Renewable Energy and Landscape Transformation: A GIS-Based and Ecosystem Services Assessment

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Abstract. Although increasing the use of renewable energy is a crucial step in reducing the effects of climate change, assessments of sustainable energy can be supported by the lens of ecosystem services to guarantee the sustainability of renewable energy production at the regional level. Land use policy plays a crucial role in this context, as it has the primary power to transform land from the planning stage to implementation. Furthermore, an environmental policy-based analysis supports urban planners in proposing more sustainable and innovative interventions. Compared to traditional planning approaches, these interventions are relatively new, and there is limited time for trial and error due to the urgency of addressing climate change. Ecosystem service indicators can support urban planners, policymakers, and other stakeholders in fostering win-win collaborations. In this study, we investigate renewable energy sources as a phenomenon that has gained significant importance in urban and energy planning. To geographically examine the integration of renewable energy with habitat quality—one of the primary components of ecosystem services—this article suggests a GIS-based methodology by considering Basilicata region as the case study. Three major sections comprise the methodological approach: First, the regional energy plan's specified policy limits. Second, the sprinkling index was used to geographically analyze the energy landscape fragmentation to evaluate how land use changes were affected by renewable energy installations. Lastly, the ecosystem services lens will guarantee the sustainability of renewable energy production at the regional level.

Keywords: Sprinkling index · Spatial analysis · Ecosystem services · Habitat quality · Renewable energy sources

1 Introduction

Global energy demand is projected to double over the 21st century, posing a significant challenge for energy security and sustainability. COP27 placed significant emphasis on securing low-cost financing to facilitate the transition to clean energy. To limit global warming to 1.5 °C, countries must electrify all energy sectors and achieve a complete transition to wind, water, and solar (WWS) power by 2050 [1]. To meet this growing

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demand while mitigating environmental impacts, the expansion of renewable energy sources (RES), particularly solar photovoltaic panels and wind turbines, is considered essential. These technologies play a crucial role in reducing dependence on fossil fuels, lowering greenhouse gas emissions, and supporting the transition toward a more sustainable energy system [2]. Furthermore, ambitious climate goals are increasingly interconnected with rising energy prices, driven by the Russia–Ukraine conflict and the global surge in energy demand following the COVID-19 pandemic recovery. Consequently, accelerating the transition to renewable energy has become more critical than ever [3]. Despite the clear economic and environmental benefits of solar and wind energy production, their installation can face local opposition due to concerns about their impact on the landscape [4]. The increasing installation of solar panels and wind turbines raises concerns about its impact on land use and ecosystem services. Understanding how solar energy development influences land use patterns over time is crucial for balancing renewable energy growth with environmental sustainability. Without regulations, RES plants could cause unintended social, environmental, and economic problems, which could slow down the transition to clean energy. To ensure sustainable and balanced implementation of RES plants, focusing on policy constraints which are not meant to block renewable energy projects, but to improve their efficiency is mandatory step in energy plan. Engaging many social, environmental and energy experts to prepare this regulation makes it more reliable as a reference for other projects and plans in urban planning. On the other hand, usually regional and national plans update periodically, so using other innovative tools beside policy-based regulation makes the process more sustainable. Ecosystem services indicators, as a tool that well defined the human-nature relationship can help planners and other stakeholders to do assessment of RES impact on environment and human life. This study investigates the evolution of land use in the Basilicata region due to solar panel and wind turbine installations over different time intervals. Using maps, spatial analysis, and statistical methods, the research examines the extent of land use changes, particularly focusing on habitat quality, landscape fragmentation, and energy dispersion. The findings aim to provide valuable insights for policymakers, planners, and researchers working on sustainable land management and renewable energy planning.

2 Materials and Methods

This study follows a multi-step approach within a GIS framework, tested on the Basilicata region as the case study. The methodological approach is structured into three main sections: Firstly, policy constraints defined in the regional energy plan (PER) are mapped to identify suitable areas for energy production from solar plants and wind turbines, considering existing regulatory limitations [5]. Secondly, the energy landscape fragmentation was spatially analysed using the sprinkling index (SPX) to assess the impact of renewable energy installations on land use changes. Lastly, to ensure the sustainability of renewable energy production on a regional scale, the lens of ecosystem services applied to support sustainable energy assessments. In this work we focus on habitat quality and degradation model of ecosystem by InVEST that combines information on LULC and threats to biodiversity to produce habitat quality maps. By integrating

all these steps, we aim to predict the impact of renewable energy sources (RES) on habitat quality in Basilicata and determine whether the relationship between RES and ecosystem services (RES-ES) is a trade-off or an asymmetrical one.

