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An Indicator to estimate the social impact in wind farms.

S. Arregui[1], S. de Uña[1], D. Garcia[1] and A. Talayero[1]

[1] Fundación CIRCE

Parque Empresarial Dinamiza, Avenida Ranillas Edificio 3D
1ª Planta, 50018, Zaragoza (Spain)

Abstract. Wind energy is the most mature and efficient renewable energy, but the proliferation of wind farms is causing social rejection.

The study of a project's technical and economic viability is intrinsic to the project itself; environmental viability is regulated by environmental legislation, but the social impact of projects is not analyzed.

Social assessment is subjective and depends on many factors. This study defines an indicator based on studies conducted to assess a wind farm's social impact and how it can be improved through different interventions.

Although is an impossible challenge to gather all scenarios into a general framework, having an early social indicator could be a powerful tool to study the viability of wind farm projects.

Key words. Wind Energy, Social Impact, Multivariable KPI, Social Acceptance, Community engagement.

1. Introduction

Wind energy is considered a mature technology due to decades of development and deployment. This maturity is characterized by wind turbines becoming more efficient, reliable, and capable of generating more energy. As the industry has grown, manufacturing and installation costs have decreased, making wind energy more competitive with traditional energy sources. Wind farms (WFs) are a standard part of the landscape in many parts of the world, contributing significantly to renewable energy production.

Despite the benefits of wind energy, the massive expansion of this technology can provoke a social or community backlash against the proliferation of wind farms. WFs can cause disappointment or rejection among local communities and citizens if some aspects are not handled carefully [1].

One issue contributing to community resistance is that wind turbines (WT) can significantly alter the visual landscape. Large turbines can be considered a form of visual pollution in areas known for their natural beauty. Another aspect is that the noise produced by wind turbines is a common complaint among nearby residents, causing discomfort and opposition. The impact on birds and bats is of concern because it can provoke resistance from environmental groups and local communities, and, although not scientifically substantiated, fears of possible health effects from noise and vibrations from the turbines also contribute to community resistance. The financial and economic aspects of the project could also become a source of conflict if the needs of the community are not taken into consideration.

This negative perception is summarised as the NIMBY (Not In My Back Yard) concept. NIMBY describes a phenomenon where people oppose certain developments (such as wind farms) when they are located near them, despite recognizing their necessity or benefit to society at large. This opposition can lead to challenges in setting up wind farms, delays in development, increased costs, and sometimes even the cancellation of projects. The PIMBY (Please In My Back Yard) concept contrasts with NIMBY, where people or communities actively welcome development projects in their area. They manifest the desire for clean energy, economic benefits like job creation or additional tax revenue, or even community ownership models where the local population has a stake in the project. Communities with a PIMBY attitude can facilitate smoother project development, create local support for renewable energy initiatives, and even become advocates for similar projects in other areas [2].

Improving communication, engaging with communities early in planning to address concerns, and incorporating local input can mitigate opposition. Employing designs that minimize visual and auditory impacts, such as siting turbines away from residential areas or reducing their visual predominance, can reduce local backlash. Moreover, ensuring that local communities benefit directly from wind farm projects through job creation, investment in local infrastructure, or community ownership models, can increase acceptance.

Balancing the benefits of wind energy with the genuine concerns of local communities is a colossal challenge, but including a community-focused approach to the project is essential to ensure that the energy transition will be sustainable and socially acceptable.

In this study, we have developed a single Multivariable Social KPI (SKPI) that approximates the general level of social acceptance that we can expect for a wind farm project. The goal is to use relatively simple inputs and open data sources to evaluate potential social factors of opposition and produce a first approximation to the problem of social acceptance. More nuanced and detailed studies can (and should) then be adopted to each community's particularities to produce a more robust study.

In the following section, we describe the definition of the SKPI.

2. Multivariable KPI definition

The inputs to estimate the SKPI are the location of the WTs and their main technical descriptions, such as hub height (HH), rotor diameter and noise level. Besides, we'll use as inputs information from public data sources (such as nearby municipalities, demographic indicators, biodiversity data, etc.). Additionally, social interventions can be considered to improve the acceptance of the WF.

