance that we will consider when calculating visual and noise acceptance.

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5.2.2. Distance to closest touristic site.

We perform a similar approach to the previous case; we only need to change the elements we are searching for with a new collection of keys and tags. OSM has a specific key 'tourism' for this case, so we simply search for every element under that key.

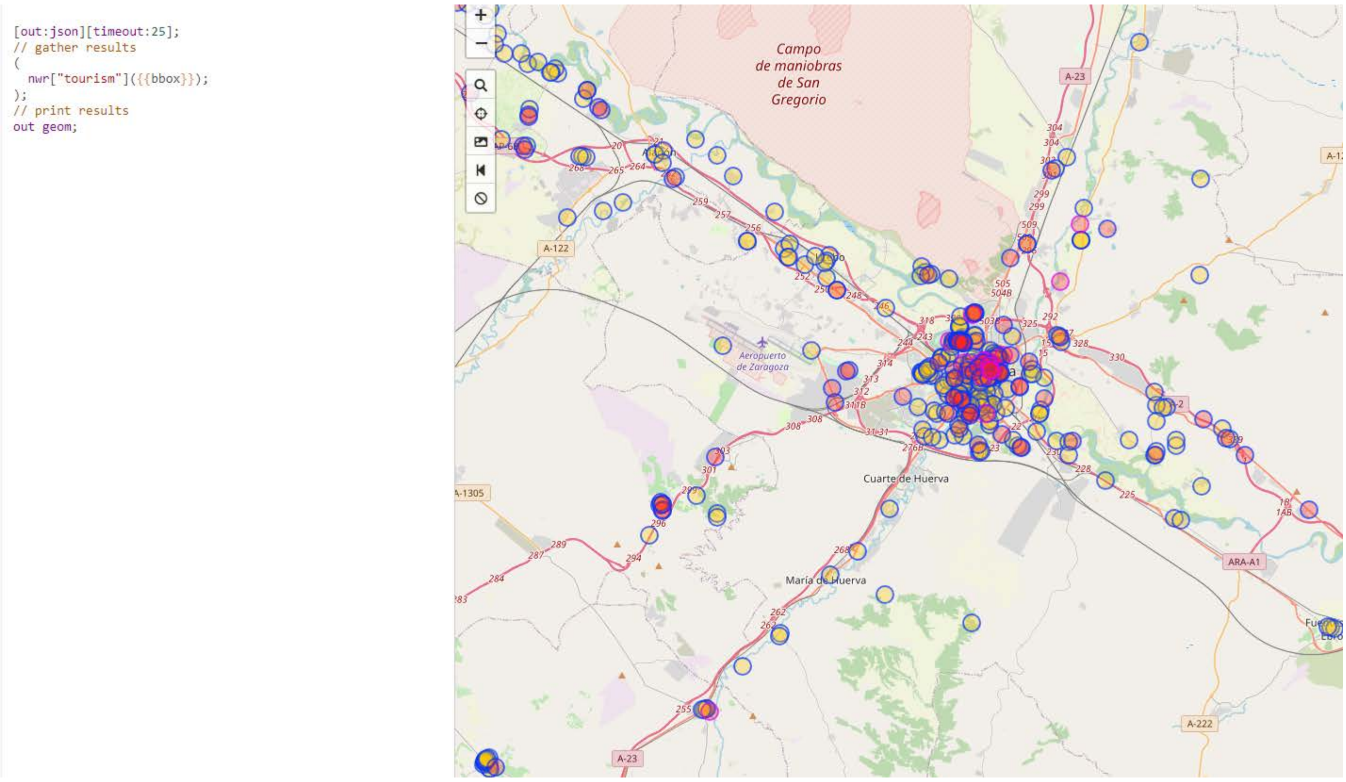

Figure 30: Example of the query to identify touristic sites in Overpass Turbo

The minimum distance to the WF is considered when computing Toursim Acceptance.

5.2.3. Percentage of landuse

In this case, we search for elements within a fixed bounding box with the WF at its center and a distance to the corner of 4 km. We incorporate to the search different tags of the key 'landuse' that apply to nature activities.

Table 18: Lists of keys and tags used to identify landuse.

Key	Tag	Description
landuse	aquaculture	The farming of freshwater and saltwater organisms such as finfish, molluscs, crustaceans and aquatic plants.
landuse	allotments	A piece of land given over to local residents for growing vegetables and flowers.

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landuse	farmland	An area of farmland used for tillage (cereals, vegetables, oil plants, flowers).
landuse	farmyard	An area of land with farm buildings like farmhouse, dwellings, farmsteads, sheds, stables, barns, equipment sheds, feed bunkers, etc. plus the open space in between them and the shrubbery/trees around them.
landuse	paddy	An area of land where the surface and shape of the land is made suitable for growing rice.
landuse	animal_keeping	An area of land that is used to keep animals, particularly horses and livestock.
landuse	flowerbed	An area designated for flowers.
landuse	greenhouse_horticulture	Area used for growing plants in greenhouses.
landuse	meadow	A meadow or pasture: land primarily vegetated by grass and non-woody plants, mainly used for hay or grazing.
landuse	orchard	Intentional planting of trees or shrubs maintained for food production.
landuse	plant_nursery	Intentional planting of plants maintaining for the production of new plants.
landuse	vineyard	A piece of land where grapes are grown.

```
[out:json][timeout:25];
// gather results
(
  nwr["landuse"="aquaculture"]({{bbox}});
  nwr["landuse"="allotments"]({{bbox}});
  nwr["landuse"="farmland"]({{bbox}});
  nwr["landuse"="farmyard"]({{bbox}});
  nwr["landuse"="paddy"]({{bbox}});
  nwr["landuse"="animal_keeping"]({{bbox}});
  nwr["landuse"="flowerbed"]({{bbox}});
  nwr["landuse"="greenhouse_horticulture"]({{bbox}});
  nwr["landuse"="meadow"]({{bbox}});
  nwr["landuse"="orchard"]({{bbox}});
  nwr["landuse"="plant_nursery"]({{bbox}});
  nwr["landuse"="vineyard"]({{bbox}});
);
// print results
out geom;
```

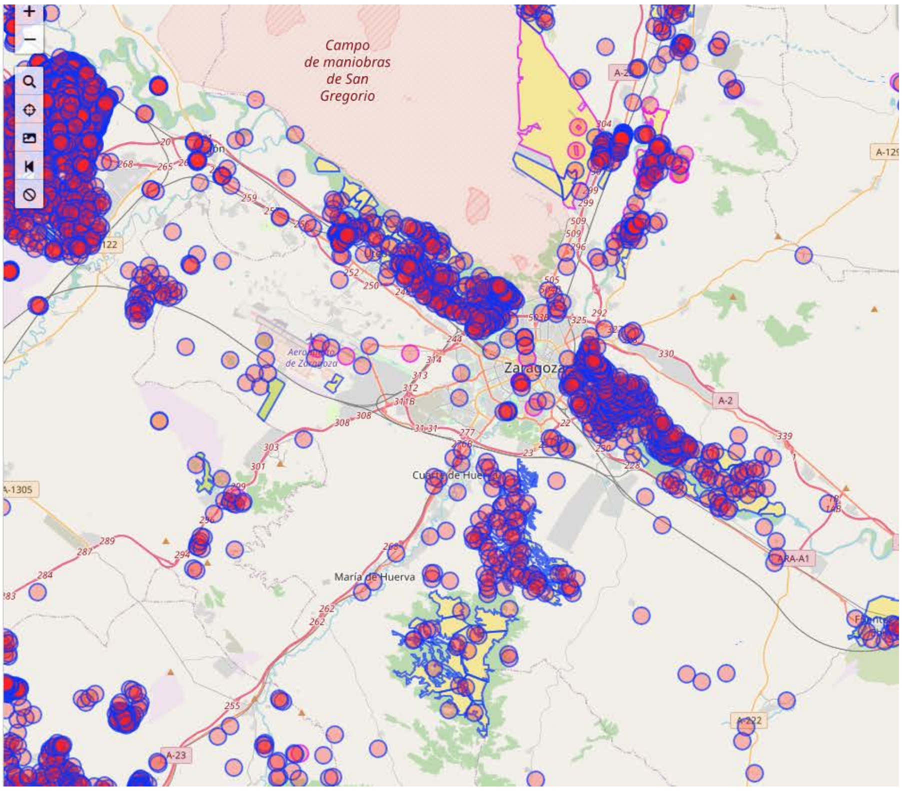

Figure 31: Example of the query to identify landuse in Overpass Turbo.

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In this case we are only interested in the polygonal elements. We obtain the ratio between the area of the intersection of these polygons with the bounding box and the area of the bounding box itself.

The percentage of landuse is introduced to calculate Nature Activities Protection, one of the features of the Social Score.

5.3. Eurostat

Eurostat is the statistical office of the European Union. It is in charge of providing high-quality statistics and data on Europe.

In this project we use Eurostat to obtain the percentage of senior population in the community of a WF. To build this information, we access the dataset "Population on 1 January by age group, sex and NUTS 3 region". This dataset is identified by the code "demo_r_pjangrp3".
(URL: https://ec.europa.eu/eurostat/databrowser/view/demo_r_pjangrp3/default/table?lang=en).

