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Research article

Advancing towards a sustainable energy model, uncovering the untapped potential of rural areas

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Abstract: Rural areas are essential to moving towards the necessary sustainable energy transition and climate change mitigation through renewable energy (RE) technologies. However, RE planning and decision-making in rural locations have not been developed to date with a focus on the local level and accompanied by a careful and thorough assessment of the simultaneous availability of alternative RE sources in a specific territory. Quite differently, RE investments in rural locations have been primarily driven by the interests of large power utilities to exploit a particular RE source, with benefits escaping from the rural economies to end up in the income statements of those large corporations. There is a need to approach RE planning at the municipal scale considering the availability of alternative RE sources. This study suggests the development of a rural RE potential index that could help in the identification of appropriate locations for the implementation of hybrid renewable energy systems (HRESs). The construction of a composite indicator to measure rural RE potential is exemplified through a case study that deals with ten indicators in the context of Galician rural municipalities, involving different RE potentials and some technical or regulatory constraints. Equal weighting and Principal Component Analysis are considered alternative methods for the index construction. Municipalities are the relevant local decision level where energy policy should be focused in order to diversify both the RE mix and the investor base. The proposed index could be the basis for future analyses aimed at optimizing the design and implementation of HRESs in rural environments at a local-regional-national scale.

Keywords: sustainable energy transition; sustainable rural development; rural renewable energy potential; composite indicator; Principal Component Analysis

Abbreviations: SD: Sustainable Development; SRD: Sustainable Rural Development; RE: Renewable Energy; HRES: Hybrid Renewable Energy System; LAU: Local Administrative Unit; CRE: Community Renewable Energy; PCA: Principal Component Analysis; EW: Equal Weighting; AA: Arithmetic Aggregation

1. Introduction

Sustainable development (SD) and climate change are two worldwide recognized priorities [1] that require actions at both global and local levels [2]. The local sphere is of paramount importance since it is where the implementation of global SD strategies falls, as acknowledged by the mantra "think globally, act locally" [3]. However, too often local authorities have not been explicitly considered in the design of global SD agendas [4], especially in the rural sphere.

In Europe, rural areas are of considerable importance [5–7], since around 90% of the territory has been classified as rural at the local administrative units (LAUs) level. These rural areas face challenges related to depopulation, loss of economic relevance and threats to the cultural and natural heritage [5,8–10]. The need for revitalizing rural economies is attracting increasing research interest [11] and the EU has deployed various strategies aimed at this end [6,12]. It is also actively involved in promoting SD and leading actions to mitigate climate change and comply with the transition towards a sustainable energy system [13,14], where renewable energies (REs) should contribute to a more decentralized and low-carbon energy system [15].

Sustainable rural development (SRD) has been recognized as being of paramount importance for achieving global SD [12,16], and rural areas can make a definite contribution to climate change goals [7,17] and the energy transition [18–20]. Energy decentralization or distributed energy, that is, small-scale production of electricity or heat close to consumption sites, has been pointed out as a necessary step in this energy transition [15,21], particularly in rural areas [22–24], and REs have been identified as an optimal source to be exploited under this model [25–27]. RE based on a decentralized energy supply can positively contribute to SRD [28,29]. According to the seventh Sustainable Development Goal, access to reliable, affordable, sustainable, and modern energy is an enabling factor for promoting social equity and economic growth because it is closely associated with access to education, health care, income-generating opportunities, and overall well-being and safety [22].

Rural areas are transcendental scenarios to promote a local development model that has RE as one of its main pillars [17,28,30]. Surprisingly, they have not traditionally been considered in energy planning [31], and in the climate change plans of many European regions, the reference to rural areas is mainly related to the primary sectors of the economy [32], without considering the potential role of RE as driver of SRD. Despite acknowledging that RE can be crucial for SRD [33], a recent EU audit concludes that their synergies remain largely unrealized [34]. Clausen and Rudolph [35] point out that the political rationale for the planning and development of RE facilities is primarily motivated by the decarbonisation of the energy sector, rather than responding to the ambitions of SRD. Katsaprakakis and Christakis [36] show how the lack of a strategic design in the Greek RE legislative framework and its distorted interpretation have led to an anarchic development of RE. Therefore, better, more balanced, and integrated policies are needed to encourage a substantial contribution of RE to SRD.

National energy planning has tended to favour large corporate developments without consideration of the wider economic effects of RE projects, treated as non-material planning considerations [35]. Rural areas have been treated as energy peripheries that depend on external decisions about technologies and locations [37]. However, the sustainable energy transition should be planned at the municipal scale [31,38]. Municipalities are crucial in the definition of strategies to ensure efficient, balanced, and sustainable renewable energy zoning in rural areas [19]. Poggi et al. [31] identify the municipality as a self-reliant system which locally adapts to the energy transition. The municipal level of analysis allows considering the notable regional heterogeneity in the potential of RE from alternative sources [39]. Sliz-Szkliniarz [40] points out that before designing any regional or local RE policy it is necessary to explore the RE potential.

