Quantitative methodology for the estimation of the environmental impact of wind farms – The case of Greece and application on the country’s operating units

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Abstract. Following the EU guidelines towards a carbon free electricity sector by 2050, wind energy is expected to contribute a large part of the produced electricity, if not the largest. In this respect, wind installations are expected to multiply over the next years. There is significant development until today and wind is generally considered as a “clean” source of energy. However, although arguably less than other sources, the impacts concerning wind installations are certainly there amidst ever-growing local opposition and will certainly grow, especially in locations with high density. Attempting to quantify the total impacts per local regions in the case of Greece, a methodology is developed for those impact factors that are considered the most important. Certain focus areas are used for applying this methodology, based on installation density, location inside natural protected areas, as well as locations of touristic value. The results show that in general the total impacts might be considered on average mild to low. The tool developed is a first attempt to evaluate impact in a cumulative way and help investors, policy makers and local communities work together in achieving the best possible outcome. Further work is necessary to further develop this methodology, verify and detail the formulas used and establish a robust pattern that will be a useful tool for everyone to use.

1. Scope
The scope of this paper is to record the main factors that may have an impact with regards to wind energy. Subsequently, a methodology will be developed for quantifying the total environmental impact of wind farms by utilizing specific KPIs, adapted to the specific conditions of Greece. According to the writer’s knowledge, no such tools have been developed yet or in any case are not widely known. The ultimate goal is to assess the extent to which existing methodological tools meet the purpose of environmental benefits and impact assessment and then to evaluate their contribution to the proposal for mitigation measures.

2. Methodology
In order to calculate the total impact of a wind farm, focus has been given to the factors described in the following paragraphs, which cover the whole spectrum of possible impacts, covering all aspects of sustainability, namely economy, environment and society.

The KPIs considered follow a simple approach, where each KPI is the product of the factors considered, which are given a grade of 1-4, based on the magnitude of impact. In general, the following formula is being used for each KPI:
where $f_i$ is a factor on a scale 0.0-1.0, which is the supposed result of a specific site investigation which evaluates the actual impact of the described and/or determined factors. For the needs of this paper, since it was not possible to undertake site surveys (both for lack of resources as well as for lack of knowledge – certain aspects require special scientists) a uniform value of 1.0 for the specific factor is considered and $x, y, z$ are the individual variables considered for each KPI and are described below:

2.1. Biodiversity

This KPI actually takes into account the whole impact on the natural environment in a sort of way. Following the guidelines of IUCN [1], we define a $b_{sp}$ depicting the importance of any given species and a variable $Z_{zd}$, dealing with the location of a project within the limits of a designated protection area and its distance from it. The classification is given in Table 1:

| Species categorization | $b_{sp}$ | Distance | $z_{d}$ |
|------------------------|----------|----------|---------|
| DD - NE                | 1        | Inside area | 4       |
| LC                     | 2        | 0-500 m   | 3       |
| NT                     | 3        | 500-1500 m | 2       |
| CR – EN - VU           | 4        | >1,5 km   | 1       |

Table 1. Biodiversity classification.

Hence, the biodiversity KPI is based on the formula:

$$I_{biod} = \frac{1}{N_p} \sum_{i} f_{sp,i} * b_{sp,i} * Z_{D,i}$$

where we divide by N for the total amount of species considered.

2.2. Avifauna

This factor, although it concerns biodiversity, is accounted for separately because it is widely considered as the main impact of wind farms with regards to the environment. In general, it follows the same principle as above [2], only now an additional parameter is introduced (see Table 2), accounting for the density of WTGs in a given area, through which birds might fly, thus underlying a potential collision risk [3].

Table 2. WTGs density.

| Density   | $N_{WTG}$ |
|-----------|-----------|
| 0-10%     | 4         |
| 10-20%    | 3         |
| 20-30%    | 2         |
| >30%      | 1         |

Thus, the total KPI for avifauna will be calculated by the following formula:

$$I_{bird} = \frac{1}{N_p} \sum_{i} f_{h,i} * b_{w,i} * p_{a,i} * N_{WTG,i}$$
2.3. Land cover
This factor takes into account the type of land occupied for the installation of a wind farm. The categorization is based on the Corine Land Cover program basic types of land use [4] and the total area coverage as shown in Table 3 below:

| Land type                        | $C_{li}$ | Area coverage | $L_{COV,li}$ |
|----------------------------------|----------|---------------|--------------|
| Artificial surfaces              | 1        | 0-2%          | 1            |
| Agricultural areas               | 2        | 2-5%          | 2            |
| Waterbodies                      | 3        | 5-10%         | 3            |
| Forest and seminatural areas /   | 4        | >10%          | 4            |
| Wetlands                         |          |               |              |

Hence, the respective KPI is based on the formula:

$$I_{COV} = \sum_{i} L_{COV,li} \times C_{li} \quad (3)$$

2.4. Visual impact
Maybe this is the first thing that comes in mind when asked “what are the impacts of a wind farm”. As such it takes into account the most sub-factors, stemming from distance and number of turbines [5] [6], perception [7] and landscape value [5] and contributes the most in the total result.