The dataset provides the population per age group (each age group includes 5 years: 0 to 5, 5 to 10, etc.) and per NUTS-3 region (the smallest administrative units considered at Eurostat) at different years. We take the data from the last available year per region and obtain the percentage of senior population simply dividing the sum of the population at the older age groups by the total population.

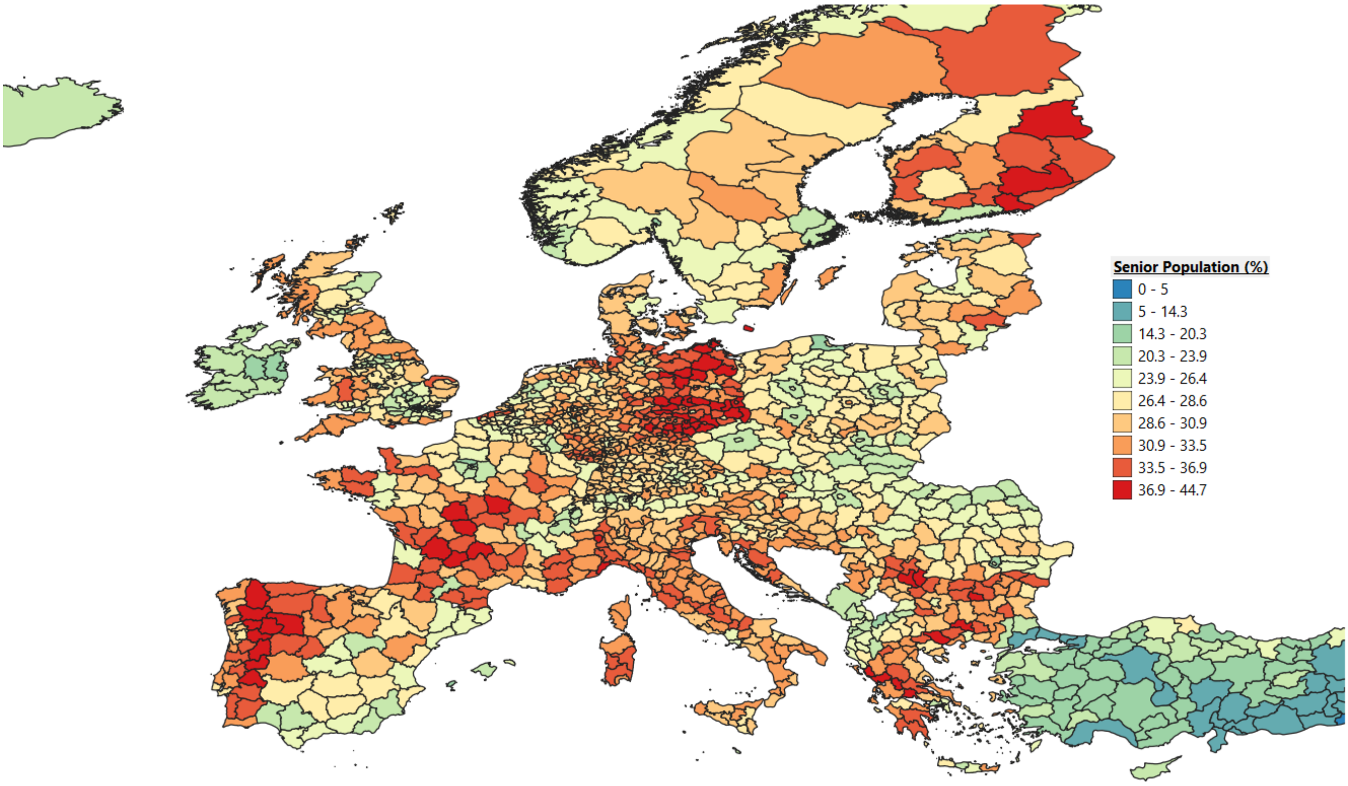

Figure 32: Senior population (%) per NUTS-3 region.

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5.4. Biodiversity Mapping

We use maps from Biodiversity Mapping [16] to assess the species richness for the Social Score.

We download the following raster maps:

- Bird Richness
- Chiroptera (Bats)
- Seabird Diversity
- Marine Mammal Diversity

We need to preprocess these maps:

1. Change CRS to EPSG:4236
2. Crop the maps to Europe's bounding box (to reduce space).

After these modifications we can consult these maps to obtain the species richness of birds and bats (onshore) or seabirds and marine mammals (offshore) with which we calculate the social feature Biodiversity Protection.

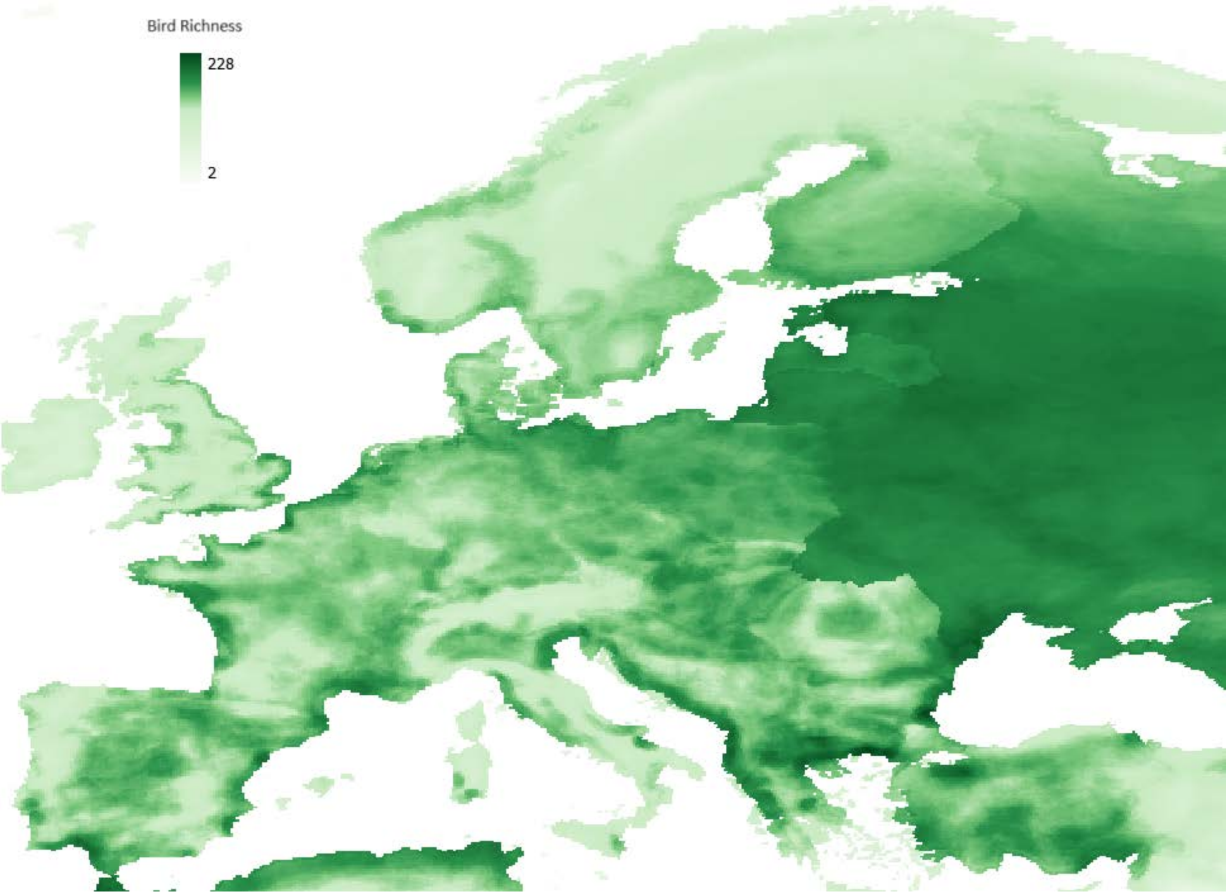

Figure 33: Species Richness Map for Birds in Europe from Biodiversity Mapping.

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The maps from Biodiversity Mapping have a resolution of 10 x 10 km. For the environmental score we will build more detailed maps of species richness. However, we decided to keep these simpler maps for the evaluation of the social feature Biodiversity Protection.

5.5. Species distribution maps

The key ingredient for the evaluation of the Environmental Score is the collection of species distribution maps. These maps contain a probability distribution for each main species of birds, bats, and marine mammals in Europe.

By building these maps we will be able to identify the most relevant species near a WF and estimate the impact it might have over them.

These maps are not directly available, we must build them from occurrence data. Occurrence data on a wide catalogue of species are available at Global Biodiversity Information Facility (GBIF) [45] , through its public API. These data consist in individual observation of species, with a date and geographical coordinates. To translate these data into raster maps with the species probability density, we use MaxEnt model, which also need some background occurrences (to reduce observation bias) and geographical climatic features that the model will correlate with the observed occurrences. These geographical features will be downloaded in the form of raster maps and used as an input of the MaxEnt model.