This study is aimed at signalling this need, suggesting the development of a composite indicator to measure the RE potential in the municipalities of a region or country. This approach is highly relevant since exploring the municipal RE potential and identifying rural areas with higher supply possibilities can be a first step in the promotion of decentralized RE projects, reducing their perceived risk and supporting their planning processes. Countries need to design comprehensive rural energy system planning schemes as an important part of their sustainable energy transition [30]. The assessment of the RE potential is a crucial initial phase for recognizing risks throughout the planning, implementation, and operational stages [41] and provides helpful references and suitable measures for harvesting more RE sources in future energy integration policy and national energy planning [42].

Few previous studies have approached the analysis of energy planning and decision-making by integrating five or more RE sources, aimed both at electrification and heating purposes, such as wind, solar, micro-medium hydro, geothermal and biomass/biogas [43,44], or have proposed this analysis across all the municipalities of a whole region [45]. This study contributes to the state of the art filling these gaps, assessing the RE potential of Galician municipalities through a composite indicator based on the sum of the potentials of six individual RE sources and the consideration of some relevant constraints revealed by previous literature. Alternative weighting methods (Principal Components Analysis and equal weighting) are considered under a transparent and ordered methodological approach to building a robust and reliable index.

The remainder of the paper is structured as follows: first, a literature review is conducted to identify how previous research has approached the analysis of RE in rural areas and the main features of the alternative RE sources that could show different potentials in the municipalities of a region; the Method section presents the case study area and specifies the variables and methodological issues for the construction of a composite indicator informative of the RE potential of Galician municipalities; the Results section details the development of the index and numerically and graphically presents the distribution of that potential; finally, a discussion and conclusion section presents the main implications of the study, as well as its limitations and possible avenues for future research.

2. Literature review

The decentralization of the energy system [15,21] and greater energy autonomy at the local level [46], intrinsically linked to community energy [47,48], have been advocated as a necessary step in the energy transition, where RE and rural areas play an important role. Poggi et al. [31] vindicate the role of rural areas as new places for expanding RE production and attracting private economic investments for the sustainable energy transition. Moreover, RE has been recognized as an important enabler of rural development [10,40].

Previous literature has also highlighted some potential negative effects of RE [40,49,50] or conflicts with other economic, social, or environmental priorities [27,51,52]. A balance is needed between land occupation with RE facilities, other land uses, and the preservation of the rural landscape [19]. Regarding small-scale decentralized infrastructure, Yildiz [53] and Lowitzsch and Hanke [54] warn about the financial difficulties, since it is not attractive to large energy companies or investment funds, so alternative sources of funding are needed. The main disadvantages of small-scale projects are the lack of economies of scale, the higher transaction costs (due to the large number of people involved) and the limited possibility to diversify risks across multiple projects [55,56]. Alternative sources of financing such as crowdfunding have been proposed as a solution [57,58], but the fundamental role of public funds cannot be disregarded. Klepacki et al. [29] acknowledge that without the support of EU funds local units would not be able to invest in RE.

The more common RE sources are solar (photovoltaic and thermal), wind, biomass, (small-medium) hydropower, and geothermal [43]. Their implementation in both urban and rural scenarios is conditioned by different sets of limitations, constraints, or barriers. García-Martínez et al. [22] identify four main categories of barriers: (1) technical barriers (efficiency of components, power quality, operation, and protection); (2) regulatory barriers (legislation limits); financial barriers (high investment costs and need for financial assistance in the implementation stage); and (4) stakeholder barriers (self-interest conflicts in a decision-making environment). In a similar vein, Ryberg et al. [59] organize constraints around four groups: (1) social and political; (2) physical; (3) conservation; and (4) technical-economic, acknowledging that all these constraints are highly spatially sensitive. Medina-Santana et al. [60] identify two big sets of challenges posed by RE: (1) Non-technical (Capital costs, Economic and market issues, Public concern, Conflicts between stakeholders, Politics, Regulation); and (2) Technical (Unpredictability, Real-time system operation, Required size). Rather surprisingly, few studies are addressing the drivers and barriers of (collective) renewable energy penetration in rural areas [15]. Hybrid Renewable Energy Systems (HRESs) are proposed to overcome some of these limitations (related to the use of a single RE source) by combining two or more sources [61]. Li et al. [44] acknowledge that rural HRESs coupled with rooftop photovoltaics, wind power, small hydropower and biogas digesters can effectively drive the rural energy transition.

A big proportion of the extant literature dealing with RE in rural settings is focused on the optimal design of HRESs involving two or more RE technologies. Criteria considered for the optimization (in terms of location and/or sizing) can include technical, economical, physical, and social aspects [45,62,63]. Quite frequently these studies are mainly related to the problems of electrification in remote rural areas of developing countries [41,61,64]. Few studies consider also heating possibilities [43]. Some other interesting conditioning factors are the interests of the different stakeholders [22]. Moreover, some studies have integrated the analysis of rural energy systems with that of water and food systems [60].

However, this previous research related to the optimal location and sizing of HRES is mainly focused on how to enhance the performance of an energy system by reducing losses, generation capacities and construction costs, while improving service quality and reliability [62], disregarding the need of integrated regional planning of the RE resource in rural settings. Planning at a regional and local level is needed to balance the competing interests for land resources and manage the multiple uses of land [40], and should/could be extended to a muti-regional sphere [44]. This study pays attention to this need, acknowledging that, before searching for optimal designs of HRESs in specific local units, regional energy planning is needed based on a mapping of the current RE potential available in all their local units.

