Energy Transition and Spatial Transformation: Looking for a Suitable Trade-Off

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Abstract. The entry of large amounts of funding and the ongoing energy crisis are drivers of large-scale land transformations for which no monitoring plan was framed. Several studies showed that already in the past the uncontrolled development of infrastructure for energy production from renewable sources led to significant environmental impacts, in some cases largely motivated by economic speculation. This paper analyzes the emblematic case study of the Basilicata Region where, since 2006, the number of wind turbines multiplied in the absence of both a monitoring system and a robust planning and programming framework. The paper proposes a spatially explicit methodology to measure the degree of sustainability of land transformations occurred, according to two approaches: ecosystem services, through the analysis of the carbon footprint related to the installation and operation of energy plants; spatial fragmentation, through a density index. The aim is to provide useful indications for addressing investments aimed at repowering existing wind farms in order to improve the overall environmental balance by increasing renewable energy production and minimizing negative environmental effects.

Keywords: Wind energy production · Carbon budget · Territorial fragmentation · holistic environmental impact assessment approach · indicator engineering

1 Introduction

In response to recent global energy crisis, the European Commission unveiled the REPowerEU plan [1] with the twofold aims of accelerating energy transition and increasing Europe's energy autonomy.

This, both in terms of economic-financial incentives and from the permitting simplifications' point of view, is chronologically the latest in a series of acts that, along the hierarchy of actors involved in land governance, has favored the development and spread of technologies for energy production from renewable sources.

Although the growth in the use of renewable energy sources is implicitly linked to an idea of sustainable development even at the local scale [2], several studies now show that the "renewable energy-sustainability" combination has been realized with

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wide variability within the Italian territory [3]. The concept of sustainability is in fact multifaceted, declining within the three dimensions (environmental - economic - social) multiplied by all the spatial scales at which it makes sense to quantify it.

The case of Basilicata Region is particularly representative of the many perspectives from which we should consider territorial transformations induced by the pursuit of renewable energy production models and justified by the sustainability of energy transition. The risk is to incur in an optical illusion (Fig. 1).

According to the R.E.gions2030 Observatory [4], founded to monitor the *fluidity of authorization processes* and to evaluate *the appeal for the development of renewables* in Italian regions, Basilicata is defined as *virtuous*.

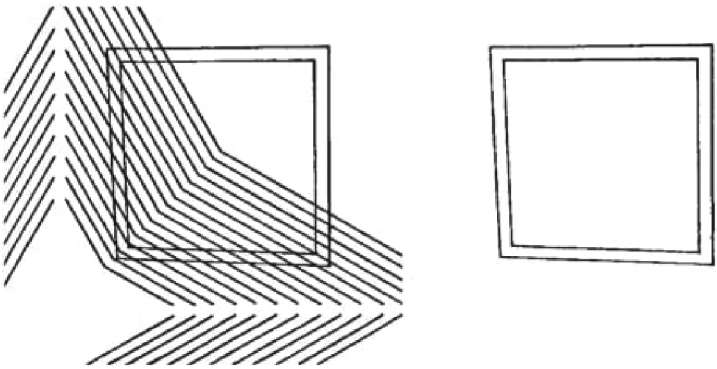

Fig. 1. Optical illusion: a frame between oblique lines appears regular. Removing the lines, it appears distorted [26]

The main reasons are as follows:

1. Basilicata has reached (and exceeded) renewable energy production targets set for 2020;
2. based on the monthly average request for authorizations in the period 2017–2021 (expressed in MW), Basilicata is the second most attractive Italian region;
3. the average time required for authorization procedures in Basilicata is approximately 6 years, an intermediate value between 1.2 years for Abruzzo and 9.2 years for Sardinia.

Several socio-economic studies [5–7], at the same time, suggest alternative readings. The development of renewable energy plants in rural areas with low urbanization, such as the Basilicata Region [8], not only do not effectively contribute to local development, but even risk worsening their marginalization [9, 10]. Furthermore, the ungoverned development of renewable energy production facilities causes significant environmental impacts [11, 12] and changes the landscape and the following territories' identity perception [3, 5].