The definition of the SKPI is disentangled in six different factors that we understand that every WF project should address:

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

For each one of these aspects $i \in \{V, T, N, P, A, B\}$, we compute an initial assessment A_i in the range [0,1], based on WTs location and technical specifications, with 0 meaning total opposition and 1 meaning total acceptance. Each aspect will have a specific procedure to be computed that will be specified in later subsections.

After the initial assessment of these social aspects are defined, it is possible to introduce interventions aimed to improve the KPI. Each aspect i has an array of interventions, I_{ij} (interventions j at aspect i), that can take two values:

- 0 if the intervention is not present.
- V_{ij} if the intervention j is present.

These values V_{ij} measure the intervention's impact on improving the corresponding social aspect. I_{ij} will be in the range [0,1], with 0 meaning that they have no impact and 1 meaning that its presence 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 I_i (1):

$$A_i^* = f(A_i, I_i) \tag{1}$$

When calculating the final assessment interventions are introduced by adding iteratively fractions until potentially reaching the perfect score of 1, given precisely by I_{ij}. For instance, in case there is one possible intervention (I_{i1}), the final assessment A_i^* would be (2):

$$A_i^* = A_i + (1 - A_i)I_{i1} \tag{2}$$

Initial assessment A_i is in the range [0,1]. Therefore, the remaining gap until the perfect score is ($1-A_i$), and we add a fraction I_{i1} of that gap to the assessment of the social aspect. Adding a second intervention, the result of equation (2) will replace the 'initial' assessment, and a new fraction of the remaining gap I_{i2} will be added. We keep iterating this process until all the interventions are accounted for. The final assessment A_i^* will always be in the range [0,1].

Unless the value associated with an intervention is considered exactly as 1, the feature will asymptotically approach 1 as we add new social interventions. It also should be noted that the final assessment will not depend on the order in which we introduce the different social interventions.

In Figure 1 we represent the general workflow of inputs and processes needed to obtain the final assessments for each social feature.

Once we have all the final assessments for each social aspect, the final score will be a weighted geometric mean (3):

$$SKPI = \left(\prod_i (A_i^*)^{w_i}\right)^{\frac{1}{\sum_i w_i}} \tag{3}$$

where w_i are the weights considered for each social aspect. These parameters are left to the user discretion, so they can be adapted to different communities.

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. Some bibliographical references [3],[4] might provide an initial value based on surveys for some specific interventions, but in general they remain to be tuned using expert consensus opinion and/or future studies.

The indicator could be used without considering any social interventions, thus providing an indicator based exclusively on WTs location and technical specifications. This use case can be useful to establish a benchmark scenario.

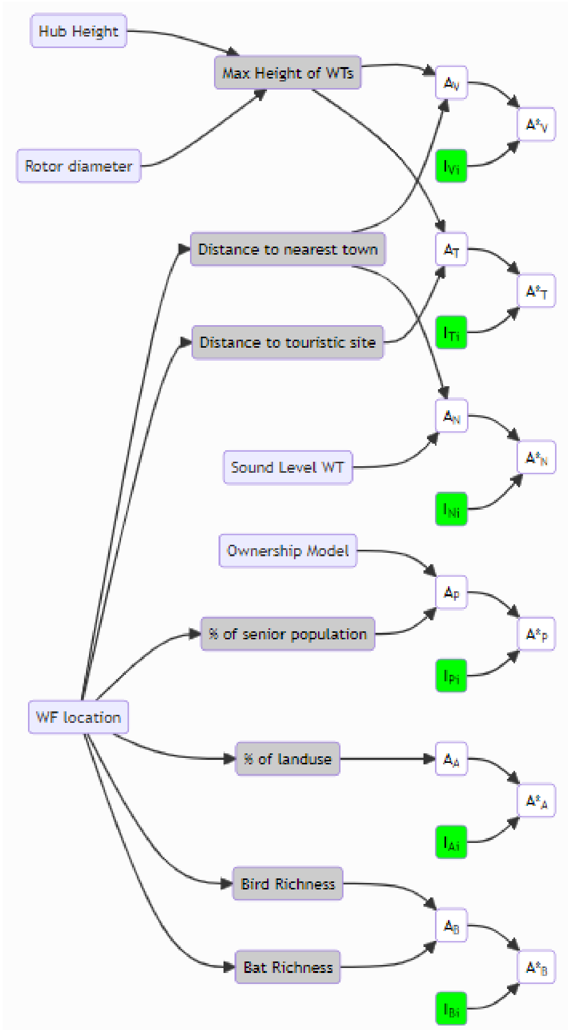

Fig. 1: Workflow to obtain the different assessment of social aspects. Purple boxes determine inputs of the model, while grey boxes are intermediate results that do not need to be provided by the user.