RE sources are distributed throughout different territories and can be measured only in specific locations. Like fossil fuels, it is not possible to convert and exploit all the potentially available energy [65]. RE potential can be defined in three different ways:

Potential energy: the gross energy of the source, e.g., the wind in a certain place.

Theoretical energy: the fraction that can be collected by the energy conversion system (e.g., the solar radiation collected by a certain surface of solar panels).

Exploitable energy: the usable fraction based on sustainability criteria related to logistic, environmental, and economic issues.

The next subsections explain which are the main conditioning factors of the potential of alternative RE sources (solar, wind, biomass/biogas, geothermal and small hydro). Other REs, such as marine and off-shore wind, are not considered due to their difficult implementation derived from both regulatory and technical factors. A final subsection refers to limitations or constraints to RE developments.

2.1. Solar resource potential

Photovoltaic and thermal systems are one of the most common ways to use solar energy for both electricity generation and thermal use. One of the main factors influencing solar potential is the availability of solar energy on the ground surface that can be converted into heat or electricity [66]. Therefore, accurate solar irradiation data is of paramount importance for the planning and successful operation of solar energy systems.

The available solar energy potential is the physically available solar radiation on the Earth's surface, which is influenced by several factors: geometry, the translation and rotation of the earth, elevation, inclination and orientation of the surface and shadows, as well as atmospheric attenuation due to polluting gases [66]. The estimated potential, that can be obtained based on *in situ data*, satellite data, or a combination of the two, is reduced by considering conversion efficiency factors [65].

The deployment of photovoltaic systems depends on several factors: irradiation; solar intermittency; capital, technological and institutional support; social acceptance; and obstacles or architectural restrictions [67]. The implementation of photovoltaic panels and solar collectors on the roofs of buildings is an opportunity with great potential in rural places to avoid land use conflicts [68], while large-scale investments could have more significant impacts on the countryside and its natural values and cultural heritage [19].

2.2. Wind resource potential

The theoretical energy potential may be limited by [65]: geography (high altitude areas, steep slope areas, etc.); socioeconomic conditions (areas close to cities, airports, or protected areas); and land uses (competition with areas for agriculture). Other relevant constraints are related to the number of wind parks per area and the various environmental impacts involving landscape, noise, bird collisions and “not in my backyard” opposition [19].

The estimation of wind energy can be evaluated on a scale of the order of a few kilometres simply by processing the available data, either with statistical models or with interpolation techniques (forecasting techniques, flow modelling, mesoscale model). The theoretical energy can be also limited by the characteristics of the wind turbines available in the market (size, efficiency, full load hours) and the limitations of the installation site [65,67].

2.3. Biomass/biogas resource potential

Biomass is a traditional fuel locally available that enables widespread energy production at reasonable costs and can contribute to mitigating climate change, developing rural economies, and increasing energy security [65]. Through chemical and biochemical processes, biomass can be transformed into secondary energy, such as electricity, heat or biofuels [69], sometimes requiring additional processing if the raw materials are not homogeneous [67].

Biomass potentials are classified according to their theoretical, techno-economic, and sustainable availability. The theoretical biomass potential can be estimated based on biophysical and agroecological factors that determine biomass growth. The techno-economic potential is estimated by considering accessibility, competition for resources, biomass logistics, production costs, and all the factors that limit the theoretical potential. The sustainable potential aims to assess the amount of biomass that can be obtained considering the socioeconomic and ecological repercussions of this type of RE.

2.4. Geothermal resource potential

Geothermal energy is the heat that could be extracted within the subsurface of the earth to be used for a wide variety of purposes such as heating and cooling, in industry, greenhouses, fish farms and spas [70].

In general, the geothermal potential accounts for the amount and form of energy stored in the subsoil, which will restrict the type of application and the extraction method [71]. Normally, the procedure for determining geothermal potential consists of four phases: initial phase, pre-feasibility phase, feasibility phase, and final phase. The initial phase is based on the selection of promising areas. The pre-feasibility phase consists of surface investigations in selected areas. The feasibility phase consists of exploratory drilling and testing of the reservoirs. Finally, the final phase consists of the development and exploitation of the energy resource [65].

2.5. Small hydro resource potential

According to the European Small Hydropower Association [72], there is no consensus among the member states of the European Union to define mini and small hydro. In Spain, it includes power plants up to 10 MW [73]. Hydroelectric power is obtained by harnessing the potential energy of a mass of water located in the channel of a river to convert it first into mechanical energy and then into electrical energy [74]. It is highly conditioned by the peculiarities and characteristics of the location, with topography influencing both the civil works and the selection of machinery [75]. Run-of-river plants depend directly on hydrology, as they have no capacity to regulate the flow that is passed through the turbine, which is highly variable, while storage plants with a dam to store water in a reservoir have the capacity to regulate the flows [73]. There are limitations to the building of various small plants in cascade in the same catchment due to technical and environmental reasons [76].

2.6. RE constraints

The first set of constraints is related to public attitudes towards RE. According to previous literature [77–79] the main reasons why citizens oppose or not the construction of RE projects are related to concerns for the environment and biodiversity. High concern for the environment or pro-environmental behaviour [78] requires minimizing the impacts on existing land uses and human activities [36].