The 4 different parameters, $V_{land}$, $V_{FOV}$, $Z_{tot}$, and $V_{WTG}$ are calculated in Table 4 below and are accounting for landscape value, the field of view coverage of any given observer, the influence zone (i.e. the radius within which a visible WTG lies) and an influence factor for the number of visible WTGs in each zone respectively.

| Land characterization                  | $V_{land}$ | FOV coverage | $V_{FOV}$ | Influence zone | $V_{WTG}$ | Visible WTGs | $V_{WTG}$ |
|---------------------------------------|------------|--------------|-----------|----------------|-----------|--------------|-----------|
| Degraded / low aesthetic value        | 1          | 0 – 10%      | 1         | 0 - 1.500 m    | 1         | 1 - 5        | 1         |
| Indifferent                           | 2          | 10 – 20%     | 2         | 1.500 – 5.000 m| 2         | 5 - 10       | 2         |
| medium aesthetic value                | 3          | 20 – 30%     | 3         | 5 – 8 km       | 3         | 10 – 20      | 3         |
| high aesthetic value                  | 4          | 30% +        | 4         | >8 km          | 4         | 20+          | 4         |

The KPI for visual impact is then calculated as:

$$I_{VISUAL} = V_{land} \times V_{FOV} \times \sum_{i} Z_{tot} \times V_{WTG} \quad (4)$$

2.5. Noise impact
The noise emitted by wind turbines might have a certain impact in dwellings depending on distance [8][9]. In this paper, the imission at the receptor is of concern. Following the guidelines of ISO 9613-2: "Acoustics - Attenuation of sound propagation outdoors, Part 2; General method of calculation" [10], the sound attenuation with distance was calculated. Based on this and the known noise levels of wind turbines, we calculated in Table 5 the zones of influence and a threshold beyond which the noise impact is considered as nonexistent.
Table 5. Noise impact calculation.

| Impact radius | I_{noise} (5) |
|---------------|--------------|
| 0-250 m       | 4            |
| 250-500 m     | 3            |
| 500-1,000 m   | 2            |
| 1,000-1,500 m | 1            |
| >1,500        | 0            |

2.6. Shadow impact
A possible impact factor is the annoyance that may be caused by the flickering of wind turbines. As it has been shown by Ellenbogen et al. [11] and Simos et al. [12], as a rule of thumb the potential impact zone is defined as a radius of 10D from a WTG, where D is the rotor diameter. The maximum impact zone is calculated at 1400 m.

Table 6. Shadow impact calculation

| Zone | Impact radius       | I_{shad,l}(6) |
|------|---------------------|--------------|
| A    | 0-400 m             | 3            |
| B    | 400-10D m           | 2            |
| C    | 10D-1400 m          | 1            |
| D    | 1400                | 0            |

2.7. Tourism / Land value impact
What is of major concern for many people living in the vicinity of wind farms is of course the potential impact it may cause on the properties. This factor is obviously highly dependent on the two previously mentioned factors. Additionally, one more parameter that must be considered is the initial “touristic” value (see Table 7) a land might have based on its location and importance.

Table 7. Land value assumption

| Land characterization | \( t_{value} \) |
|-----------------------|-----------------|
| Indifferent           | 1               |
| Medium traffic        | 2               |
| Touristic             | 3               |
| Highly touristic      | 4               |

Then, the total impact is calculated based on the formula below:

\[
I_{\text{t, total}} = f_{\text{val,l}} \cdot t_{\text{land,l}} + I_{\text{visual}} + I_{\text{noise}}
\]

(7)

2.8. Environmental injustice
In an attempt to define environmental injustice, one may say it is the unbalanced allocation of the environmental burden on any location or social group or the exploitation of them in favor of the wider population or other areas or groups. The “environment” is considered the socioeconomic and natural environment as a whole.