2.1 Case Study: Basilicata Region, Italy

Basilicata is an administrative region in Southern Italy, bordered by Campania to the west, Apulia to the north and east, and Calabria to the south (Fig. 1). The region spans approximately 10,000 km^2 (3,900 sq mi) and had a population of just over 540,000 in 2021. (istat2024) Basilicata is the most mountainous region in the south of Italy, with 47% of its area of 9,992 km^2 (3,858 sq mi) covered by mountains. Of the remaining area, 45% is hilly, and 8% is made up of plains (https://www.istat.it/). At the spatial level, Basilicata offers relatively favorable conditions compared to central and northern Italy. This is even more evident when contrasted with central and northern European countries, where renewable energy technologies are widely adopted despite less favorable environmental conditions [5]. Furthermore, in 2018, the Basilicata Regional Authority in southern Italy approved the regional law on "Decarbonisation and Regional Policies on Climate Change (Basilicata Carbon Free)." This law aims to minimize climate change risks, preserve natural heritage, and protect public health, well-being, and assets. To achieve ambitious greenhouse gas (GHG) emission reduction targets, the law supports measures that encourage the adoption of Kyoto Protocol mechanisms, technological innovation, and improvements in energy efficiency across both the private and public sectors [7].

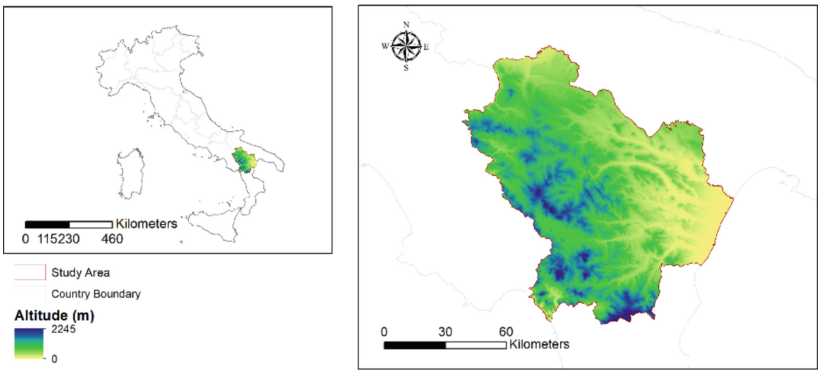

Fig. 1. Introduction map of Basilicata in Italy

2.2 Suitable Areas for RES Production Through Policy Lenses

To ensure sustainable and balanced implementation of RES plants, this part focuses on policy constraints which are not meant to block renewable energy projects, but to improve their efficiency. Without regulations, RES plants could cause unintended social, environmental, and economic problems, which could slow down the transition to clean

energy. In the PER of the Basilicata region, the "suitability of land for energy production" is defined through a set of constraints specific to each renewable energy source RES. However, this study considers suitable areas for RES production through policy lenses. The following map presents the constraint elements used to identify suitable land for energy production from wind turbines and solar farms. The suitability map is the result of overlaying multiple vector shapefiles, we downloaded from the geoportal website and filtered to exclude areas outside the study region. The Fig. 2 Shows the proportion of both restricted areas, and suitable areas.