Boon and Dieperink [80] and Loomis et al. [81] show the positive effect of environmental awareness in supporting RE projects. Similarly, the need to reduce greenhouse gas emissions has led to increased investments in RE and energy efficiency [82]. Individuals can join initiatives that care about the environment, thus generating a positive effect on the willingness to participate in RE projects [78,83,84].

Another relevant limitation is related to the conflicts in land use. Economic and demographic growth has led to an increase in the demand for land use [85]. The limited availability of land means that a balanced portfolio of social, economic, and environmental services is needed [86]. Consequently, the different RE sources compete with each other for land, as well as with other land uses, such as agriculture, recreation, and ecological conservation [40].

Wind power has higher land use efficiency (energy yield per unit of land used) than biomass and solar power. Also, unlike the production of energy crops or solar farms, the land under a wind farm can be used for other purposes, such as agriculture, because wind turbines occupy only a fraction of the area of a farm [40]. However, this type of power generation can have adverse effects on ecologically sensitive areas and landscape aesthetics, affecting conservation and amenity [87].

Unlike wind farms, solar systems deployed as solar farms have only small negative impacts on ecosystems but are incompatible with most other land uses [88,89], with an evident reduction of arable land. Chiabrando et al. [88] suggest that solar farms should only be allowed if a building-integrated installation is not economically viable or energy efficient. According to Dijkman and Benders [90], competition for arable land could be reduced if large photovoltaic parks were located on marginal land, unsuitable for agricultural production. This would ensure that there is no competition with food and biomass production. However, other competing needs for land use cannot be excluded.

Similarly, biomass energy production can affect land use, requiring land for cultivation, storage, and crop generation [90,91]. In addition, intensive biomass production can deplete soil nutrients, thus affecting its productivity, and can contribute to biodiversity loss [92,93]. Biomass production is not only in conflict with food and fodder production but also with other energy crops. For example, biomass can be used in different technologies that give rise to electricity, heat, or biofuels. Annual and perennial crops to produce energy compete for space with conventional plants.

Landscapes are also directly affected by energy systems [79]. The development of RE projects poses many relevant challenges, particularly concerning the visual impact and noise perceived by inhabitants [94], or the interference with flora and fauna [88]. Perceptions about these impacts vary across rural and urban settings and are also related to economic issues such as job creation opportunities [77].

3. Methodology

This section first presents the case study area, justifying its suitability to exemplify the construction of a rural RE potential index across the municipalities of a region. The variables or indicators considered to build the composite indicator are explained, as well as the main methodological issues related to its mathematical configuration.

3.1. Case study area

We explore the design of a rural RE potential index in a Spanish province. Spain is an interesting context for this study because it represents a sort of energy island, due to the limited interconnections with other countries, which makes it difficult to import and export energy [95]. The development of RE in Spain was driven by a supportive legislative environment until 2015, when it entered a kind of paralysis [58,96], and only recently new regulation has been enforced to support decentralized energy and distributed generation [97,98]. There are few community initiatives, mainly constituted as cooperatives [99–101].

To adequately characterize the rural scenario, the level of municipal disaggregation is chosen. This is the lowest level of disaggregation with statistical data available from official sources. In Spain, the municipalities are the smallest LAUs. The municipalities are grouped into provinces and the provinces into autonomous communities. Within each municipality, there may be several population groups (cities, towns, suburbs, villages, and scattered buildings). The Spanish municipal structure is highly fragmented, with a north-south dichotomy that shows smaller municipalities in the north [102]. The autonomous community of Galicia shows an extreme dispersion of its population, with more than 30,000 population centres distributed in its 313 municipalities, which represents almost half of the total population centres in Spain. These population centres are divided into centres where at least 10 buildings form an urban space (10,400) and population centres with less than 10 scattered buildings (20,711). According to the Eurostat methodology, 240 municipalities are classified as rural and, therefore, considered in this study to analyze their RE potential.

Galicia is among the European regions most affected by the depopulation of its rural areas [103,104]. Historically it has lagged behind Spain in terms of population and GDP growth [105,106]. Depopulation poses serious risks to the sustainability of its rural areas, with relevant threats such as forest fires [107,108]. It also has a rich capital of RE sources [109]. RE generation represents approximately 7% of the Spanish one and comes from two main sources, hydro and wind energy [110]. The development of wind energy in rural areas experienced rapid growth [111], but without community participation [108]. Concerning solar energy, despite the absence of high radiation levels in Galicia, there is a high efficiency compared to other regions with greater solar exposure [112]. Biomass is the third source of RE in Galicia [110], although its use is not the most advantageous [113]. Regarding limitations or constraints to RE deployment, Galicia shows a similar distribution to other European regions where mountain ranges give rise to conservation, technical-economic, and physically motivated exclusions, surrounded by large areas where social and political exclusion areas dominate [59].