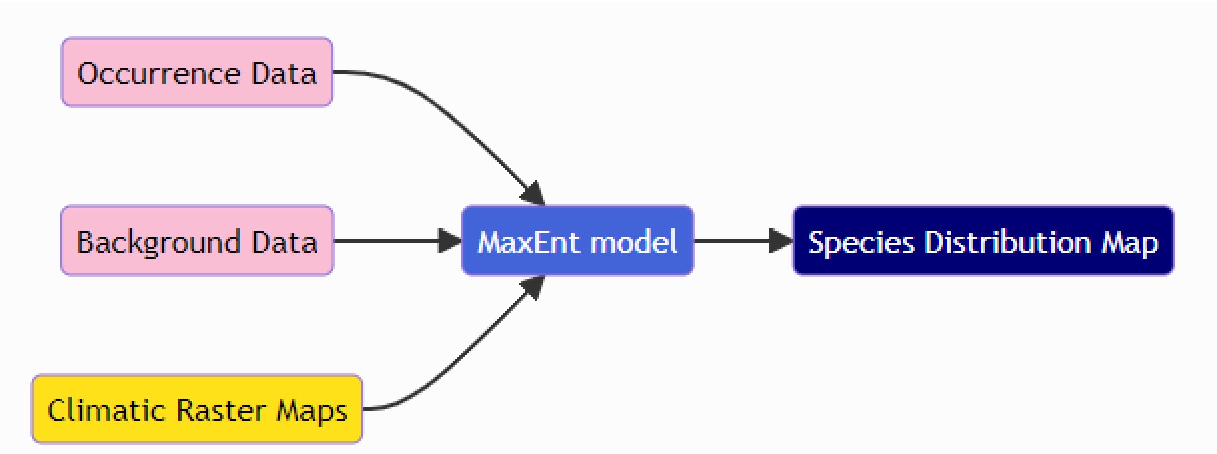

Figure 34: Scheme of workflow for obtaining species distribution maps.

5.5.1. Climatic Raster Maps

As discussed before, one of the inputs we need to build the species distribution maps is a set of climatic features in the form of raster maps. The MaxEnt model will learn the characteristics of the zones where

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the observations of a particular species occur in order to extrapolate the presence of the species to other zones with similar conditions.

For the onshore case, we consider the following features:

- Elevation
- Annual Mean Temperature
- Temperature Seasonality
- Annual Precipitation
- Precipitation Seasonality
- Mean temperature of warmest quarter (only for bats)
- Mean temperature of coldest quarter (only for bats)

We can find this information in World Clim [46]. These data appear as independent raster maps under the collection “Bioclimatic variables”, except for elevation that can be found independently at the same source. We download these maps, selecting a resolution of 30s, and unify them to the same CRS and the bounding box we consider for Europe.

For the case of offshore, we introduce a different set of features:

- Bathymetry
- Annual Mean Seasurface Temperature
- Annual Mean Surface Salinity
- Annual Mean Primary Productivity
- Annual Mean Current Velocity

Most of these features are downloaded from Bio-ORACLE [47], except for bathymetry that is downloaded from Global Wind Atlas [48]. Again, all these raster maps are unified to the same CRS and bounding box.

5.5.2. Occurrences

5.5.2.1. Taxonomic Information

In order to search the occurrences of species, we need to identify the taxon key assigned by GBIF for each particular species. The species will be organized in functional groups, which will show the same values for the key parameters needed for the evaluation of PDF in each pathway.

We will follow the same categorization in functional group from deliverable 3.1 of this project [17]. In table S1 we could find a relation between different families and their respective functional groups. We will run a quick search of all species in those families and keep those species with a number of occurrences in Europe larger than 50 in the last year (2023).

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In the case of bats, table S2 from deliverable 3.1 [17] already contain the species of bats found in Europe, associated with a functional group based on echolocation capacities, so we do not need to apply the extra search in this case.

For marine mammals we follow the categorization found in the paper by Southall et al. [26] and again run a search for each species belonging to the genus listed in table 1 from that paper, that we reproduce here:

Table 1. Proposed marine mammal hearing groups, applicable auditory weighting functions, genera or species within each proposed group, and the associated appendix within which available data on hearing, auditory anatomy, and sound production are reviewed

Marine mammal hearing group	Auditory weighting function	Genera (or species) included	Group-specific appendix
Low-frequency cetaceans	LF	Balaenidae (*Balaena*, Eubalaenidae spp.); Balaenopteridae (*Balaenoptera physalus*, *B. musculus*)	1
		Balaenopteridae (*Balaenoptera acutorostrata*, *B. bonaerensis*, *B. borealis*, *B. edeni*, *B. omurai*; *Megaptera novaeangliae*); Neobalenidae (*Caperea*); Eschrichtiidae (*Eschrichtius*)	
High-frequency cetaceans	HF	Physeteridae (*Physeter*); Ziphiidae (*Berardius* spp., *Hyperoodon* spp., *Indopacetus*, *Mesoplodon* spp., *Tasmacetus*, *Ziphius*); Delphinidae (*Orcinus*)	2
		Delphinidae (*Delphinus*, *Feresa*, *Globicephala* spp., *Grampus*, *Lagenodelphis*, *Lagenorhynchus acutus*, *L. albirostris*, *L. obliquidens*, *L. obscurus*, *Lissodelphis* spp., *Orcaella* spp., *Peponocephala*, *Pseudorca*, *Sotalia* spp., *Sousa* spp., *Stenella* spp., *Steno*, *Tursiops* spp.); Montodontidae (*Delphinapterus*, *Monodon*); Plantanistidae (*Plantanista*)	
Very high-frequency cetaceans	VHF	Delphinidae (*Cephalorhynchus* spp.; *Lagenorhynchus cruciger*, *L. austrailis*); Phocoenidae (*Neophocaena* spp., *Phocoena* spp., *Phocoenoides*); Iniidae (*Inia*); Kogiidae (*Kogia*); Lipotidae (*Lipotes*); Pontoporiidae (*Pontoporia*)	3
Sirenians	SI	Trichechidae (*Trichechus* spp.); Dugongidae (*Dugong*)	4
Phocid carnivores in water Phocid carnivores in air	PCW PCA	Phocidae (*Cystophora*, *Erignathus*, *Halichoerus*, *Histriophoca*, *Hydrurga*, *Leptonychotes*, *Lobodon*, *Mirounga* spp., *Monachus*, *Neomonachus*, *Ommatophoca*, *Pagophilus*, *Phoca* spp., *Pusa* spp.)	5
Other marine carnivores in water Other marine carnivores in air	OCW OCA	Odobenidae (*Odobenus*); Otariidae (*Arctocephalus* spp., *Callorhinus*, *Eumetopias*, *Neophoca*, *Otaria*, *Phocarctos*, *Zalophus* spp.); Ursidae (*Ursus maritimus*); Mustelidae (*Enhydra*, *Lontra feline*)	6

Figure 35: Table 1 from Southall et al.

After these searches for species, we finally isolated 682 species which distribute in the different functional groups.

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Table 19: Number of species for each functional group considered in this work.

Type	Functional Group	Number of Species
Bird	Corvids	16
Bird	Gallinaceous birds	21
Bird	Gulls	38
Bird	Herbivorous songbirds	55
Bird	Insectivorous songbirds	86
Bird	Non-passerines	38
Bird	Owls	14
Bird	Polyphagous songbirds	96
Bird	Raptors	43
Bird	Seabirds	34
Bird	Waders	65
Bird	Waterbirds	50
Bird	Waterfowl	77
Bat	SRE (Short-Range Echolocator)	13
Bat	MRE (Mid-Range Echolocator)	6
Bat	LRE (Long-Range Echolocator)	6
Marine Mammal	LF (Low-frequency cetaceans)	2
Marine Mammal	HF (High-frequency cetaceans)	7
Marine Mammal	VHF (Very high-frequency cetaceans)	1
Marine Mammal	PCW (phocid carnivores in water)	3
Marine Mammal	OCW (other carnivores in water)	11

5.5.2.2. Retrieving of occurrences data

Once we have identified the taxon key of each species we want to analyze, we can use them to run search queries at GBIF [45].

These queries can be run with temporal and geographical restrictions. We will limit to occurrences obtained in the last year (2023) and to the continent of Europe.

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There exists a limit of 100,000 occurrences that can be extracted for any given set of parameters. If the count of occurrences exceeds that limit, we divide the search in a 5x5 grid. If for any cell we surpass the limit again, we recursively apply a 5x5 grid to divide the occurrences in smaller searches.

Another limitation is that the occurrences only can be extracted in batches of 300 occurrences. Thus, we need to make many different calls to the GBIF API, which affects heavily on computation time. We parallelize this process.

5.5.3. Background data

To reduce observer's biases, MaxEnt models also use background observations. Otherwise, we might be overrepresenting location with a large density of observations throughout all species.

We download the background data by searching for occurrences at random, without specifying species. We loop through a grid (each cell having 1 degree latitude x 1 degree longitude), drawing data with random offsets in bags of 10 occurrences each. This procedure is not entirely unbiased as consecutive occurrence data might be correlated. Reducing the size of the bag will reduce the bias but at the cost of a higher computational cost.

To select the number of background occurrences we need to draw at each cell, first we decide on the total number of background occurrences we want to extract. We decided on 50000 random occurrences. At each cell, we extract first the total number of occurrences located in that cell and perform the ratio with the total number of occurrences in Europe. We use that ratio to draw for each cell the corresponding amount of background occurrences.