This paper aims to investigate the cumulative environmental impact of the impressive development of wind energy in the Basilicata Region, proposing analyses and indicators at the territorial scale. The aim is to obtain values with which to compare transformation

performance at municipal scale and thus be able to orient future investments towards repowering actions that pursue the dual objective of increasing clean energy production and minimizing impacts deriving from new installations.

The paper presents the case study by describing the increase in number of wind turbines (divided by capacity classes) for different time steps (Sect. 2) and then illustrates the methodology used for calculating the comparison parameters (Sect. 3).

Finally, the results are presented (Sect. 4) and limitations and simplifications adopted in terms of methodology are highlighted (Sect. 5). At the end, the conclusions (Sect. 6) highlight the importance of this work as a contribution to the search for tools to compare performances of territorial transformations.

2 Study Area and Dataset

According to the report of the national (Italian) Energy Services Manager (GSE), in Basilicata region there are 1417 wind farms. The regional wind farm represents in terms of numbers 25% of the national wind farm and in terms of installed power only 12% of the total power of the national wind farm [13].

To understand the magnitude of the phenomenon and the inefficiency of the distribution of wind turbines with respect to the power produced (in the Basilicata region), we point out that on average for the entire national wind farm the installed power is 1.93 MW per turbine (source: GSE) while only for the Basilicata region it is 0.91 MW per turbine. The discussion gets worse if we consider that the GSE surveys do not consider the entire mini wind farm (that with a power output lesser than 1 MW) which in Basilicata region represent a big amount of share.

In this work, reference is made to a larger dataset, obtained through the integration of various databases including the one of the GSE and the one concerning large-scale plants made available on the regional geoportal.

By 2020, there are a total of 2201 turbines with a total installed capacity of approximately 1274 MW.

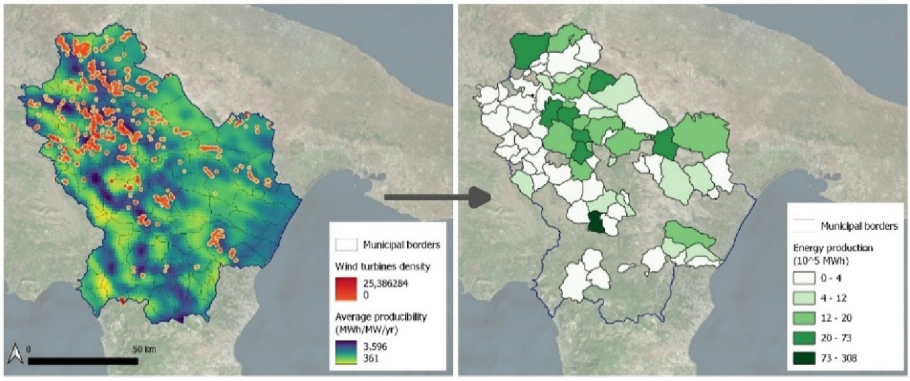

Fig. 2. From the average annual producibility [source: RSE] (MWh/MW/yr) and turbines' capacity (MW) dataset, the overall energy production (MWh) at 2030 was derived.

As can be seen from Fig. 2, the installation of wind turbines has affected a significant part of the regional territory: 72 out of 131 municipalities have at least one installation.

The evolution over time did not happen for everyone in the same way: while in some of them wind farms (capacity $\geq$ 1 MW) prevailed whose authorization process required an Environmental Impact Assessment (EIA), in many others many small size plants (capacity $<$ 1 MW) were installed with no authorization but subjected to a simple notification to the municipal administration.

The result of this uncontrolled transformation process is that in some municipalities there are more than 100 turbines (the regional capital – Potenza - holds the sad record of almost 300 installations) differing in shape, size, height, technology, power.