3.2. Variables

10 indicators (Table 1) are considered to grasp the potential deployment in Galicia of six RE technologies: solar, onshore wind, geothermal, small hydro, biogas, and biomass. The six indicators used to measure the generation potential of RE with these six technologies are extracted from institutional databases with the support of GIS software, being the technical calculations similar to those applied in previous literature [27,40,114,115]. Appendix A provides more detailed information. Four additional indicators are included as facilitating or limiting factors of the different RE potentials. Similar to Benedek et al. [114], the proportion of land surface included in Red Natura 2000 should be incorporated as a limiting factor for any of the RE technologies considered. In addition, the previously

installed capacity of small hydro is also considered a restriction for the deployment of new installations of small hydroelectric plants, since the existing ones have altered the water flow [116]. On the contrary, the existence of previously installed capacity of wind and solar energy is considered a facilitating factor, since there are no obvious restrictions on the installation of more turbines or solar panels and, instead, a positive predisposition of the population is assumed [117]. Table 2 shows the descriptive statistics for the variables considered.

Table 1. Definition of indicators.

RE potential Code	Indicator	Period	Sign	References
POT_SUN	Solar Potential (in kWh /m^2 /day, see Appendix A)	2022	(+)	[40,114]
POT_WIN	Wind Potential (in W/m^2, see Appendix A)	2022	(+)	[40,114]
POT_GEO	Geothermal Potential (in MW/m^2, see Appendix A)	2022	(+)	[118,119]
POT_BGS	Biogas Potential (in m^3, see Appendix A)	2020	(+)	[40,114,115]
POT_BMS	Biomass potential (in tons/ha/year, see Appendix A)	2022	(+)	[27,114]
POT_SHY	Small hydro potential (in km^2, see Appendix A)	2022	(+)	[116]
PRO_LAN_RN2000	Percentage of area included in Red Natura 2000	2018	(–)	[114]
ICP_WIN	Installed capacity of wind farms	2022	(+)	Own proposal based on Langer et al. [117]
ICP_SOL	Solar energy installed capacity	2022	(+)	Own proposal based on Langer et al. [117]
ICP_SHY	Small hydro installed capacity	2022	(–)	Own proposal based on Corcoran et al. [116]

3.3. Method

Composite indicators are powerful tools for defining complex multidimensional concepts that cannot be easily described by a single indicator. Although their use is not without criticism [120], they can help to visualize or demand attention to important issues that require social or political intervention [121,122] and facilitate communication between researchers, policy makers, and the public [123]. Building a composite indicator is a methodological challenge, as combining many indicators into one is not easy and requires rigorous and transparent data and process management, involving several steps [124]. The OECD handbook on constructing composite indicators [125] provides a detailed explanation of these common steps. The first is the selection of individual indicators, which should be placed in the context of a robust and in-depth literature review. The next step involves data collection, analysis, and preparation (normalization and/or standardization). Researchers are then faced with two crucial steps, related to deciding on the individual contribution of each to the overall index (weighting), and how to aggregate those individual indicators to obtain the final index (aggregation). Finally, a sensitivity or robustness analysis is recommended, especially concerning alternative methods that can be applied in the weighting and aggregation steps.

Table 2. Descriptive statistics of the variables.

RE potential	Mean	Standard deviation	Min	Max
POT_WIN	273.89	79.71	112.09	528.32
POT_SUN	3.35	0.19	2.99	3.92
POT_GEO	84.85	10.15	55.28	104.70
POT_BMS	179.35	99.42	0.69	497.75
POT_BGS	17.68	20.30	0.00	146.27
POT_SHY	0.011	0.020	0.00	0.099
PRO_LAN_RN2000	0.10	0.19	0.00	0.98
ICP_WIN	126.47	233.48	0.00	1663.43
ICP_SOL	0.45	1.39	0.00	12.30
ICP_SHY	15.56	54.40	0.00	699.19

There are two categories of weighting methods: statistical ones and those based on expert/participant evaluation. The latter usually leads to the application of equal weights (EW), while among statistical methods Principal Component Analysis (PCA) is the most commonly applied [124]. Regarding aggregation, linear/additive aggregation (calculating the arithmetic average) and geometric/multiplicative aggregation (calculating the geometric average) are the most typical procedures for combining indicators or dimensions in a composite index [126].

PCA is a multivariate technique introduced by Pearson [127] and popularized by Jolliffe [128], to reduce "the dimensionality of a data set composed of a large number of interrelated variables, preserving as much as possible of the variation present in the data set" [129]. PCA transforms a multivariate data set into a smaller number of uncorrelated vectors, or Principal Components (PCs), that can be ordered so that (accounting for the largest proportion of the variance) they retain most of the original variation present in the data set [130]. These retained factors can be rotated so that each original indicator is loaded in only one of the PCs [120]. Among its various applications, PCA can be used to derive weights in the construction of a composite indicator [125,126], based on the variance and covariance of the data set, which constitutes an objective and easy-to-calculate method [123]. However, subjectivity is present to a certain extent, since the researcher must choose the number of PCs to be retained or the rotation method to use [126].

PCA-based composite indicators have been used to capture or measure quite different and complex phenomena [123], such as national, regional, local, or business sustainability [121,122,131,132], rural development [8], regional sustainability [133], resilience [123,134] and vulnerability [135] to different threats, or spatial planning efficiency [133].