Since it is quite difficult to define definite parameters to “measure” this factor, it is proposed to make a simple comparison of the energy produced in an area, compared to the energy consumption by the inhabitants. Should this factor I_{env} be >1, it is a sign that there is some sort of injustice in the study area.
Table 8. Environmental injustice calculation

| Consumption / Production ratio | I_{envj}(8) |
|-------------------------------|-------------|
| 1-5                           | 1           |
| 5 – 10                        | 2           |
| 10 – 20                       | 3           |
| >20                           | 4           |

2.9. Total impacts

The total impacts are calculated as the simple sum of all the factors from the formulas (1)-(8) described above:

\[ I_{TOTAL} = I_{biod} + I_{avt} + I_{cov} + I_{visual} + I_{noise} + I_{value} + I_{envj} \] (9)

Furthermore, to make the result more understandable, the total value will be adjusted on a 0-100 scale. In order to achieve this reduction, the result is multiplied by 100 and divided by the maximum possible value the KPI $I_{TOTAL}$ can reach, which simply the sum of all KPIs when considering their respective maximum values.

3. Results

Certain focus areas where considered for the application of the methodology. In total more than 50% of the country’s total installed capacity is being examined, both in terms of projects and wind turbines. The study areas are given in Table 9 below:

Table 9. Focus areas

| Nr. | Location   | WF | WTG | Total power (MW) |
|-----|------------|----|-----|------------------|
| 1   | Argolida   | 11 | 78  | 174.7            |
| 2   | Evoia      | 56 | 550 | 650.725          |
| 3   | Evros      | 20 | 203 | 358.5            |
| 4   | Kefalonia  | 5  | 68  | 107              |
| 5   | Voiatia    | 17 | 140 | 336.25           |
| 6   | Nafpaktos  | 6  | 41  | 88               |
| 7   | Fokida     | 5  | 32  | 84.4             |
| 8   | Siteia     | 18 | 140 | 86.4             |
| 9   | Lesvos     | 4  | 27  | 13.725           |
| 10  | Dervenohoria | 10 | 93  | 194.75           |
| TOTAL |           | 152 | 1372 | 2094.45         |

The main input has been assessed using QGIS opensource software. By applying the formulas (1)-(9) as described in Chapter 2 above, the total impacts are presented in Figure 1 below for the considered study areas. Likewise, the individual assessment for each study area is presented in the following Figures 2-11.
Figure 1. Total impacts assessment.

Figure 2. KPI Assessment Argolida.

Figure 3. KPI Assessment Evoia.

Figure 4. KPI Assessment Argolida.

Figure 5. KPI Assessment Evoia.
4. Discussion
This paper adds a quantification method that aims to help popularize this assessment and serve as a means of further developing wind energy and familiarize people with it. The methodology developed is first step towards developing a holistic approach in the evaluation of the various possible impacts of wind farms. The method provides a tool for assessing the impact of a wind farm in conjunction with other projects (existing and/or under development) in a certain area and thus provide valuable information regarding its footprint as well as insight to which aspects need extreme caution and mitigation measures.

The general mathematical approach used gives the basic layer for structuring a detailed ad hoc approach when and where necessary. It is without saying that special and sometimes extensive site surveys must take place in order to have the best available data to assess a project properly. Data
collection is imperative for better assessing impacts and adjusting the formulas of the proposed method. Special case studies and data collection over time will certainly help in evaluating and confirming the methodological approach.

All in all, the paper may help in a future attempt to assess wind farm impacts cumulatively in a quantifiable way. Additionally, it may serve researchers calculating and monetizing the environmental cost of wind farms (through the typical methods of LCA and LCOE), thus providing a useful comparison tool against other sources of energy.

5. Conclusion
From the analysis above certain useful conclusions can be drawn. First and foremost, one might argue that the attempt to quantify the total impacts of wind farms in an area are quite useful, especially on a 1-100 scale, which is easily read and can give a first impression of the impact and an order of magnitude. Furthermore, by adjusting and examining each KPI individually, focus can be directed to these factors that have the major contribution and require special attention.

As a whole, it can be seen, that in the case of Greece, even in areas with high density of installations the total impacts may be considered from medium down to mild or even small. However, it can easily be seen that certain factors have a big impact, mainly with regards to visual impact and land coverage. In any case, as it is also concluded in various case studies, the main areas of concern are those of social background. Hence, apart from the fact that these factors are not easily measured due to their highly subjective nature, the conclusion cannot be definite.

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