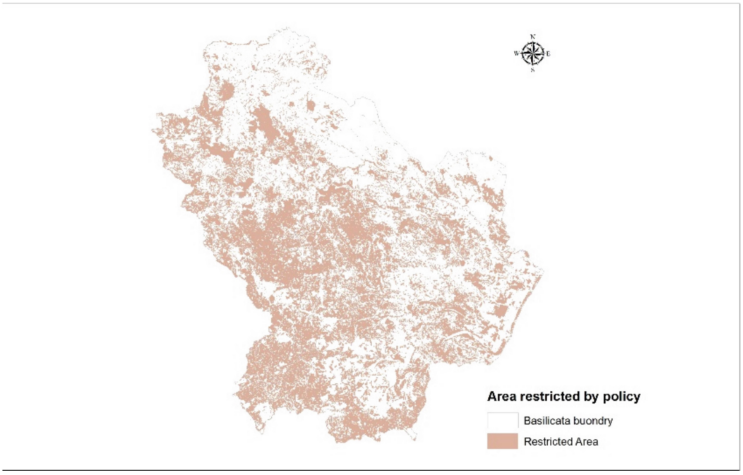

Fig. 2. Prohibited area by law for RES intervention

2.3 How is Fragmentation Trend of RES in Basilicata Region?

Creating a reliable data set for assessment on RES impact on environment is the very beginning and the most important step. The fundamental geographical information structure consists of a database of RES installations, gathered from TRC (https://rsdi.regione.basilicata.it/dbgt-ctr/), produced by the Basilicata Region and distributed through OGC standards within the RSDI; additionally, GSE (https://www.gse.it/). Due to missing or outdated data, we conducted the digitization of installations using aerial photogrammetric surveys carried out at different times, incorporating orthophotos. In the final year of the survey, 1,819 wind turbines and 327 solar panels were identified.

The methodology is applied across three different time intervals to analyze both spatial and temporal aspects. The selected time periods are: (i) 2008–2012, (ii) 2012–2018, and (iii) 2018–2021. Additionally, for a more comprehensive analysis, wind turbines are classified into three main categories based on their installation power and size: mini, medium, and large. Firstly, the study area is divided by a 1 km^2 grid. SPX index assumes that the most compact form of agglomeration growth is the circular one and is based on the Euclidean distance between two or more geometries within each cell. Secondly,

to assess the land take of wind turbines and photovoltaic fields, we considered the area surrounding each RES installation within an influence radius proportional to its power output. For solar panels, we applied a 25-m buffer, as their large surface area allows for effective spatial analysis, and this buffer enhances the comprehensiveness of the assessment. Given the relatively small footprint of wind turbines, we analyzed their distribution patterns using a two-step buffering approach. The first buffer was applied around each installation based on its power capacity: 15 m for micro turbines, 25 m for medium-sized turbines, and 35 m for large turbines. Since the expected effects (e.g., loss of habitat quality) extend beyond the immediate footprint of individual installations, wind turbines were aggregated within a maximum distance of 250 m. It is therefore assumed that this entire area is permanently repurposed from its previous land uses. Thirdly, the energy landscape fragmentation was spatially calculated by using the sprinkling index (SPX) [10]. The SPX index assumes that the most compact form of agglomeration growth follows a circular pattern. It quantifies spatial clustering by measuring the Euclidean distance between multiple geometries within each cell. In this analysis, these geometries correspond to photovoltaic fields and clusters of wind turbines. The index is calculated using the following formula:

$$SPX = \frac{\sum \sqrt{(xi - x*)^2 + (yi - y*)^2}}{R}$$

where xi and yi are the centroid coordinates of each polygon, representing photovoltaic fields and clusters of wind turbines within a 1 km^2 grid cell. $x*$ and $y*$ correspond to the centroid coordinates of the largest concentration of installations within the cell. R represents the radius of a circular area with a total surface equivalent to the combined area of all RES installations in the cell. Furthermore, after computing the SPX for all RES clusters, we joined the SPX values to the corresponding grid cells containing each cluster to enhance visualization (Fig. 3).

2.4 How Does the Expansion of RES Affect Habitat Quality?

After analysis of the previous part that shows the noticeable expansion of RES, during years of study, in this part we are going to figure out how it affected the environment. Maintaining biodiversity is an important ecosystem service that is closely linked to other services [11]. It can directly affect other ecosystem services, like pollination and pest control, which depend on specific species communities [12]. It can also indirectly affect ecosystem services related to biological processes, like carbon and nutrient sequestration, by influencing internal ecosystem processes and species activities. [13] For this study we selected habitat quality as a representative of ecosystem services. This can help with land-use planning and identifying areas for ecological conservation [14].

