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ORIGINAL PAPER

Integrating MCDM and GIS for renewable energy spatial models: assessing the individual and combined potential for wind, solar and biomass energy in Southern Spain

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Abstract

The present study aims to develop an integrated methodology using multi-criteria decision-making methods and geographical information systems for a renewable energy spatial planning model. This methodology has been applied to the province of Malaga (Southern Spain), which is characterised by high energy demand for both residential and touristic use. Criteria and restrictions are defined, weighed and combined in order to identify high potential areas for the construction of single- or combined wind power, solar power and biomass generation facilities. Finally, a cluster analysis is carried out in order to classify municipalities within the province according to the availability of medium and high potential land for the construction of these facilities. Results suggest that for the three types of energy analysed (wind, solar and biomass), single- or combined solar and wind power facilities are the best options in the province of Malaga. The breakdown of these results at the municipality level is of great interest from the point of view of spatial planning. For instance, in some municipalities less than 1 km^2 is regarded as having a medium-to-high potential in terms of renewables. Some of these municipalities, situated on the Costa del Sol, must meet high current- and future energy demands, owing both to population density and the volume of touristic demand, which is the highest in the region of Andalusia. The methodology used can be applied to other regions and will be of interest for planners, managers and investors, all of whom can use this information for spatial- and energy planning, and the definition of targets and strategies, and, therefore, as and to aid decision-making.

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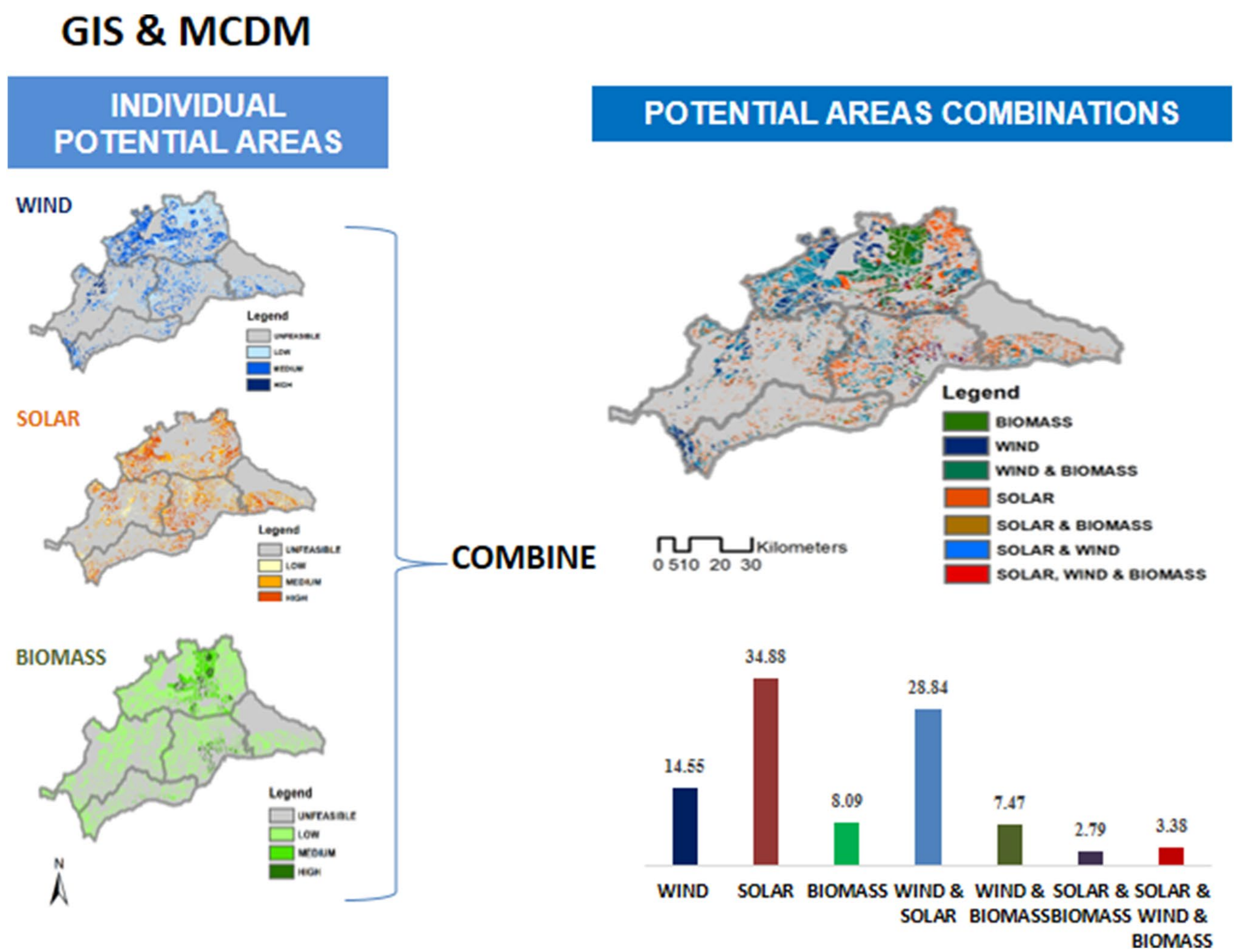
Graphic abstract



Keywords Geographical information systems (GIS) · Multi-criteria decision-making (MCDM) · Renewable energy · Implementation models · Combined systems

Introduction

Currently, guaranteeing energy supply while energy models adapt to the impact of climate change is one of the main concerns for most governments. The European Union—EU—has put forward several strategies in order to ensure a transition towards a more efficient and diversified energy model, in order to combat climate change. This transition is based on the reduction of greenhouse-gas emissions, the promotion of renewable energy and increasing energy efficiency. New renewable energy targets were published by the European Parliament in November 2018, according to which member states must ensure that, by 2030, 32% of the energy consumed comes from renewable sources (Directive 2018/2001), and that energy consumption is reduced by 32.5%.