Although PCA has some advantages over alternative methods such as data envelopment analysis [122], it also has limitations. Since this study is only assessing a specific dimension (RE aggregated potential) integrated by specific indicators, we overcome some of the limitations pointed out by Gan et al. [120] and Greco et al. [126], related to the difficulty in defining the real meaning of the dimensions extracted using PCA and the fluctuation in the number of dimensions extracted based on different methods of extraction of the PC. The weights derived from PCA and assigned to each indicator should not be understood as a measure of their relative importance, but as a way to reduce the redundancy of the data model [135]. For the PCA analysis, the R Studio software, version 1.1.463, was used.

To take into account the sensitivity and robustness of the composite indicator, and following Salvati and Carlucci [122] and Tapia et al. [135], this study considers the alternative application of PCA and EW as weighting methods.

3.4. Index construction

After the selection of indicators and the construction of the database, the development of the composite indicator encompasses four main procedures: normalization and standardization of the indicators; calculation of weights; aggregation; and finally, the construction of the index under a sensitivity and robustness analysis.

4. Development of a rural RE potential index for Galician municipalities

In this section, the four aforementioned steps to complete the index construction are developed and the results of each step are presented.

4.1. Standardization and normalization of indicators

All indicators were visually monitored for outliers using boxplots [135]. Different transformation methods were tested for each indicator [136]. For each indicator, the transformation method that most reduced the asymmetry within the distribution, if any, was selected (Table 3).

To adequately treat the indicators with different magnitudes [125], a Min-Max standardization was carried out [5,122]. Table 1 shows the expected contribution, negative or positive, of each indicator to the index. For indicators that contribute positively to the index, Eq 1 is used, while for indicators with a negative contribution, Eq 2 is used.

$$z(x_{i,j}) = \frac{x_{i,j} - x_{min,j}}{x_{max,j} - x_{min,j}} \quad (1)$$

$$z(x_{i,j}) = 1 - \frac{x_{i,j} - x_{min,j}}{x_{max,j} - x_{min,j}} \quad (2)$$

where $x_{i,j}$, represents the value of the indicators for a sample unit (municipality), and $x_{max,j}$ and $x_{min,j}$ the maximum and minimum values of the indicator in all the municipalities.

Table 3. Indicator database transformation methods.

RE potential	Asymmetry (Before transformation)	Transformation method	Asymmetry (After transformation)
POT_SUN	0.782	inverse square	–0.388
POT_WIN	0.441	Square root	0.009
POT_GEO	–1.047	Quadratic	–0.356
POT_BGS	2.409	Cube root	0.066
POT_BMS	0.630	Square root	–0.091
POT_SHY	2.509	Fourth root	0.504
PRO_LAN_RN2000	2.655	Fourth root	0.246
ICP_WIN	2.791	Logarithm	0.462
ICP_SOL	6.301	Fourth root	0.791
ICP_SHY	8.965	Fourth root	1.280

4.2. Weights of indicators

The EW and PCA methods were alternatively considered to calibrate the contribution of each indicator to each dimension of capital. The suitability of the data set for the PCA application was tested through the Keizer-Meyer-Olkin (KMO) measure of sampling adequacy [122,123,125]. A KMO of 0.66 and a Cronbach Alpha of 0.55 are obtained. Although values greater than 0.6 are recommended [125], values greater than 0.5 are also considered acceptable [137]. Following Tapia et al. [135], given the nature of the individual indicators, high values were not expected for this study.

The PCA analyzes the correlation structure shown by the indicators or dimensions to configure the PCs and extract a certain number of them according to three criteria [135,138]: i) eigenvalues greater than one; (ii) individual contribution to the overall variance greater than 10%, and; (iii) cumulative contribution to the overall variance greater than 60%. Varimax rotation, the most common rotation method [125], was used to minimize the number of indicators with a high load in a specific PC [123] and maximize the variance of the loads [135].

Table 4. PCA factor loadings.

RE potential	factor loadings
POT_SUN	0.06097324
POT_WIN	0.08165595
POT_GEO	0.06165849
POT_BMS	0.05724926
POT_BGS	0.04576099
POT_SHY	0.04653829
PRO_LAN_RN2000	0.04769929
ICP_WIN	0.08759028
ICP_SOL	0.02367868
ICP_SHY	0.48719551

The PCA weights (Table 4) were defined based on the matrix of factor loadings after rotation, following Tapia et al. [135]: “First, square factor loadings are computed; subsequently, weighted intra-factor loadings are calculated by dividing the square factor loadings by the proportion of variance explained by each factor; then across-factor weighted loadings are generated by dividing intra-factor weighted loads by the proportion of variance explained by each factor in relation to the total cumulative variance explained by all factors; finally, those individual indicators with the highest factor loadings across all factors are selected and re-scaled to unity, as final weights”.

Note that the small hydro potential indicator receives the highest weight after calculation through the procedure explained by Tapia et al. [135]. It is convenient to remember that this indicator had been negatively standardized (showing higher values for municipalities without small hydro facilities and lower values for those where they are already installed).

4.3. Aggregation of indicators

Given that the presence of some indicators with zero values prevents the possibility of applying a geometric aggregation (they would annul the calculation of the composite indicator for certain municipalities), only the arithmetic aggregation (AA) is applied in this step.

4.4. Construction of the index under a sensitivity and robustness analysis

Two possible configurations for the composite indicator are considered: A) AA with the PCA weights for each indicator; B) AA with equal weights.

Since the results of an index that identifies RE potential in rural municipalities can hardly be validated, this procedure increases the reliability of the construction of the index and the transparency of the methodological choices made.