5.5.4. Species distribution maps using MaxEnt models.

We obtain the species distribution by applying the MaxEnt model [49] by using the elapid package [50] in Python.

We apply the MaxEnt model to each species we have isolated. The input data we need is the occurrences, background data and climatic raster maps. We parallelize the code to build several maps at the same time.

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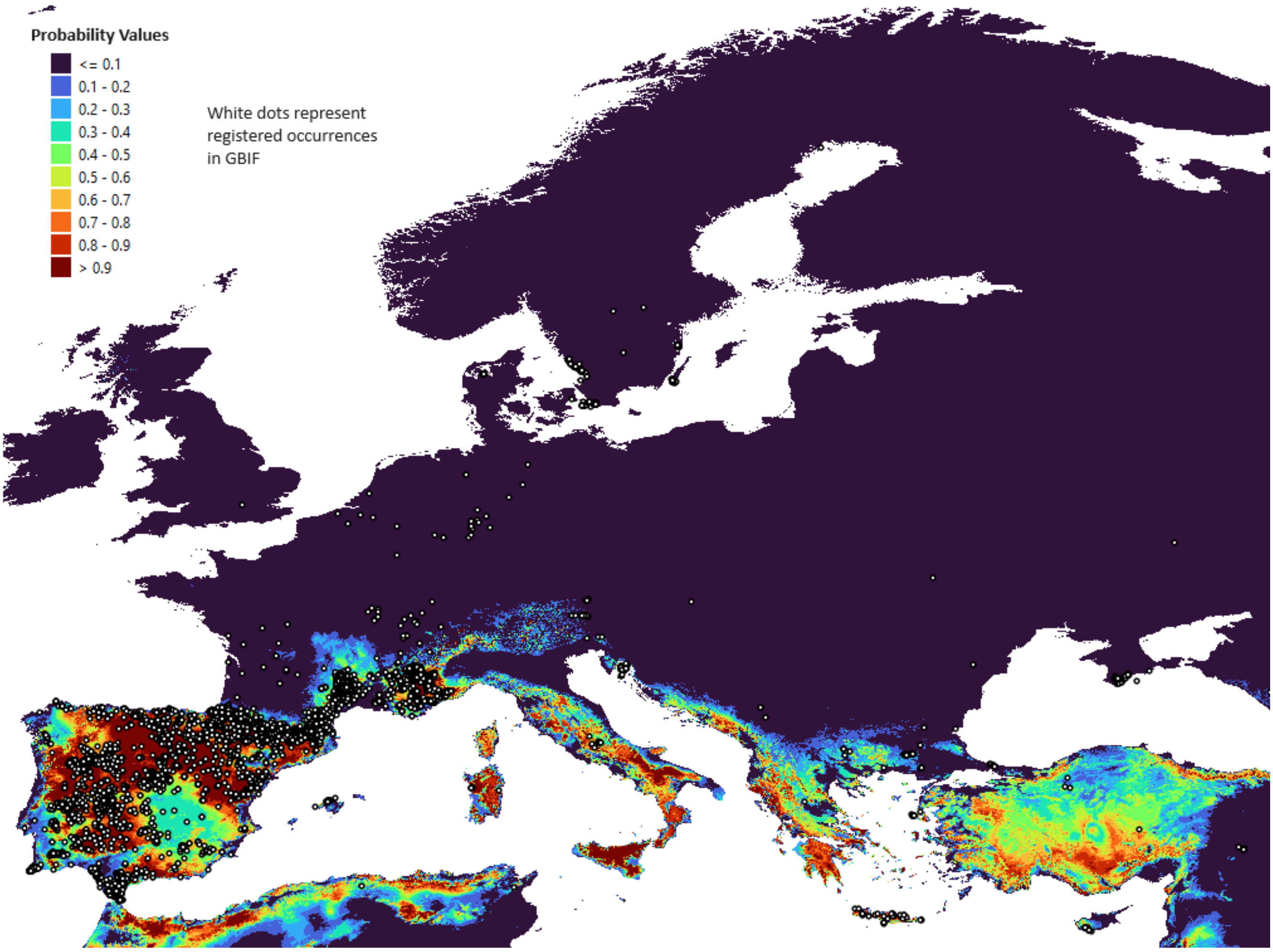

Figure 36: Distribution map and occurrences for *Gyps fulvus.*

5.5.5. Functional groups maps

The Environmental Score calculates the PDF at the level of functional groups. To obtain the species richness maps at the level of functional group, we simply sum the individual distribution maps of all species belonging to that functional group.

5.6. Connectivity Maps

For the evaluation of the barrier effect, the underlying map will not be the distribution maps of the species. In this case we want to analyze the impact that the WF might have on migration routes, thus we need a map that considers the connectivity instead.

Connectivity will be modelled for each species applying circuit theory in Omniscape [51]. This approach predicts omni-directional connectivity among every pair of locations in the landscape by

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iteratively applying Circuitscape to every cell through the species distribution maps and calculating cumulative current flow [51]. The inverse species distribution maps will be used as resistance rasters and source strength will be set equal to the species probability of presence in Omniscape. Thus, habitat suitability measures the conductance to movement across the landscape. The cumulative current flow for each species s ($C_{s,i}$) can then be calculated and normalized in the range (0,1) to aggregate them into connectivity maps for each functional group.

5.6.1. Species Connectivity Maps

To obtain the species-wise connectivity maps, we need to run a Julia script to run Omniscape using a INI configuration file.

```julia
using Pkg; Pkg.add(["Omniscape"])
using Omniscape

repo_path = pwd()
filename = "src\\julia\\omniscape.ini"
filepath = joinpath(repo_path, filename)

run_omniscape(filepath)
```

Figure 37: Julia script to run Omniscape.

Thus, our code that is primarily in Python, will loop over the species distribution maps we have obtained and perform the following operations:

1. Prepare the input:
    a. Read the map.
    b. Resample. For computational purposes, we can not perform Omniscape over the full resolution maps.
    c. Apply a minimum threshold. This prevents error due to a small value of conductance.
    d. Write the resulting map to be the input of the Julia script.
2. Run the Julia script.
3. Prepare the output:
    a. Read the map.
    b. Scale it to (0,1) by dividing by the maximum value.
    c. Write the resulting map at its final destination folder.

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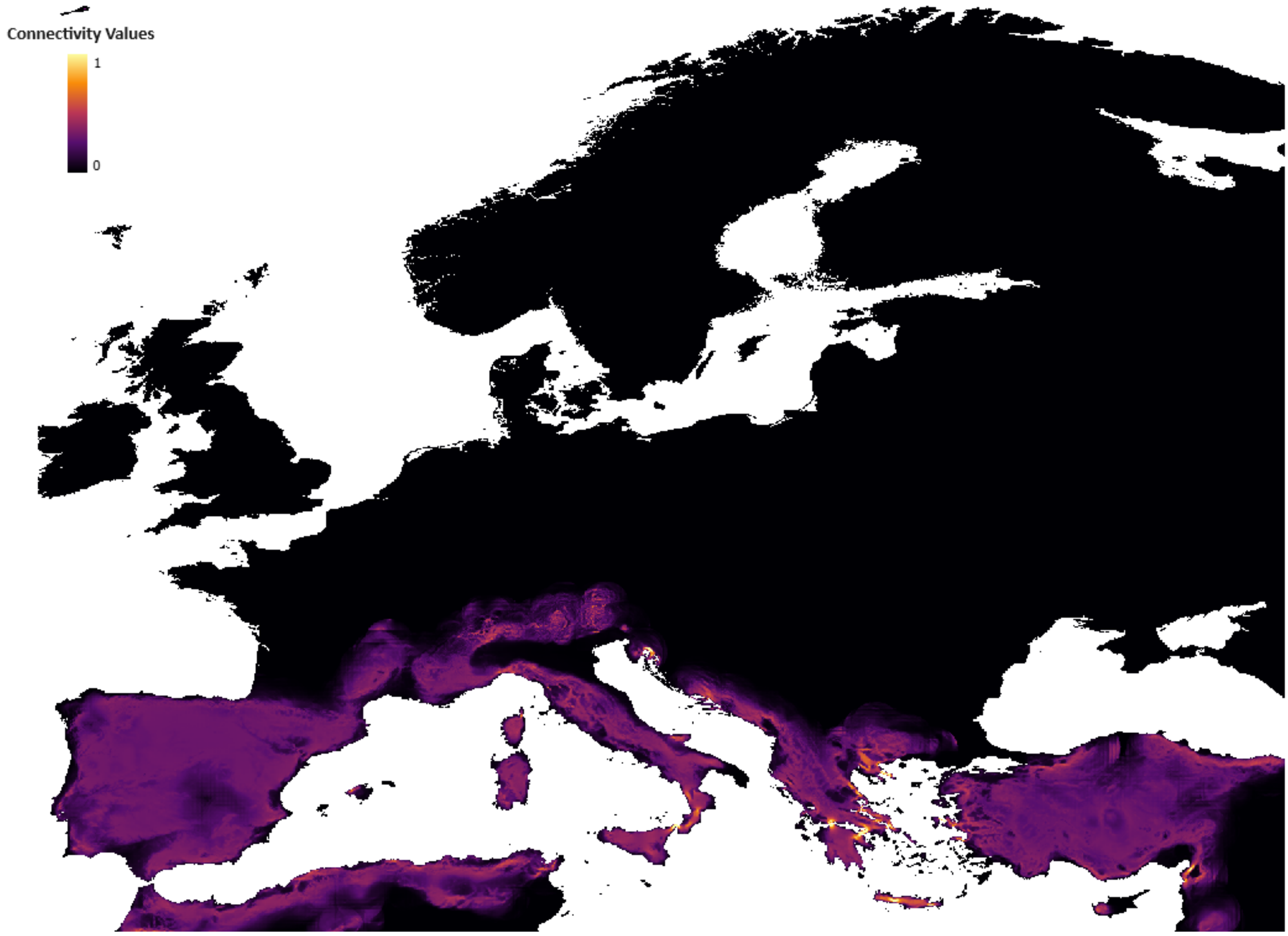

Figure 38: Connectivity map for species *Gyps fulvus*

5.6.2. Functional Group Connectivity Maps

As in the case of the species distribution maps, the Environmental Score only computes the PDF at the level of functional groups. Again, we build the functional groups connectivity maps by summing the connectivity maps of the corresponding species.