3 Methodology

The purpose of this paper is to formulate a methodology to support repowering investments and interventions aimed at improving the energy production-environmental impact balance. The first component, related to energy production, is based on a detailed geodatabase describing the development of renewable energy sector in the Basilicata Region set out in four different time steps (2008-2013-2017-2020).

Instead, the second was structured to integrate two different approaches to assessing land transformations: ecosystem services and territorial fragmentation.

The methodology consists of several steps. The first one analyzes the carbon balance related to energy production of each wind turbine currently on operation at the regional territory. The result of this phase is the comparison of different plants in terms of their performance as measured by carbon balance. The aim is to obtain a priority scale that identifies which plants reveal ample room for improvement in their carbon balance.

The next step, on the other hand, has the objective of formulating alternative scenarios to the existing one and aimed at conserving/improving the share of energy produced by assuming partial restoration interventions and minimizing the value of spatial fragmentation. A description of the methods and datasets used is given in the following paragraphs for each of the stages just mentioned.

3.1 The Evaluation of Wind Farms' Carbon Budget

The carbon balance is computed by comparing, on the one hand, CO_2 emissions savings due to displacement of fossil fuel sourced electricity from the national supply and, on the other hand, the CO_2 emitted for installation and for turbines' entire life.

The installation-related contributions, in particular, concern both the change in land use occurred during project execution, and the loss of carbon storage due to the removal of vegetation cover during the whole operation period of energy production infrastructures.

The reference year for carbon balance calculations is 2030 as it is of particular importance for the achievement of targets set at European level.

The following paragraphs describe the individual components one by one.

CO_2 Emission Savings

Carbon dioxide emissions from power generation depend on the type of fossil fuel or fuel mix used to produce electricity. Each of these fossil fuels corresponds to an emission factor (E) useful for calculating the tons of CO_2 emitted into the atmosphere for each megawatt-hour of energy produced. Within the scope of this work, ε is equal to $0.337 tCO2/MWh$ [14]. By knowing the capacity of each turbine $c_{turb}(MW)$, the average annual production $\varepsilon(MWh)$ was calculated according to the following equations

$$\varepsilon = c_{turb} \cdot \mu_{50} \tag{1}$$

$$\varepsilon = c_{turb} \cdot \mu_{75} \tag{2}$$

where μ_{50} and μ_{75} are the annual average producibility $\left(MWh{\cdot}MW^{-1}{\cdot}yr^{-1}\right)$ values at 50 and 75 m above the ground, respectively.

Specifically, in order to consider the different size of existing plants, Eq. (1) was used for turbines of less than $1MW$ capacity, equation number (2) for large generation turbines ($c_{turb} > 1MW$).

The producibility data are derived from the Wind Atlas made available in a grid format by the Italian Energy System Research (RSE) [15] and based on an anemological database consisting of 30 years of data at hourly and spatial time steps of 1.4 km, using the Weather Research and Forecasting (WRF) meteorological model combined with statistical post-processing based on Analog Ensemble (AnEn).

CO_2 Emission Due to Land Use Change

This component of the carbon budget includes two contributions. The first concerns the emissions of carbon stored in the soil and due to land use changes, that occurred following the construction of the access road, crane hard-standings, works compounds and turbine foundations. The extent of this overall sealed surface varies with plant size and was calculated using an experimental formula already tested for the context of the Basilicata Region in previous works published by the same authors [11, 16]. This surface is in fact approximated to a circular area having a radius proportional to wind turbines' capacity. The land use class considered is the one present at the time of installation of wind turbine.

The second contribution concerns the loss of carbon fixing capacity within different soil layers by the removed vegetated covers. To this end, the lack of carbon absorption relating to the overall operating period of each turbine was calculated. The annual average storage rate for each land use class were derived from literature data collected by the European Environment Agency (EEA) [17]. Also in this case, the working hypothesis

is that the land use class would not have undergone variations during the operating time of energy production plants.