Table 5 shows the municipalities with the highest and lowest scores in this index, on a scale from 0 (low RE potential) to 1 (high RE potential), considering both EW and PCA weights. Results for all Galician municipalities are presented in Figure 1.

Table 5. Municipalities with the highest and lowest scores for the rural RE potential index with PCA weights and EW.

Ranking position	PCA		EW	
	Municipalities	Province	Municipalities	Province
1	Paradela	Lugo	Paradela	Lugo
2	Esgos	Ourense	Esgos	Ourense
3	Cariño	A Coruña	Taboadela	Ourense
(…)				
238	Arnoia	Ourense	Folgoso do Courel	Lugo
239	Quintela de Leirado	Ourense	Cervantes	Lugo
240	Ribadavia	Ourense	Manzaneda	Ourense

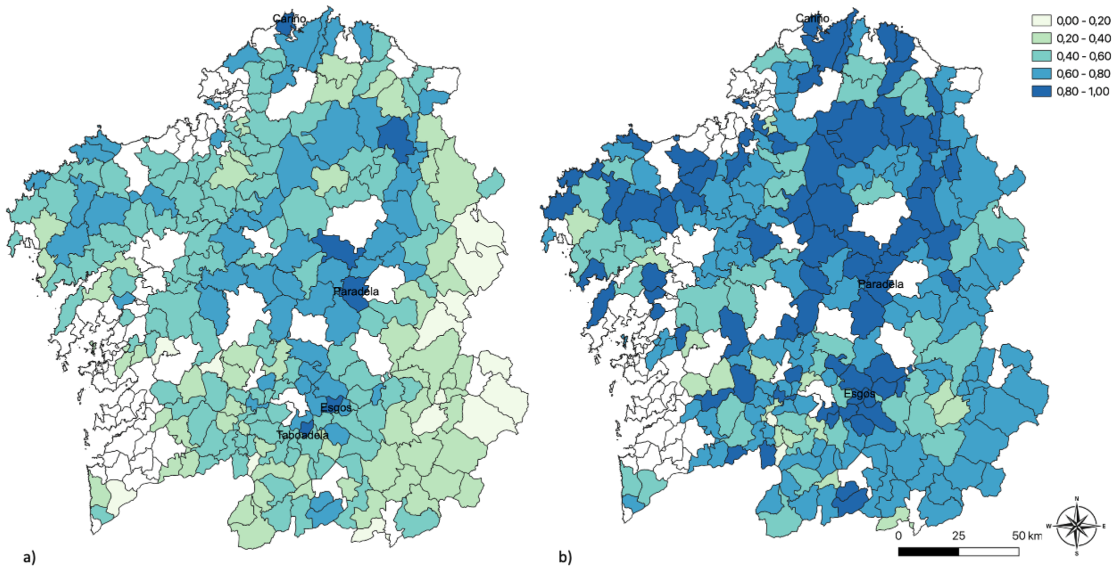

Figure 1. Ranking of the Galician municipalities according to their RE potential with PCA weights and EW – a) EW b) PCA.

Non-rural municipalities are coloured white in Figure 1. These municipalities are mainly concentrated along the Galician coast and under the influence of the two biggest Galician metropolitan areas of A Coruña and Vigo. Although there is no sense in trying to find any pattern in the distribution of the municipalities with the highest and lowest values through the map, since we have insisted on the spatially dependent character of the RE potential concept, it is interesting to note how the municipalities with the highest scores are somehow aligned with the main river courses within the community and the main mountain systems. The municipalities with the lower values for the index are mainly located in the south of the region. The two alternative configurations considered for the index with PCA weights and EW show the same distributional pattern (higher values of the index along river courses and mountain systems), but the index values seem to be softer in the EW version, where many of the municipalities with very high index values in the PCA weights version represented in Figure 1b (in dark blue) show more moderate (but high) values in Figure 1a. In the EW version, the average value of the rural RE potential index in the municipalities considered was 0.471, with a maximum value of 0.718 corresponding to the municipality of Paradela, and a minimum of 0.253 corresponding to the municipality of Manzaneda. In the PCA weights version, the average value of the rural RE potential index in the municipalities considered was 0.642, with a maximum value of 0.837 corresponding to the municipality of Paradela, and a minimum of 0.202 corresponding to the municipality of Ribadavia. As can be seen, the proposed composite index is highly consistent in the classification of the rural municipalities with high or very high RE potential (>0.6), while for the municipalities with lower values, the two proposed versions of the index show more inconsistencies. Anyway, comparing the two maps of Figure 1, very similar behaviour of the ranking of municipalities provided by the index is verified.

This rural RE potential index can be taken as a coherent and rigorous framework to be integrated into energy and spatial planning, allowing to compare municipalities and/or regions and identify attractive locations for HRESs, where further work should be done to explore the possibilities of implementation trying to involve rural stakeholders and to guarantee that the social, economic, and environmental benefits are retained in the rural communities. It can also be integrated as part of a more comprehensive index involving other dimensions relevant to the development of rural areas, such as social, human, economic or infrastructure factors. This could also complement the analysis of alternative scenarios and spatial strategies to drive the sustainable energy transition.