5.7. Wind Characterization at New European Wind Atlas

In order to extract the expected Annual Energy Production, which is key to obtain the technical viability of the WF, we need to obtain several data to characterize the available wind resource.

We will obtain this data from the microscale modelling API offered by NEWA [38]. For instance, the following URL will allow us to access the values of Weibull's parameters A and k and air density at the coordinates (42º, -1º) and a height of 100 meters.

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```
https://wps.neweuropeanwindatlas.eu/api/microscale-atlas/v1/get-data-point?latitude=42&longitude=-1&height=100&variable=weib_A_combined&variable=weib_k_combined&variable=air_dens
```

Figure 39: Example of URL request to NEWA API

By formatting a template URL to introduce the desired parameters, we can call the API from Python code, using the standard requests library.

The response is provided in the form of a .nc file that can be read using the netCDF4 package [52].

5.8. Map of total costs

For the computation of the Techno-Economic Score we have seen that the costs can vary between countries, and more dramatically between onshore and offshore. We could have both the country and the type of WF as an input, and calculate the costs based on the provided values, but to facilitate the user experience, we assign the costs based on the coordinates.

To achieve that we have created a map with the expected total costs per installed kW. First, we need to be able to differentiate between onshore and offshore. For this we use a land mask from EEA [53]. Some countries are missing from this map (Andorra, Ukraine, Moldova and Belarus), we try to incorporate using the elevation and bathymetry maps from Global Wind Atlas (GWA) [48], marking negative elevation as sea and vice versa. However, this last method is less accurate, and some randomly scattered cells onshore are marked as corresponding to the sea.

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Figure 40: Land mask for Europe, white cells correspond to land, black cells to sea.

To differentiate between countries as well, we will download different country-wise maps from GWA [48]. In this case the layer is not important, we are only using this as a base. We will cross this map with the land mask we obtained before to divide the cells at each country between onshore and offshore. Then we can assign the specific cost for onshore/offshore associated with that country and merged all the countries to generate a pan-european map of total costs per kW.

Once we have this cost map, given the coordinates of the turbine, we can check the value in the cost map for those coordinates and multiply by the nominal power of the turbine to obtain the final total cost of the turbine. By adding all turbines in a WF we obtain the total cost of the WF.

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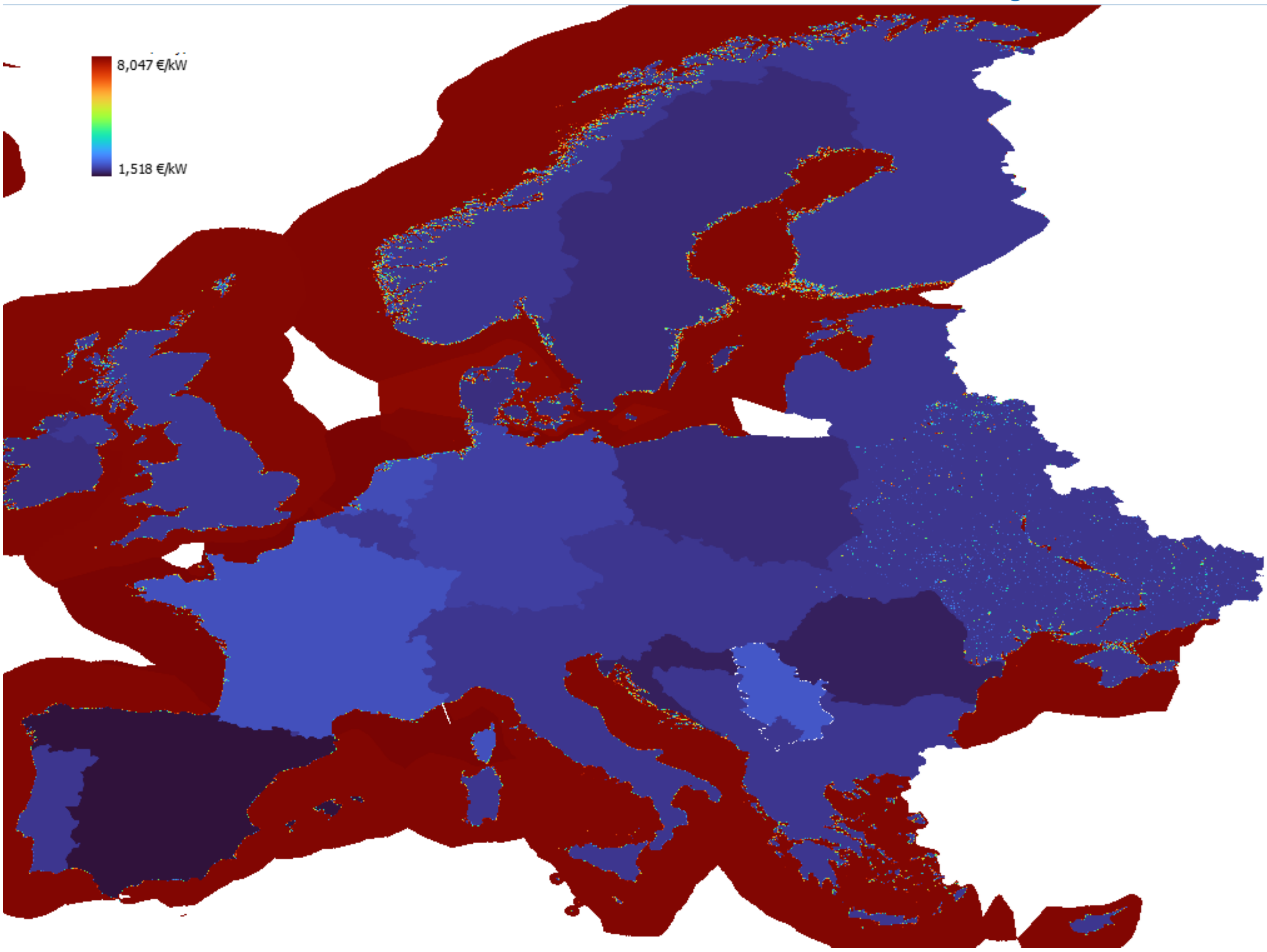

Figure 41: Map with the total costs per installed kW

5.9. Random Sample of Data Points

In order to transform the biodiversity PDF and LCOE into the respective Environmental and Techno-Economic Scores, we took a statistical approach. We study the distribution of values obtained at a randomly generated sample points across Europe, to obtain a mapping function that resembles that distribution of values.

We obtain the sample of random points with the software QGIS. Using QGIS we obtain a sample of 5000 random points within the bounding box or Europe. We use UTM coordinates to ensure that the points are homogeneously distributed in space. From those random points we need to discard 2633 for not being located inside our maps. From the remaining points, 1444 correspond to onshore and 923 to offshore.

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At the following figure we show the map of randomly sampled points that we are considering. Notice that the invalid points lie mainly in countries we are not considering for this project (mainly Turkey and Russia).

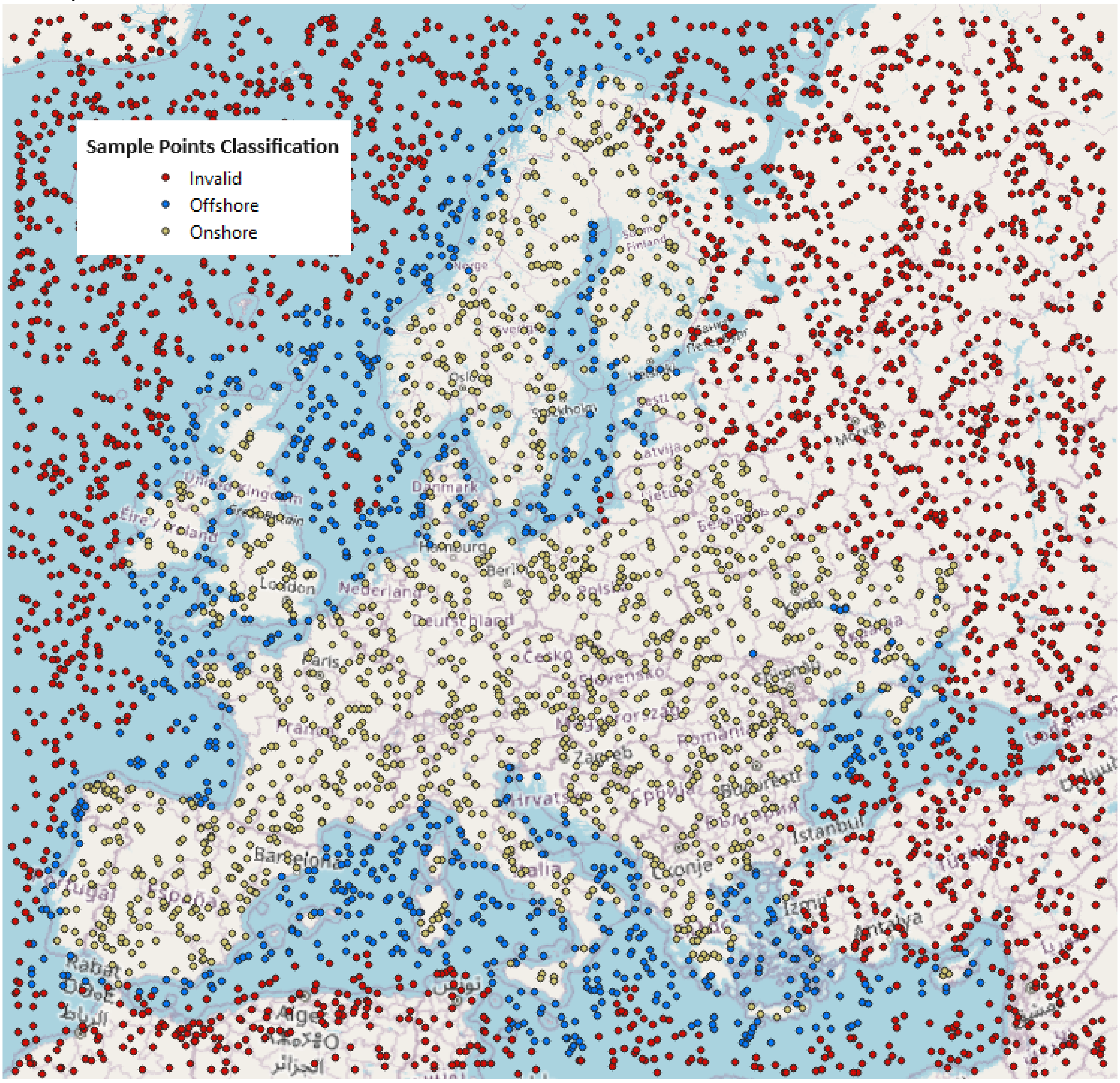

Figure 42: Map of random sample of points, used for the final calibration of Environmental and Techno-Economic Scores.

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6. Online tool

The KPI that we have developed will be deployed as an online tool in the KEP platform. The development of this online tool is not fully completed; thus, some details of the specifications and the visual aspect of the tool might change.

For simplicity, we have placed some limitations:

- We can only place a single turbine
- The turbine model must be selected from a dropdown list. This will select the hub height, rotor diameter, sound at source and power curve.
- We cannot select social interventions.

The tool will have two tabs. The first one will allow to select the location of the turbine. We can click on the map or fill the coordinates in the form. The Wendy symbol will mark the chosen location. In a blue polygon or circle we can see the location of the closest populated area, and with the camera symbol we can see the closest site of touristic interest. In the left form we must also select the ownership model (social, hybrid or corporate) and the wind turbine model.

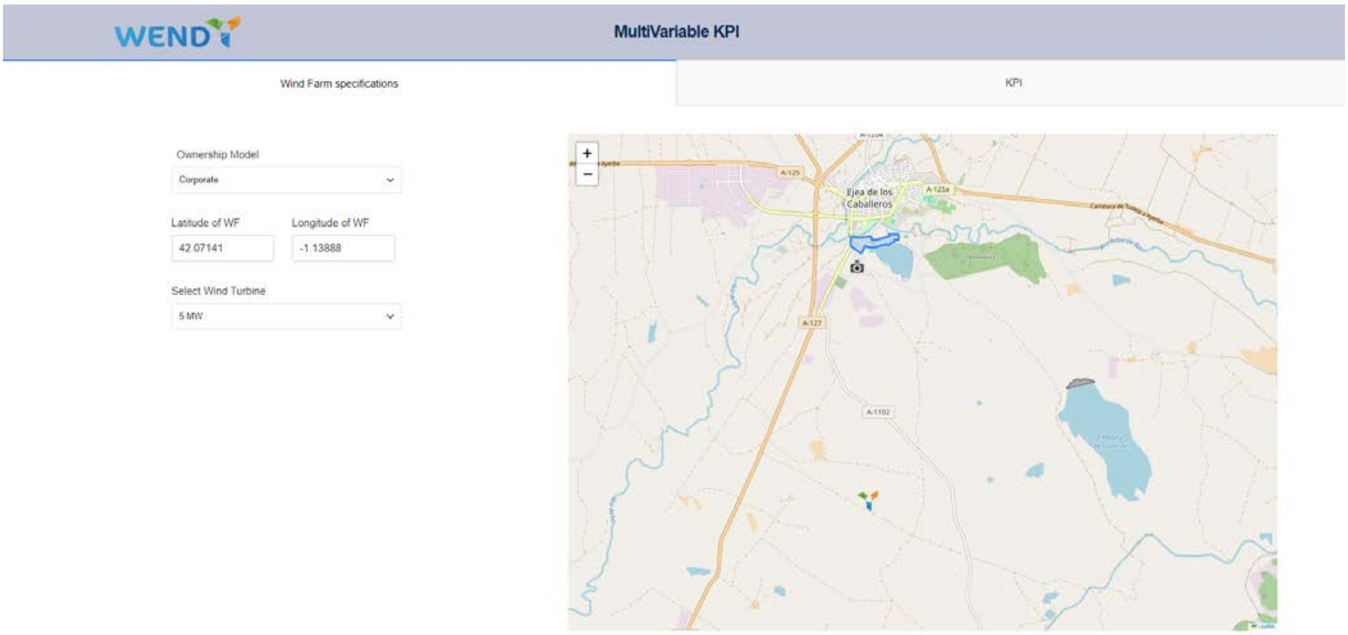

Figure 43: First tab for the multi-variable KPI online tool

In the second tab, we can visualize the results. Before the calculations are made, we can adjust the weights that we give to each one of the three dimensions (social, environmental and techno-economic). We click on the button 'COMPUTE' and the final results are shown in the right.

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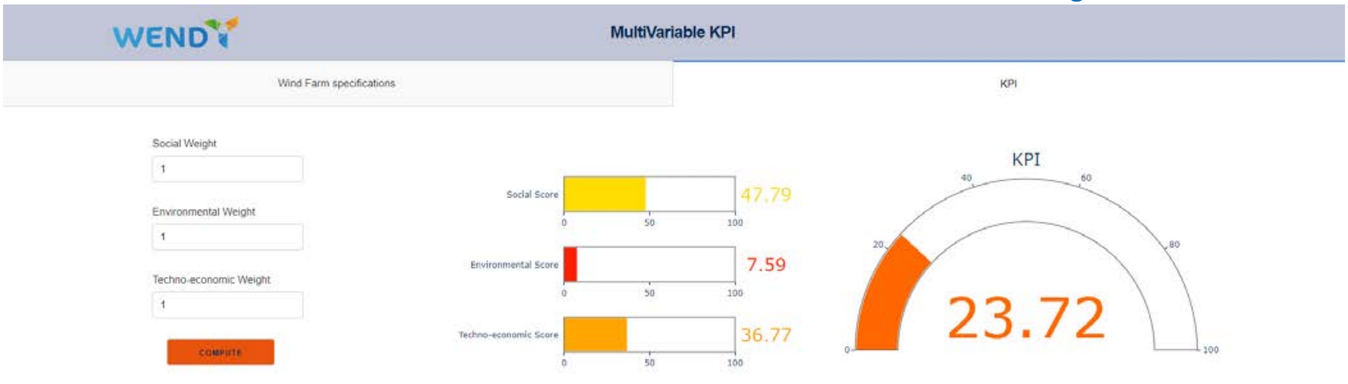

Figure 44: Second tab for the multi-variable KPI online tool

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7. Sustainability Readiness Levels

7.1. Conceptual framework

Sustainability should be considered holistically in all aspects of wind energy development, from first concept to decommissioning. Current global and national guidelines measure different aspects of sustainability separately, for example environmental impacts are measured nationally in an Environmental Impact Assessment whereas social impacts are often only measured at the early stage of a development using global standards on social responsibility. There is need to be able to measure and track progress towards the "sustainable wind energy development" throughout the entire life-cycle of a wind farm in a way that allows direct comparison between developments and can aid planners in sustainability reporting according to Environmental, Social and Governance (ESG) standards. To support this, together with the wind industry and through a co-creation dialogue process, we have developed the concept of Sustainability Readiness Levels (SustRLs), which extends the Technology Readiness Levels (TRLs) as a method for tracking of the level of maturity with Societal and Environmental Readiness Levels. This was done as part of the Norwegian Research Centre on Wind Energy – NorthWind [54]. Here the concept of Sustainability Readiness Levels for wind farm development are described. A similar concept has been developed as well for wind turbine design.