CO_2 Emission Due to Life Cycle Assessment
The life cycle analysis should consider for each turbine installed specific data relating, for example, to the type of engine, the materials used, the place of production, etc… Since these data were not available, two literature equations [18] were used:

$$L_{life} = 517.62 \times c_{turb} - 0.1788 \tag{3}$$

for turbines of capacity less than $1MW$, and

$$L_{life} = 934.35 \times c_{turb} - 467.55 \tag{4}$$

for turbines with $c_{turb} > 1MW$.

As stated by the authors, these two equations were derived through a linear regression analysis based on 21 case studies collected across Europe.

3.2 Territorial Fragmentation

Fragmentation caused by wind turbines has been the subject of several studies [11, 16, 19] by the same authors in which different indices such as sprinkling index [20] have been tested. The spatial fragmentation caused by the installation of wind turbines was assessed by means of a density of nucleus aggregation (D_{agg}) [20]. In this research, nucleus is understood to be the footprint of the wind turbine useful for considering the area occupied for the construction of the sub-services necessary for the wind turbine's operational use. The core was calculated by means of a buffer whose radius is a function of the power of the blade, the methodology of which was tested in previous research by the same authors [16]. The formulation of this index is given below:

$$D_{agg} = \frac{\Delta n_{agg}}{\Delta \overline{A}} \tag{5}$$

where: Δn_{agg} represents the change in the number of nuclei from a time t1 to a time t0. The range of values can be positive or negative. A positive value represents an increase in the number of nuclei at time t1 compared to time t0. This results in an increase in the fragmentation of the territory. Conversely, a negative value represents a decrease in the number of cores that is significant of a compaction phenomenon. That is, from time t0 to time t1, new wind turbines were built close to the existing ones at such a distance that they formed a single nucleus. $\Delta \overline{A}$ represents the change in average nuclei area from time t1 to time t0. An increase in the average area of the nuclei is reflected in more large nuclei; a decrease, on the other hand, means an increase in small nuclei. The index can take negative or positive values. A value of 0 represents a static situation, while as the absolute value of the index increases, the degree of fragmentation increases. For ease of reading, therefore, the index will be used in absolute value.

4 Results

Carbon Balance

The first result is a representation of the two components of the carbon budget per municipality (Fig. 1), CO_2 emissions from land use change and turbine life cycle, and CO_2 savings calculated by considering the emission equivalent from fossil sources for the same energy production.

The first evidence is the relevant number of municipalities included in the lowest class for both components. Comparison of the two maps shows a good degree of correspondence between the two classifications of municipalities. Thus, an almost linear proportionality between the two components can be assumed, except for some municipalities in central Basilicata.

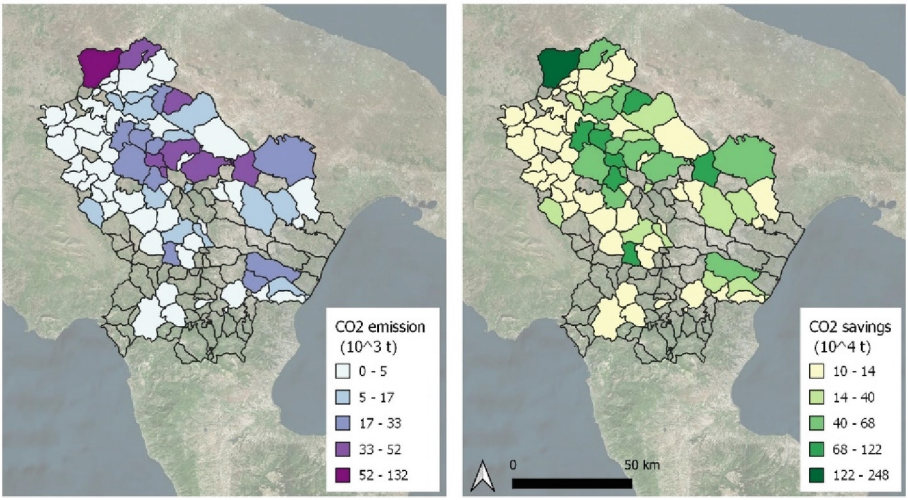

Fig. 3. Comparison between CO_2 emissions (10^3 t) and CO_2 savings (10^4 t) at municipal scale

By subtracting CO_2 savings emissions, Net CO_2 savings were achieved. The map (Fig. 3) then returns a carbon balance picture by 2030 within the municipalities of Basilicata region.