Current habitat quality (HQ) assessments often concentrate on regional species evaluations, but these can be constrained by the high costs associated with data collection, limiting their applicability for large-scale analyses. To address these challenges, the InVEST model has emerged as a practical and efficient tool for conducting spatiotemporal HQ assessments [15]. The InVEST model defines HQ as the ability of ecosystems to support species' survival, reproduction, and activities [16]. The changes in HQ were

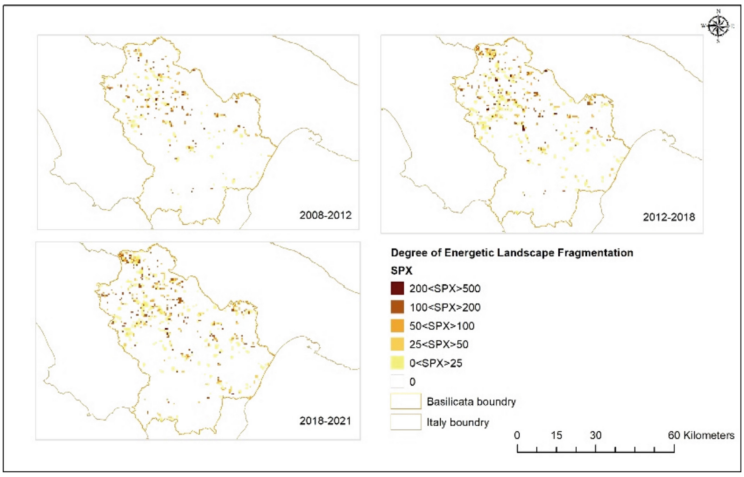

Fig. 3. Energy fragmentation index changes

used to explain variations in habitat area, a key process in habitat loss and fragmentation. The formula for HQ is as follows: the HQ of patch x, in land use type j (LULCj), is represented by Qxj:

$$Qxj = Hxj(1 - (Dxj/(k + Dxj)))$$

where z and k are scaling parameters, and Hj represents the suitability of land use type j for the species. Generally, natural areas are considered to have relatively high suitability, while human-dominated lands are much less suitable [13]. The InVEST Habitat Quality model uses LULC data and biodiversity threats to generate habitat quality maps. For this study, we analyzed changes between 2008 (pre-renewable energy installations in Basilicata) and 2021 (significant growth in renewable energy sources) and using Copernicus Corin land cover data. (https://www.copernicus.eu/en) The model also considers threats, here we consider agriculture, urbanization, industry, mining, roads, and renewable energy installations as threatening elements for habitat quality. The Fig. 4 shows the result of habitat quality for the year 2008, and year 2021, additionally their differences. The map shows a general view of changing trends during the period of study for both years' result shows lower quality in upper side of area.

3 Result

The comparative analysis of data from 2012, 2018, and 2021 reveals a notable increase in the territorial impact of renewable energy installations (RES) in the Basilicata region. The findings underscore that, without proper governance through spatial planning instruments, the energy transition can lead to increasingly pronounced dynamics of landscape fragmentation. This critical issue aligns with the concerns raised by Murgante and Scorza, who emphasized the importance of integrating energy planning with landscape planning—particularly in environmentally vulnerable regions such as Basilicata.