The wide use of technology readiness levels means that it is a familiar concept for industry and policy makers. However, it has not yet been adapted to assess environmental sustainability of a technology, product or process. Here we bring together all the aspects of technology, societal and environmental sustainability into three pillars within the Sustainability Readiness Levels. The Sustainability Readiness Levels score how sustainable a wind farm is based on a holistic assessment of technological, societal and environmental aspects throughout the entire development process. Scoring on a consistent scale also allows direct and holistic comparison of the sustainability maturity of different developments. The Sustainability Readiness Levels are not intended to replace existing standards and sustainability measures, but instead provides a framework in which to work through these standards and measure progress by providing an overall sustainability readiness score. Standards, guidelines and best practices will also change over time, and it is important that the most up to date versions are always consulted. The following existing standards and guidelines are included in the Sustainability Readiness Levels:

- ISO standard 26000 – Social Responsibility
- ISO standard 14000 – Environmental Management
- Strategic Environmental Assessment & Environmental Impact Assessment (2001/42/EC, and 2011/92/EU as amended by 2014/52/EU)
- Taskforce on Nature-related Financial Disclosures (TNFD) framework
- Global Reporting Initiative (GRI) standards
- International Finance Corporation Performance Standards on Environmental and Social Sustainability

Tracking progress:

The readiness levels are intended to be "balanced readiness levels" [55], where each pillar is assessed individually and progress along each pillar does not necessarily occur at the same rate. Each of the nine levels has a corresponding description which can be used to assess progress within each pillar. To reach a certain level on a pillar the development must meet all the requirements within the level description. Levels are assessed individually for each pillar and then combined to create an overall readiness level score. This overall score is proposed to be calculated as the geometric (product) mean as this assumes that scores for all perspectives should be fulfilled simultaneously:

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$$SustRL = \sqrt[3]{\prod[ERL, SRL, TRL]}$$

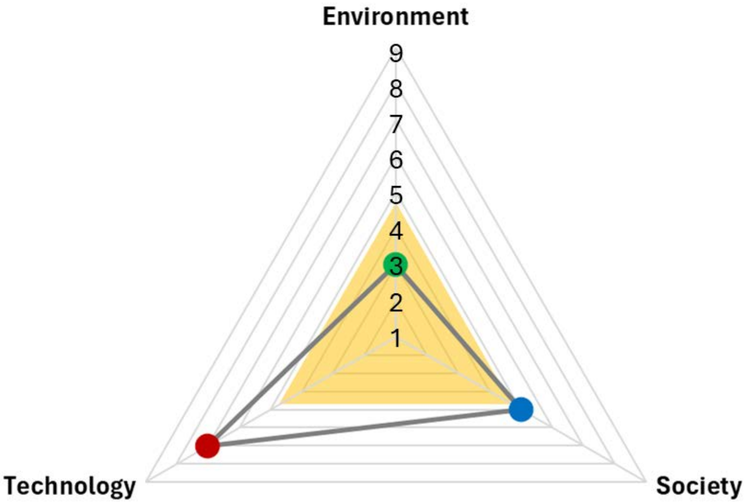

Figure 45: Example of how Readiness Levels can be visualized, with the overall Sustainability Readiness level given as the shaded area.

7.2. Description of the Readiness Levels

The Development Sustainability Readiness Levels start at the planning stages with stakeholder engagement and the Strategic Environmental Assessment carried out at the same time as the energy requirements and scope of the development are established (Level 1). It incorporates pre- and post- construction monitoring with adaptive management and ends with community inclusive and nature positive development from the concept stage through to decommissioning and restoration (Level 9). Sustainability is measured across the three pillars of Technology, Social-economic and Environmental Sustainability Readiness levels.

The goal of the Technology pillar is to build a wind energy development that meets all energy requirements and includes all environmental and social impact mitigations up to decommissioning and restoration. The Technology pillar follows the standard stages of a wind energy project from the initial scope through to decommissioning. If social and environmental impact mitigation measures are not considered at each stage of the development, then it cannot progress on to the next Technology Sustainability Readiness level. A complete plan for recycling and repurposing of the wind energy development must be in place to reach Level 9, but it does not need to have been implemented i.e. the wind farm can still be operational.

The goal of the Society pillar is to ensure stakeholder inclusion in the entire development process from concept through to site decommissioning and restoration. The initial mapping of relevant stakeholders, potential impacts and community needs at Level 1 should follow the guidelines of the International Finance Corporation Performance Standard 1. The stakeholder engagement plan should cover all levels of *inform*, *consult*, *involve*, *collaborate*, and *empower* at every stage of wind farm development. This pillar also extends beyond the footprint of the wind farm development and includes additional local infrastructure such as electricity grids, port infrastructure and waste management.

The goal of the Environmental pillar is to ensure that the wind farm development goes beyond just environmental impact mitigation measures, and that the development construction, operations, and decommissioning stages

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are all nature positive. As nature positive development is a relatively new concept, led by the goals of the Convention on Biological Diversity's Kunming-Montreal Global Biodiversity Framework, detailed international standards and guidelines for industry are still being developed. However, there are several guidance documents and reports from reputable organisations that can be consulted:

- Pollination Group & Taskforce on Nature-related Financial Disclosures: "Nature Positive Strategy: Practical Guidance for Corporates"
- World Business Council for Sustainable Development: Roadmaps to Nature Positive: Foundations for all businesses
- World Economic Forum Briefing Document: Clean Energy as a Catalyst for a Nature-Positive Transition

The Environment pillar also includes disclosure of how nature-related *governance*, *strategy*, *risk*, and *impacts* are managed within the wind farm development through the use of the Taskforce on Nature-related Financial Disclosures (TNFD) Recommendations. Although the recommendations have only recently been finalised (September 2023) they are consistent with the Task Force on Climate-related Financial Disclosures (TCFD) recommendations, the International Sustainability Standards Board (ISSB) guidelines and the GRI standards.

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Overview of Development Sustainability Readiness Levels

Readiness Level	Technology Readiness Levels	Social-economical Readiness Levels	Environmental Readiness Levels
Level 1	Proposed plan for meeting energy needs outlined, including scale & location of project	Stakeholder mapping and engagement plan developed for all levels of engagement	Strategic Environmental Assessment conducted
Level 2	Notice of proposed wind energy development is circulated for consultation and approved by the relevant authority	Communications plan for informing stakeholders is formulated	Environmental Impact Assessment of development site conducted
Level 3	Application for license, environmental impact assessment and initial stakeholder engagement is completed	Communications plan is implemented	Environmental impact mitigation measures are included in the development plan & all environmental issues disclosed
Level 4	Detailed plan for development and impact mitigation measures completed	Stakeholders consulted on development plan and proposed mitigations for social impacts	Pre-construction monitoring completed
Level 5	Construction of development is nature and society inclusive	Construction of development considers socio-economic impacts	Construction of development is nature inclusive
Level 6	Development is operational and standard operations meet energy needs	Stakeholders are involved in formulation of development plan and mitigation measures	Post-construction monitoring is implemented