The only municipality in the highest class is Melfi, located in the northern area of the Region. A cluster of municipalities united by a medium-high budget is also located

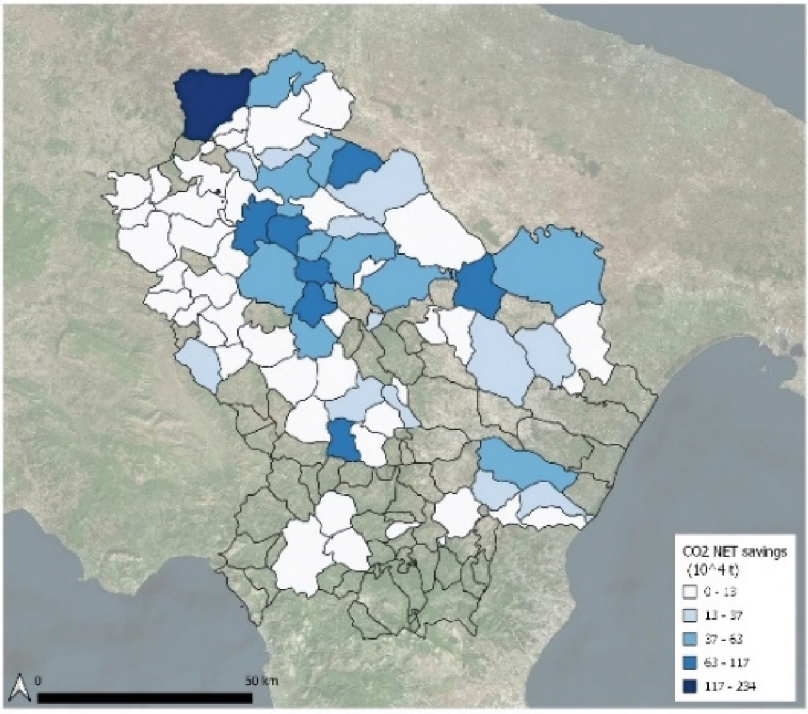

Fig. 4. CO_2 NET savings (10^4 t) at municipal scale

in the central area of the regional territory. Municipalities located in the western part of the Region confirm the small contribution to the contrast to climate change.

Territorial Fragmentation

The density index of nucleus aggregation was calculated for the Basilicata region for each municipality and in the three-time steps: 2013-2008, 2017-2008 and 2020-2008 and are shown in Fig. 5. The maps are representative of the spatial transformations that have occurred as a result of the installation of wind turbines and the degree of fragmentation they have produced on the territory. Municipalities in grey are those in which there are no wind turbines. Fragmentation was assessed by means of the density index of nucleus aggregation, applying it cumulatively in order to make the result comparable with the indices concerning the carbon balance. A value of 0 in the index corresponds to a static situation from one year to the next or very low index variations that cannot be classified as spatial fragmentation.

From 2008 to 2020, the number of municipalities classified as highly fragmented increases from 2 to 9. The municipality of Melfi, which in the previous analysis on CO_2 NET savings (see Fig. 4) falls in the highest class, is also the municipality where wind turbines caused a high degree of fragmentation. Also looking at the CO_2 NET savings, the municipalities located in the western part of the Region show a medium-high degree of fragmentation, while making a small contribution to factors related to climate change.