A. *Visual Acceptance*

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 [5] with the top of the wind turbine (4):

$$\beta = \tan^{-1}\left(\frac{h}{L}\right) \quad (4)$$

where h is the height of the turbine considering the tip of the blade, and L is the distance of the observer, that we locate at the nearest town or critical point to the WF location. The critical point can be located through a query to OpenStreetMap [6].

It is assessed that up to an angle of 0.5º, the visual impact is not significant. The WT is potentially visible between 0.5º and 2.5º and becomes predominant from 2.5º. Following that progression, we modelize the visual acceptance as a sigmoid-like function given by (5):

$$A_V = 1 - \frac{e^{(\beta-\beta_0)}}{1-e^{(\beta-\beta_0)}} \quad (5)$$

with β_0=2.5º. This produces a visual acceptance that increases with distance to the turbines and decreases with the height.

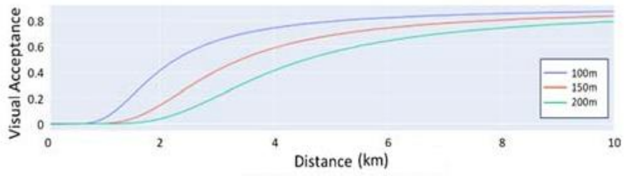

Fig. 2: Initial Visual Acceptance vs distance to the critical point (usually chosen as the closest municipality to the WF), for three different maximum height of the turbine (100 meters, 150 meters and 200 meters)

Possible interventions that can improve visual acceptance include visual absorptive elements, promoting sponsored visits, improving an existing public space, or creating a new one.

B. *Tourism Acceptance*

Near relevant tourism sites, concerns could be raised regarding a loss in tourism activities in the area due to the proximity of the WF and its visual effect on the scenery [7].

Thus, we can assess tourism acceptance using the same methodology developed for the so-called visual acceptance but locating the observer at the closest touristic site (which can also be obtained through OpenStreetMap [6]). So, the initial tourism acceptance A_T can also be obtained with equation (5).

The social interventions aimed to modify this assessment include consult seasonal residents, project the WF as a tourism destination, or develop other activities in the area.

C. *Noise Acceptance*

Noise disturbance is one major concern regarding a wind farm installation. Similarly to visual impact, the noise that will reach the population will mostly depend on distance and the technical specifications of the turbines. There exists many different studies and advanced commercial noise propagation models such as ISO 9613-2:1996 or WindPRO DECIBEL module. It is not within the scope of this work to try to match those models, only to obtain a raw evaluation that produces a first approximation, as we already stated at the introduction of this paper.

Thus, we will follow a simple model used by the Swedish Environmental Protection Agency [8] that expresses the sound level at a location L_P with the formula (6):

$$L_P = L_w - 8 - 20\log r - \alpha r \quad (6)$$

where α is the absorption coefficient, r is the distance and L_w is the sound level at the source. The coefficient α depends on the temperature, frequency, and relative humidity. For a temperature of about 10ºC, a relative humidity in the range 20-80% and a low frequency of about 100 Hz, we can fix α at 0.5 dB/km [8].

L_w will be an input of the model. Its value is usually around 100 dB [9]. Using formula (6) we can obtain the sound level as a function of the distance:

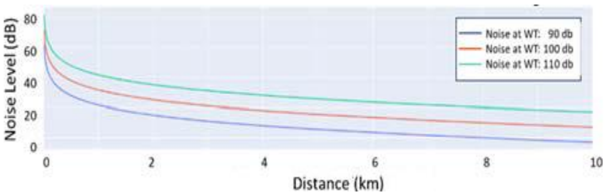

Fig. 3: Noise level as a function of the distance for three different levels of noise generated at source.