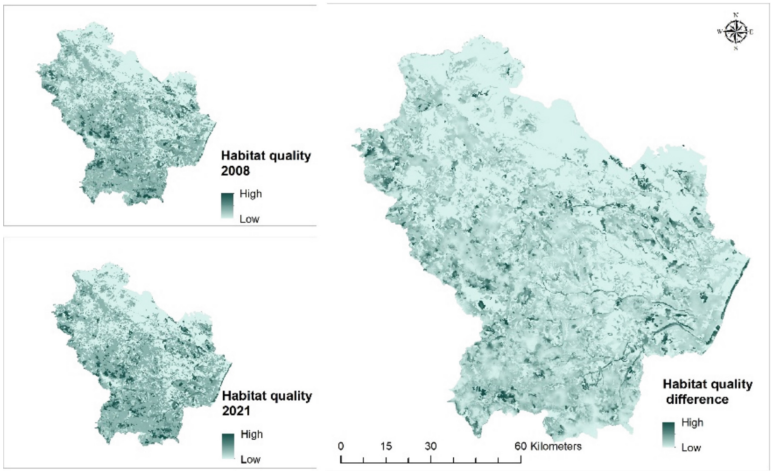

Fig. 4. Habitat quality differences of Basilicata region

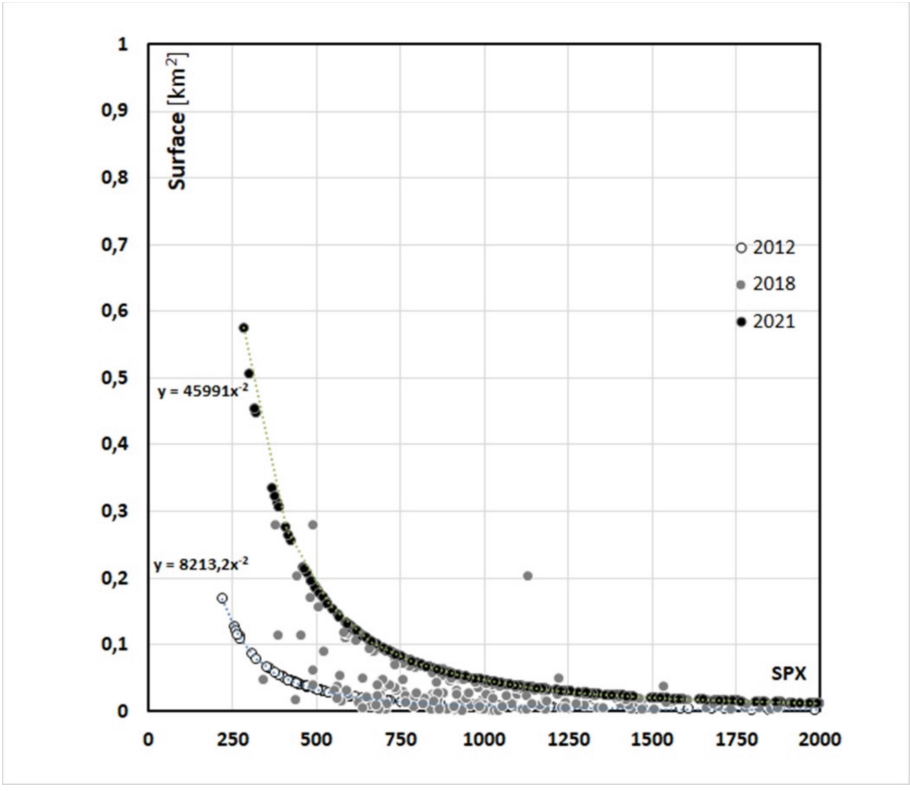

Fig. 5. Comparison of SPX and aggregates surface variation between 2012 and 2021

Figure 5 illustrates the relationship between the fragmentation index (SPX) and the area occupied by RES in the Basilicata region across three time points: 2012, 2018, and 2021. In 2012, both the SPX values and the occupied area were relatively low, indicating an early stage of development characterized by concentrated installations and minimal spatial dispersion. During this initial phase, the impact on the landscape was limited, as installations were primarily located near existing infrastructure or in areas already modified by human activity. The year 2018 marks a noticeable transitional phase. The intermediate positioning of the 2018 data between the 2012 and 2021 clusters indicates a significant shift in installation dynamics. During this period, three key trends emerge: (i) a progressive saturation of the most suitable sites for renewable energy development, (ii) the beginning of a shift toward more dispersed spatial distribution of installations (iii) a noticeable escalation in SPX values, reflecting emerging fragmentation. This transitional phase may reflect the early effects of energy policies—especially those introduced by the 2010 PIEAR—even though their full impact had not yet reached the critical level seen in 2021.