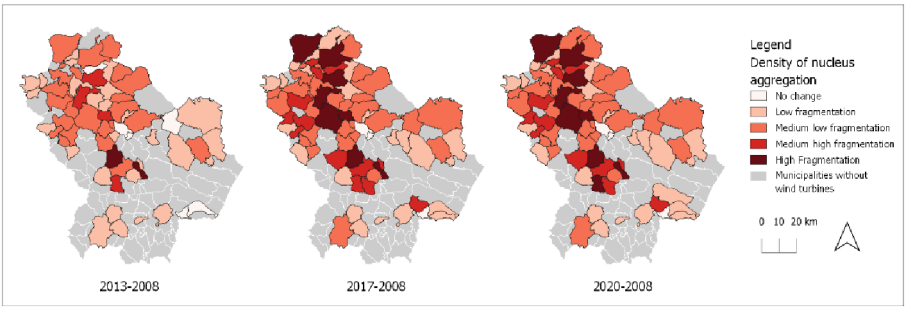

Fig. 5. Density of nucleus aggregation at different years

5 Discussion and Caveats

Environmental sustainability is a complex concept that, for evaluation purposes, needs to be represented from multiple perspectives. Carbon balance and spatial fragmentation are relevant aspects: the former constitutes the foundational motivation behind any transformation dictated by the energy transition; the latter is a direct measure of the transformation-induced change in the environment in which it is embedded, significantly affecting ecological continuity, ecosystem functionality and their ability to deliver ecosystem services.

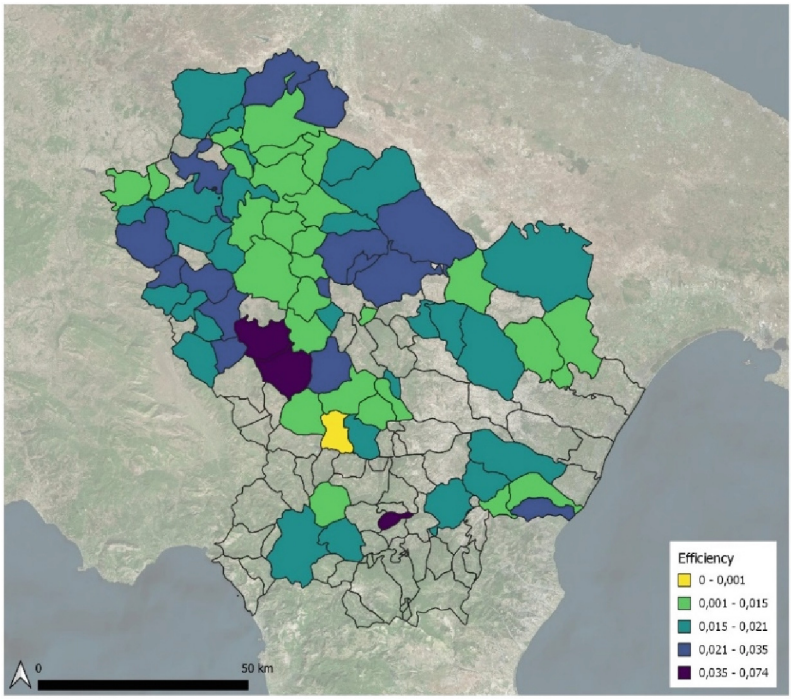

Fig. 6. Transformation efficiency (t CO_2 emissions/MWh) equal to the ratio between total emissions and energy produced at municipal scale

Regardless, therefore, of the value assumed by the indicators considered, a reflection is due first of all with regard to the large number of municipalities that have allowed a profound and irreversible transformation of their territory in the face of negligible energy production. Values such as landscape perception, naturalness, and a sense of belonging to landscapes unchanged in living memory have been sacrificed for a handful of kWh irrelevant to climate change and irrelevant to local development.

The above results provide a static 2030 image of wind turbines impacts measured in terms of carbon balance and territorial fragmentation. An indicator that could better summarize the performance of the ecological transition-induced transformations is the ratio of total emissions and energy produced. We called it "Transformation efficiency" (Fig. 6).

This means that, with equal energy produced by 2030 (see Fig. 2), territorial transformation processes have induced land use changes that result in a variability between performance ranging between three different efficiency classes.