In the case of having multiple WT, different noise levels (L_1, L_2, …) are calculated from them with distances referred to the same geographical point (i.e. nearest town, residential area, etc.), and then added together using the formula (7)[10]:

$$L_P = 10 \log\left(10^{L_1/10} + 10^{L_2/10} + \cdots\right) \tag{7}$$

The sound levels are transformed into the noise acceptance initial assessment using a sigmoid function (8):

$$A_N = 1 - \frac{\exp(k(L_P - L_0))}{1+\exp(k(L_P - L_0))} \tag{8}$$

L_0 is considered 35 dB, and k=0.2. These values are defined based on a study that analyses people's perception of wind turbine noise [11]. This study concludes that 35 dB is acceptable for 50% of the people, 20 dB (similar to a ticking watch) is accepted by 95% of citizens, while at 50 dB (the level of moderate rainfall) acceptance drops to around 5%. This functional form approximately match does values.

In Figure 4 we represent the noise acceptance as a function of the distance.

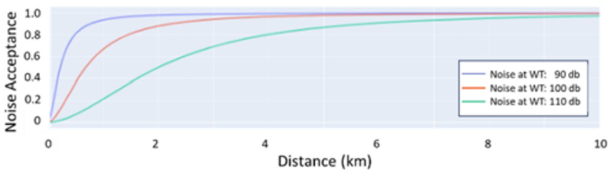

Fig. 4: Noise acceptance as a function of the distance, for three different levels of noise at source

The sound level at source depends on the WT model and is an input of the model, while distance is extracted using OpenStreetMap as we did for visual acceptance.

Among the interventions that can improve noise acceptance we find the sharing of information, the development of noise demonstration kits and the installation of noise damping panels.

D. Project Acceptance

Independently of possible specific objective impacts, as previously discussed, people have a different predisposition to embrace a wind farm project based on their own beliefs and biases. For instance, it is well known that age reduces the acceptance of WF [12]-[14]. Specifically, opposition arises abruptly among individuals older than 60 years of age [14].

Thus, an initial predisposition to the project, A_{p0}, is estimated using the percentage of senior population in the community (9). This percentage can be obtained from raster maps found in WorldPop [15] or the database from Eurostat [16].

$$A_{P0} = 1 - \frac{\exp(\delta(s - s_0))}{1+\exp(\delta(s - s_0))} \tag{9}$$

with s being the percentage of senior population and fixing the sigmoid parameters at s_0=25 (approximately the mean of Europe) and δ=0.2.

Beyond the age factor, social ownership models might enjoy higher levels of acceptance by default compared to corporate models. Thus, we incorporate an economic factor of 1 for social models, 0.41 for corporate models and 0.7 for hybrid models. We chose this ratio based on general levels of trust in energy suppliers [17]. Applying this economic factor we obtain the final project acceptance (10):

$$A_P = A_{P0} \cdot \text{ Economic Factor} \tag{10}$$

Project acceptance as a function of the percentage of senior population is shown in Figure 5:

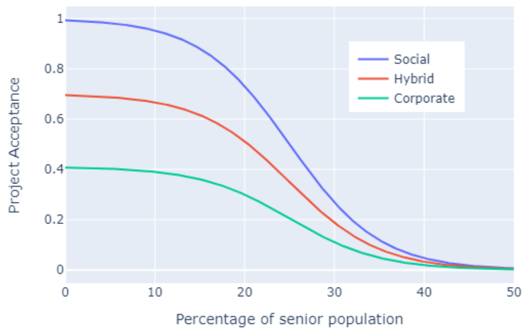

Fig. 5: Project acceptance as a function of the percentage of senior population in the community for three different ownership models: Social, Hybrid and Corporate.

There is a wide range of possible social interventions that can raise project acceptance: create a community engagement plan, public consultations, appointing a local liaison officer, creation of local jobs and training opportunities, the development of a Community Development Fund, institutionalize community benefits, etc.

E. Nature Activities Protection

In communities where livelihoods are dependent on nature (for instance the case of farming lands for onshore WF), there is an additional source of potential discontent as people perceived that their lifestyles are put in danger.