5. Discussion and conclusion

This study has highlighted how a composite indicator showing the RE potential in rural areas can be used to integrate alternative RE sources and consider different types of limiting or enabling factors, contributing to the planning of HRES developments at the local level that should then be extended to a regional/national sphere. This focus on the local level and the simultaneous consideration of various RE technologies are the main contributions of this study for theory and method, and for project promoters and policy makers as well.

Assuming that REs is the key to accelerating the energy transition and achieving SRD, the rural RE potential index could help identify where regional planning should focus the efforts to consolidate rural RE projects. RE expansion will be easier when the most successful initiatives can be replicated and shared. In addition, successful RE developments in a municipality can generate positive indirect effects on the economic development of neighbouring municipalities. RE projects could thus become a driving force for endogenous rural development originating in local communities [139] and an endogenous transition towards sustainability [18]. Obviously, the positive contribution of RE to rural development in the short, medium, and long term would require a set of policies aimed not only at developing RE projects but also at promoting local economic activity, combining support for both supply and demand for energy [18]. Government support should be flexible and tailored to the specific characteristics of rural communities [140], simultaneously developing sectoral policies that address the structural disadvantages of communities, and regional territorial policies that consider their specific rural conditions [141]. This could change the perception of RE as an environmental issue exclusively related to climate change mitigation to see it as a powerful instrument for socioeconomic development, considering it as an integral and critical element of both rural development plans and energy plans [31,32].

A crucial issue is the reduction of the financial risk of small-scale and decentralized RE projects. In addition to supporting policies, formal and informal institutions and new business models could be decisive for the consolidation of RE projects in rural areas and the reduction of their financial risk. Community energy and other forms of community action in rural areas can be important drivers of the expansion of RE. The rural RE potential index proposed in this study could also play a relevant role as a risk mitigation instrument, reducing the risk associated with the choice of suboptimal locations [114].

As mentioned in the previous section, once the rural RE potential of a region has been mapped, it should be necessary to start to consider aspects related to planning processes, social acceptance, and technical and economic issues that need to be properly assessed and managed once a potentially interesting location for RE developments has been identified. In addition, a careful assessment of the environmental, social, and economic impacts along the entire supply and distribution chain would be necessary [26].

The main implication of this study for potential promoters of rural RE projects is that the proposed index may indicate not only where these initiatives might be most feasible, but also what type of projects (relative to the RE technologies implemented) should be better adapted to each specific local context without losing sight of the possibilities of the other. Policy makers can integrate this information in the design of individualized strategies that address the potential of a municipality and of integral strategies that deal with the RE potential of the whole region. For researchers, the proposed index opens many avenues to further advance in the analysis of the preconditions of the rural sustainable energy transition, as well as to suggest alternative configurations of the index, i.e, considering emerging RE technologies such as concentrating solar photovoltaics, enhanced geothermal power, cellulosic ethanol, or artificial photosynthesis [142]. Other possible expansions would consist of also integrating economic viability considerations, as suggested by Sliz-Szkliniarz [40], considering incompatible areas for RE facilities [13], or evaluating whether the RE potential can satisfy a specific percentage of energy demand [143]. The assessment of the RE potential could also be complemented with an analysis of the resources available not only for power generation, but also for storage, transmission, and distribution [41]. Further, it would be interesting to integrate, besides electricity and heating demands, those from cooling, industry, and transport sectors [42], to facilitate the generation of large-scale energy planning strategies.

The main limitations of our proposal are the unavoidable ones in the construction of a composite indicator. If they are not backed by a robust and transparent methodology, they can provide misleading information [144]. Although in the construction of the rural RE potential index an attempt has been made to minimize the presence of subjective and discretionary choices, there is still a certain degree of subjectivity in the indicator selection process and the decision on the sign of their expected relationship with the index. Furthermore, the accurate characterization of complex concepts such as RE potential is always a challenge, and it is often affected by limitations in data availability. More efforts could be made to improve data collection or identify new data sources. Although the consideration of only some RE technologies and enabling or constraining factors could also be considered a limitation, it should be noted that composite indicators are aimed at serving specific purposes that depend on who and what is constructing the index for, under a fitness-for-purpose basis [125]. As mentioned before, researchers, project promoters, and policy makers can easily adapt the index to their own needs by adding or removing indicators. This study has signalled the need to measure the hybrid RE potential of rural locations and suggested the way to do it. From this point, researchers, project promoters, and policy makers can 'take up the gauntlet'.

Despite these drawbacks, the combination of the use of an index such as the one suggested in this study, the contribution of support policies and appropriate financing channels, and the establishment of solid collaborative relationships between different agents, can promote the development of REs in rural areas and make them a key factor in the transition towards a sustainable energy system and the achievement of SRD.

Unfortunately, in the context of Galicia, the latest planning frameworks related to rural development and climate change do not address energy planning issues but are mainly focused on proposing actions in the agricultural and forestry sectors [32, confirm the same reality in Scotland]. Although the positive impacts of REs cannot be taken for granted [33–35] and it is not evident that REs automatically contribute to rural development [145,146], we hope that the regional administration becomes aware of the need to promote an energy transition in rural areas that, based on adaptation to local resources and needs, and citizen participation, contributes to their sustainable development.

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Conflict of interest

All authors declare no conflicts of interest.

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