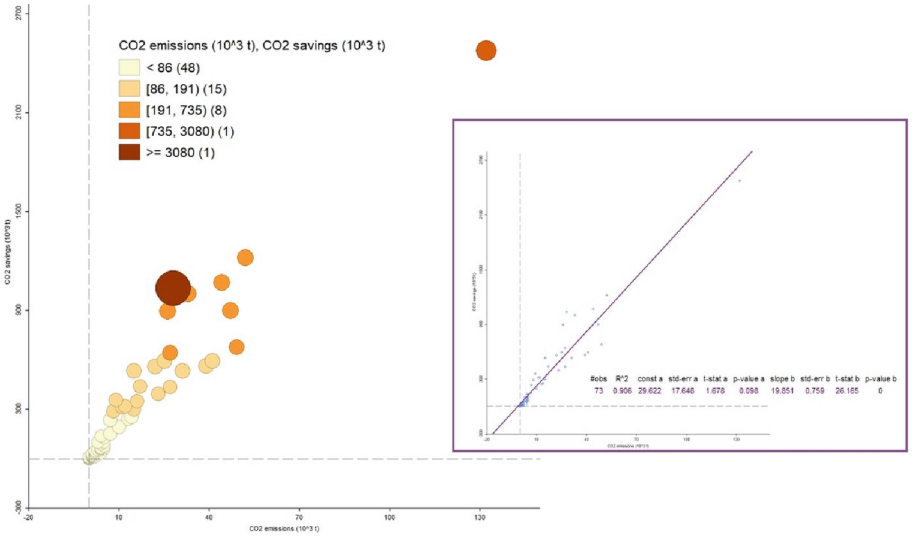

Fig. 7. Bubble chart representing CO_2 emissions (10^3 t) on x axis, CO_2 savings (10^3 t) on y axis. Bubbles' size is proportional to Energy Production (10^4 MWh). In the box, the same regression is showed without considering Energy production.

A further way of looking at this data is the representation in Fig. 7 that depicts the relationship between the two components of the carbon balance (CO_2 emissions and savings) as well as the forecast of energy produced by 2030 (expressed in MWh).

It can be seen that most of the 72 municipalities with wind power plants are located in the lower part of the quadrant, following a linear trend ($R^2 = 0.91$). As the values increase, the individual points deviate from the interpolation line. The distance and position with respect to the interpolation line is not an absolute measure, but it does denote a behavior that can be taken as a benchmark in the panorama of municipalities in the Basilicata region.

6 Conclusions

The paper explores the topic of the integration of energy transition-related dynamics within the wider frame of spatial transformations, also offering a critical reading of tools that spatial planning put in place to manage and monitor these processes. The speed with which these new forms of settlement have spread, in fact, has been much greater than the speed with which plans at different scales have adapted.

The need for rapid decarbonization first, and the recent energy crisis later, have become the main drivers of spatial transformations affecting mainly low-density contexts characterized by fragmented urbanization and scattered settlements of rural nature [21, 22].

The result is a heterogeneous set of landscapes and settlement forms that have greatly altered the quality of scenery, transformed morphological and environmental structures, affected the identity character of local communities, and only in some cases produced energy in non-negligible quantities.

Assessing the sustainability of these transformations becomes even more crucial when thinking about the already wide gap between land take rates and population decline that characterizes these areas [23].

This paper intervenes in this debate by proposing suitable indicators for measuring the sustainability of transformation. Indeed, they concern two key aspects for the purposes of this assessment: transformation efficiency, understood as the ratio between energy production and CO_2 emitted, and spatial fragmentation [24].

The paper applies them to the Basilicata Region case study, showing the contribution they make to an ex-post evaluation and comparison of what happened within different municipalities. The results obtained support several reflections regarding how effectively transformation processes were managed by municipal governments, which are directly responsible for small-scale installations exempt from Environmental Impact Assessment (EIA) [11, 25].

Future research developments will be aimed at exploring the potential of the above indices as components of decision support systems also suitable for comparing alternative transformation scenarios.

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