To assess this feature, we consider as an input the percentage of land used in agricultural or rural activities near the WF. This value can be obtained through a query to OpenStreetMap [6] using a bounding box around the WF location. We obtain an initial assessment of the nature activities protection as a linear decreasing function that reaches 0 at 40% (11). The value of 40% is selected as it is approximately the percentage of cultivation land in Europe [18].

$$A_A = \begin{cases} 1 - \frac{l}{40}\ ; & l \leq 40 \\ 0 & ; l > 40 \end{cases} \tag{11}$$

where l is the percentage of landuse near the WF.

Social interventions aimed at improving acceptance necessarily involve strengthen benefits in communities where livelihood depend on nature and offer land-tenure security.

The assessment developed in this subsection refers exclusively to onshore WF. Similar procedures could also be proposed for offshore WF with the focus on fishing practices instead.

F. Biodiversity Protection

We might also find local opposition in the case of many birds and bats species in the area. Instances of avifauna colliding with turbine blades constitute a major concern [19].

Using raster maps from Biodiversity Mapping [20] we can obtain values of species richness for both birds and bats with a 10 km^2 resolution. Birds and bats are considered two different factors, both combined into a unique biodiversity protection assessment (12):

$$A_B = \left(1 - \frac{\exp\left(\gamma(n_{\text{bat}} - n_{\text{bat,o}})\right)}{1+\exp\left(\gamma(n_{\text{bat}} - n_{\text{bat,o}})\right)}\right)\left(1 - \frac{\exp\left(\rho(n_{\text{bird}} - n_{\text{bird,o}})\right)}{1+\exp\left(\rho(n_{\text{bird}} - n_{\text{bird,o}})\right)}\right) \tag{12}$$

with n_{bat} and n_{bird} being the number of species of bats and birds in the vicinity of the WF, and setting the parameters as $n_{bat,0}$=15, $n_{bird,0}$=175, γ=0.3 and ρ=0.04, to approximately match the distribution of the number of species we can find across Europe.

In Figure 6 we show the initial assessment of biodiversity protection as a function of both the number of bird and bat species in the area.

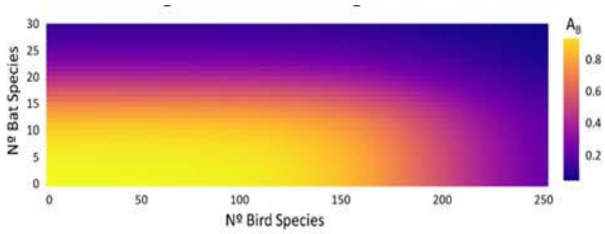

Fig. 6: Initial assessment of biodiversity protection, A_B, as a function of the number of bird species (x-axis) and bat species (y-axis) found near the WF.

In the past years different technologies and measures have been implanted to mitigate the environmental impact of a WF, such as the creation of buffer zones, remote sensing with radar or thermal detection, air bubble curtain techniques, etc. Other possible mitigation or compensatory measures include avoid sensitive periods at construction, employ an on-site ecologist or re-develop vegetation.

3. Conclusion

In this study we have developed an indicator of social acceptance of a wind farm by analysing six different factors independently. The final score is obtained through a weighted geometric mean, which implies that having a low score in only one of the six factors could seriously decrease the overall social indicator.

Each different feature has been developed based on basic project information and public data sources. This allows for the obtention of a preliminary result before the start of the project and allows for the preparation of interventions to improve social acceptance even before the project is set up.

In that regard, the indicator shows some limitations in the assessment of each of its features. It does not intend to replace proper assessments of visual, noise and tourism and recreation (T&R) impact, as well as biodiversity sensitivity mapping that should still be performed in detail according to the particularities of the location and project.

The proposed working scheme leaves open as free parameters the weights of each social feature to be tuned according to the sensitivity of the community. Also, it allows for the free inclusion of social interventions and their possible impact values on improving social perception. As there is a lack of bibliographical references regarding the impact of these interventions, at least from a quantitative perspective, future studies could help to fill this gap.

Overall, this indicator is a good tool for planning new projects as it allows an early assessment of the population's perception. Through the inclusion of interventions, it also can be used for the search of tentative solutions that could ensure the viability of a new WF project or look for new insights for those projects under construction or operation that present social problems.

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