Level 7	Development is operational with adaptive management implemented	Continued stakeholder engagement	Adaptive management is implemented
Level 8	Development operations are nature positive and community inclusive	Development operations are community inclusive	Development operations are nature positive
Level 9	Plan for decommissioning includes recycling or re-use of components, repurposing of existing infrastructure and both social-economic and environmental restoration	Community inclusion in entire development process from concept to site decommissioning and restoration	Nature positive measures are followed during decommissioning

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Technology Readiness Levels

Levels 1-3: Project plan → Application

Levels 1 to 3 closely follow the existing Environmental Impact Assessment framework. To reach Level 3 stakeholder engagement and environmental impact mitigation needs to be considered at all stages of the development planning process. The process must have followed all national requirements and guidelines for best practice, with full transparency and disclosure at every stage. Level 3 of the Technology Sustainability Readiness Level pillar can only be achieved if Levels 2 of both the Socioeconomical and Environmental Sustainability Readiness Level pillars have been reached.

1	**Proposed plan for meeting energy needs outlined, including scale & location of project**
	• Energy needs for the country/region have been assessed within a strategic environmental assessment and the proposed site has been identified as suitable in line with national energy infrastructure plans. • Proposed site and scale of wind energy development to meet energy needs has been identified – this includes a geospatial file of the windfarm footprint (e.g. shapefile), the number and size of turbines, and location of turbines within the windfarm footprint. • Full transparency around scale of plans and details are published on a publicly accessible website.

2	**Notice of proposed wind energy development is circulated for consultation and approved by the relevant authority**
	• Detailed note on proposed wind energy development is produced and circulated with adequate time allowed for consultation and evaluation. E.g. in Norway a notification note is completed and approved by the Municipality.

3	**Application for license, environmental impact assessment and initial stakeholder engagement is completed**
	• Ability to build wind energy development is proven to relevant national regulatory body • Potential environmental and socio-economic impacts have been assessed as set out in Level 2 of the Social-economic and Environmental Sustainability pillars.

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Levels 4-6: Design → Construction

Levels 4 to 6 ensure that all social-economic and environmental impact mitigation measures which have been identified are fully implemented at the construction and operations stages. At Level 5 the development must be nature inclusive wherever possible (e.g. creating artificial reefs or habitat restoration) but it does not need to be nature positive – this is only required to reach Level 8. Transboundary effects are an important consideration at this stage and the assessed impacts of development construction and operation will need to go beyond just the footprint of the wind farm. To reach Level 6 the development must be fully operational with all the identified impact mitigation measures implemented.

4	**Detailed plan for development and impact mitigation measures completed**
	• The development environmental, construction and transport plan meets all impact mitigation requirements following stakeholder engagement and environmental impact assessments. • Development plan is evaluated against IFC Performance Standards on Environmental and Social Sustainability.

5	**Construction of development is nature and society inclusive**
	• Includes re-purposing of existing infrastructure for development e.g. oil platforms or existing roads are used for construction of the new development. • Waste impacts are minimised and local waste-management facilities are used to offset transboundary effects. • Recycled materials are used wherever possible.

6	**Development is operational and standard operations meet energy needs**
	• Wind energy development is constructed, integrated to the grid and operational with all impact mitigation measures implemented.

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Levels 7-9: Operation → Decommissioning

Levels 7 to 9 take the wind energy development beyond mitigating impacts to being nature positive and community inclusive. Sufficient monitoring will be necessary to demonstrate that the overall impact of the development is positive. Standards and guidelines for nature-positive strategies are still in development, but there are a number of resources available in the Taskforce on Nature-related Financial Disclosures knowledge hub including "Nature Positive Strategy: Practical Guidance for Corporates" developed by Pollination and the Roadmaps to Nature Positive: Foundations for all businesses from the World Business Council for Sustainable Development. A complete plan for recycling and repurposing of the wind energy development must be in place to reach level 9, but it does not need to have been implemented i.e. the wind farm can still be operational.

7	**Development is operational with adaptive management implemented**
	• Development has plan and flexibility to adjust for additional environmental impact mitigations e.g. switching off turbines during peak migration. • To reach Level 7 here it is essential that post-construction monitoring and adaptive management is implemented as required in Levels 6 and 7 of the Environmental Sustainability pillars.

8	**Development operations are nature positive and community inclusive**
	• All impacts are mitigated or offset, and the overall impact of the development is positive for both social-economic and environmental factors e.g. jobs growth, increased biodiversity. • Long term monitoring of the development post-construction will be necessary to measure whether operations are nature positive and community inclusive.

9	**Plan for decommissioning includes recycling or re-use of components, repurposing of existing infrastructure and both social-economic and environmental restoration**
	• Recyclability of turbines at end of life or re-use of components is considered from the start of development. • Repurposing of existing infrastructure for future wind farms is planned during installation and decommissioning.

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Societal Readiness Levels

Levels 1-3: Project plan → Application

Levels 1 to 3 cover the processes of stakeholder mapping and development of an engagement plan. The engagement plan should cover all levels of *inform*, *consult*, *involve*, *collaborate,* and *empower,* however it is not expected that all these actions will have been implemented at level 3. Involvement occurs later in the pillar at levels 4 and 5, collaboration at level 6 and empowerment at levels 8 and 9.

1	**Stakeholder mapping and engagement plan developed for all levels of engagement**
	• Mapping of relevant stakeholders, potential impacts, and community needs, following the guidelines of IFC Performance Standard 1. • Develop long-term plan for stakeholder engagement - starting at an early stage and goals identified for minimising impacts. • Engagement plan should cover all levels of *inform*, *consult*, *involve*, *collaborate*, and *empower*.