The 2021 data present a stark contrast, revealing a significantly altered situation. The sharp increase in both SPX values and the occupied area confirms the establishment of an increasingly dispersed settlement model. Notably, the comparison of the quadratic regression equations is telling: In 2012, the equation was $y = 8E + 06x2$, whereas in 2021 it had risen to $y = 5E + 07x2$. The increase in the quadratic coefficient of more than six times indicates that, for the same increase in SPX, the area needed for new plants has become significantly larger. This quantitative data confirms a fundamental qualitative trend: the fragmentation of the territory does not grow linearly with the expansion of plants but accelerates disproportionately as new installations are made. The implications of this evolution are particularly relevant for territorial planning: The intermediate phase of 2018 could have been a wake-up call to intervene with corrective policies. The absence of adequate regulatory tools has allowed the continuation of increasingly less sustainable settlement dynamics. The quadratic relationship between SPX and occupied area suggests the existence of critical thresholds beyond which territorial impacts become particularly severe. About habitat quality Fig. 6 shows a general trend of RES effect on habitat quality. The x-axis in the graph represents habitat quality scores, ranging from 0 (poor habitat quality) to 1 (high habitat quality), while the y-axis indicates the frequency of pixels with each value. A peak at 0 suggests that a significant portion of the area experienced low habitat quality for both years. Both years show a major concentration of values around 0.3 to 0.4, indicating that habitat quality remained relatively stable in certain regions. However, the differences in frequency across the distribution highlight shifts in habitat conditions over time. The overlapping areas reveal the extent to which the two distributions align or differ. This visualization suggests that while some areas retained similar habitat quality, others experienced a decline, potentially due to land use changes or anthropogenic impacts.

These results highlight the pressing need to balance the goals of the energy transition with the protection of landscapes and ecosystems. The study illustrates how temporal comparative analysis can uncover key turning points in territorial evolution, providing valuable insights for more informed and sustainable energy transition planning.

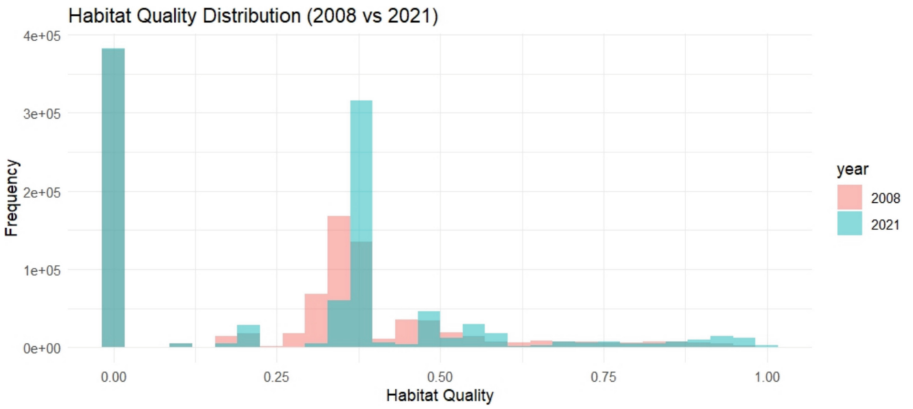

Fig. 6. Comparison of habitat quality between 2008 and 2021

4 Conclusion

In conclusion, the results indicate that to meet the increasing demand for clean energy and achieve the goals set at COP27 [19], traditional planning approaches are not inherently efficient. Basilicata in this work consider as an example, the increasing trend of RES in Basilicata shows, that although policy-based interventions in somehow can significantly prevent the scattered expansion of renewable energy infrastructures, but in terms of examining environmental factors, it requires more precise tools and equipment. In other words, effective implementation of energy and climate policies necessitates the development of new models of multilevel governance. [20] In this work ecosystem services lenses, and specifically habitat quality as a key concept in ecology, conservation biology, and environmental planning, is presented as an innovative tool. Combining the result of both traditional and new methods can help us for having more clear prediction of future impact of RES intervention on human-nature relation and ecosystem services. Furthermore, from a governance perspective, the findings advocate for the development of new multilevel and cross-sectoral planning models that integrate ecological data with socio-economic objectives. These models must enable cooperation between local authorities, regional planners, environmental scientists, and energy stakeholders. By doing so, it is possible to better align RES development with both sustainability goals and landscape resilience.

Future research should focus on enhancing habitat models to include species-specific responses to different types of RES infrastructures. Exploring the socio-cultural dimensions of landscape change due to energy transitions. Developing integrated planning platforms that merge spatial, ecological, and policy data in real-time to support adaptive governance. By refining planning strategies through the lens of ecosystem services, and promoting interdisciplinary collaboration, the transition to renewable energy can be better managed to ensure it is not only technologically feasible and economically viable but also ecologically and socially just.

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