2	**Communications plan for informing stakeholders is formulated**
	• An initial plan for mitigating social-economic impacts and process for communicating this is outlined prior to stakeholder engagement.

3	**Communications plan is implemented**
	• Extensive outreach to local community where wind farm will be located and all other relevant stakeholders. • Outreach aims to understand stakeholder concerns and values.

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Levels 4-6: Design → Construction

Levels 4 to 6 provide increasing involvement of stakeholders in the development plan to the point of the plan being formulated in collaboration with relevant stakeholders. This is the stage at which a development becomes beneficial to a local community.

4	**Stakeholders consulted on development plan and proposed mitigations for social impacts**
	• Development plan addresses stakeholder concerns, with aims to reduce socio-economic impacts and enhance benefits. • Stakeholder feedback is considered in final development plan.

5	**Construction of development considers socio-economic impacts**
	• Develop dedicated goals to reduce socio-economic impacts and enhance benefits during the construction phase e.g. use local workforce and supply-chain. • Transparency around local infrastructure requirements and expected impacts e.g. port infrastructure or electricity grid upgrades.

6	**Stakeholders are involved in formulation of development plan and mitigation measures**
	• Development plan is formulated in collaboration with relevant stakeholders.

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Levels 7-9: Operation → Decommissioning

Levels 7 to 9 further empower community stakeholders with continued engagement and involvement right the way through to the decommissioning stage. The wind farm development provides socio-economic benefits to the community (Level 8) and includes them in the site restoration process (Level 9).

7	**Continued stakeholder engagement**
	• Plan formulated for continued stakeholder engagement and collaboration throughout the operational phase of the development. • Long-term stakeholder engagement plan, including informing community of any changes to the development and addressing any new concerns that arise.

8	**Development operations are community inclusive**
	• Develop dedicated goals to reduce socio-economic impacts and enhance benefits. • Share plan for infrastructure requirements and discuss indirect impacts such as port infrastructure or electricity grid upgrades with community. • Community benefits could include shares in the development or lower energy costs. • Plan for local jobs with realistic assessment of job stability during operations phase.

9	**Community inclusion in entire development process from concept to site decommissioning and restoration**
	• Community is engaged and involved in plan for site decommissioning and restoration (both social and environmental). • Long term follow up is planned e.g. job continuity.

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Environmental Readiness Levels

Levels 1-3: Project plan → Application

Levels 1 to 3 follow the standard environmental impact assessment process that happens in most countries – a national Strategic Environmental Assessment identifies development areas, developers then complete an Environmental Impact Assessment for their proposed site and an impact mitigation plan is completed. At levels 2 and 3 the Taskforce on Nature-related Financial Disclosures (TNFD) framework should also be followed.

1	**Strategic Environmental Assessment conducted**
	• Strategic Environmental Assessment at a national or regional level is used to identify problem sites, habitats, or species. • Baseline studies & sensitivity mapping of potential locations conducted as early as possible. • Transparency & sharing of baseline datasets.

2	**Environmental Impact Assessment of development site conducted & all environmental issues are disclosed**
	• Environmental Impact Assessment completed and evaluated in line with national regulations. • Nature-related issues for the construction and operation of the wind farm are disclosed and assessed using the Taskforce on Nature-related Financial Disclosures (TNFD) framework.

3	**Environmental impact mitigation measures are included in the development plan**
	• Proposed mitigation plan is completed in line with national regulations e.g. in Norway an Environmental, construction and transport plan (MTA) is completed, and includes response to the nature-related issues identified using the TNFD framework. • Plan includes adapted strategies for area specific mitigations e.g. painting turbine blades black, locating turbines in the area where they will have the least impact.

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Levels 4-6: Design → Construction

Monitoring and transparency are important aspects of levels 4 to 6, and the Global Reporting Initiative standards should be followed for all reporting at these levels. Level 5 incorporates nature inclusive design in the development plan, however at this stage it is not expected that the development is nature-positive – i.e. the benefits to nature do not need to outweigh the impacts even though the impacts should still be minimised as much as possible.

4	**Pre-construction monitoring completed**
	• Pre-construction monitoring at the development site. • Data used for assessment of potential impacts and estimated reduction in impacts from proposed mitigation measures. • Any necessary adjustments are made to the mitigation plan to reduce environmental impacts.

5	**Construction of development is nature inclusive**
	• Development construction considers multiple uses of landscape and sea space and is timed to minimise impacts. • Includes solutions for nature inclusive design e.g. positive reef effects, mooring solutions with less seabed impact, use of electric installation vehicles.

6	**Post-construction monitoring is implemented**
	• Continued monitoring of development, evaluation of impact mitigations, disclosure of results, and sharing of data throughout the lifetime of the development. • Global Reporting Initiative standards are followed for reporting.

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Levels 7-9: Operation → Decommissioning

Levels 7 to 9 ensure that the wind farm development goes beyond just environmental impact mitigation measures, and that the development construction, operation, and decommissioning stages are all nature positive. See the introduction to this section for suggestions of the various nature positive guidelines that could be followed here.

7	**Adaptive management is implemented**
	• Post-construction monitoring and impact evaluation feed into a plan for adaptive management. • Additional environmental impact mitigation measures are implemented if needed e.g. switching off turbines during peak migration.

8	**Development operations are nature positive**
	• All environmental impacts during the operations phase are mitigated or offset and the overall impact of the development is positive e.g. increased biodiversity.

9	**Nature positive measures are followed during decommissioning**
	• Restore nature after decommissioning; restore to "pre" development stage or leave nature positive measures in place e.g. artificial reefs.

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