Each member state incorporates these targets into so-called renewable energy plants, in which energy demand analysis and projections are examined, targets for each source of renewable energy set up, and strategies to be followed according to different analytic scenarios outlined. The EU also demands that member states present a National Integrated Energy and Climate Plan 2021–2030 identifying the main challenges and opportunities throughout the EU: decarbonisation—including use of renewables, energy efficiency, energy security, the internal energy market and research, innovation and competitiveness.

In Spain, a country with a high energy dependence rate (73.3% in 2017)—Agencia Andaluza de la Energía (AAE)

(2018a)—each region develops its own energy targets, which often surpass those established at the European and national level. For instance, in the Estrategia Energética de Andalucía (AAE 2016), a planning document that presents the region's targets and strategies, the target for 2020 was to ensure that 25% of gross energy consumed came from renewable sources, while the EU target for this year was only 20% (European Commission 2007, 2010).

Concerning the construction of renewable energy plants in Andalusia, we must highlight that although Article 11 of the Act of Renewable energy, published in 2007, recommended identifying areas compatible with the generation from and transformation to renewables, this has not resulted in the publication of a document defining what is understood in the regional context by this compatibility. In fact, the installation of renewable energy plants has followed simple protocols based on availability of the resource and of an electricity grid with which to transport the energy thus generated, without taking into consideration the wider suitability of the chosen location or the combination of various energy sources (Díaz 2013).

For this reason, and given that the Plan de Energías Renovables (2011–2020)—IDAE, 2011—and the Estrategia Energética de Andalucía (2015–2020)—AAE 2016—come to an end in 2020, it is desirable that the new Estrategia present consistent targets for renewables that take into consideration the potential of the territory to which they will be applied.

In line with this, the present work aims to develop a methodology with which to assess the potential of the territory for the construction of single- or combined renewable energy plants (wind power, solar power and biomass). In order to meet this target, a location model has been built by integrating geographical information system—GIS—and multicriteria decision-making methods—MCDM.

GIS and MCDM are widely used for renewable energy planning and assessment (Siksnelyte et al. 2018; Mukhamediyev et al. 2018; Stojčić et al. 2019). This is due to the great potential for the processing, management and analysis of spatial information provided by GIS, which also allow the incorporation of different criteria, and the easy implementation of multi-criteria analysis. This results in a wide range of spatial analysis capabilities for decision-making and site-selection problems (Lovett and Appleton 2007; Afshari and Yusuff 2012; Wimmler et al. 2015).

Although multiple studies have examined the potential and performance of hybrid or combined renewable energy plants (Liu and Wang 2009; Alsayed et al. 2014; Tégani et al. 2014), the use of GIS and MCDM for the identification of suitable locations for facilities of this sort has received less attention. Most studies focus on identifying suitable locations for a specific kind of energy plant. Significant works in this regard are Sánchez et al. (2013, 2014), Uyan (2013, 2017), Sánchez et al. (2014), Noorollahi et al. (2016) and Davtalab and Alesheik (2018). Other works examine the suitability of sites for two types of plant (Watson and Hudson 2015; Sadegui and Karimi 2016), but the analysis of hybrid models—those which allow for the combination of different technologies, so that the weakness of one system might be compensated by the strengths of the other—is rarely explored (Hongxing et al. 2009). In this point, the work of Palmas et al. (2015), analyses individual and hybrid models for three different kinds of renewable energy potential in Hanover region (wind, solar and biomass/maize energies).

Therefore, the main contribution of the present paper is that it analyses the territory's potential for the installation of single or combined wind energy, solar energy and biomass energy generation facilities. As such, in this study, grid-connected individual renewable energy systems and renewable energy system combinations are evaluated.

Another contribution of the present paper regards the territory chosen for the case study, the province of Malaga (Southern Spain), first, because of the high current and future energy demands that are due to its large population and the importance of its tourism sector, and second because, as far as the authors are aware, this is the first time the whole province has been evaluated in terms of renewable energy potential. This will be of great use for planners, managers and investors, each of whom can use this information for spatial and energy planning, to define targets and strategies and, therefore, to aid decision-making.

Study area

The study area is the province of Malaga in the region of Andalusia, Southern Spain (Fig. 1). With a population of 1,641,121 (Institute of Statistics and Cartography, IECA 2019a), which is approximately 20% of the overall Andalusian population, and an area of 7307 km^2, the province is subject to substantial anthropic pressure, especially near the coast, given the importance of the tourism sector and its competition with other sectors, especially agriculture.

The province comprises 103 municipalities, 14 of which are on the coast. In 2018, these municipalities offered 178,450 units of tourist accommodation, approximately 35% of the Andalusian total (IECA 2019b). The province of Malaga ranks third in Andalusia in terms of primary energy consumption at 2104 Ktep; and second, in terms of electricity consumption at 6110.7 GWh in 2017 (AAE 2018b). Recent research has indicated that energy consumption in Andalusia and the province of Malaga in particular will increase as a result of climate change (Limones et al. 2018).

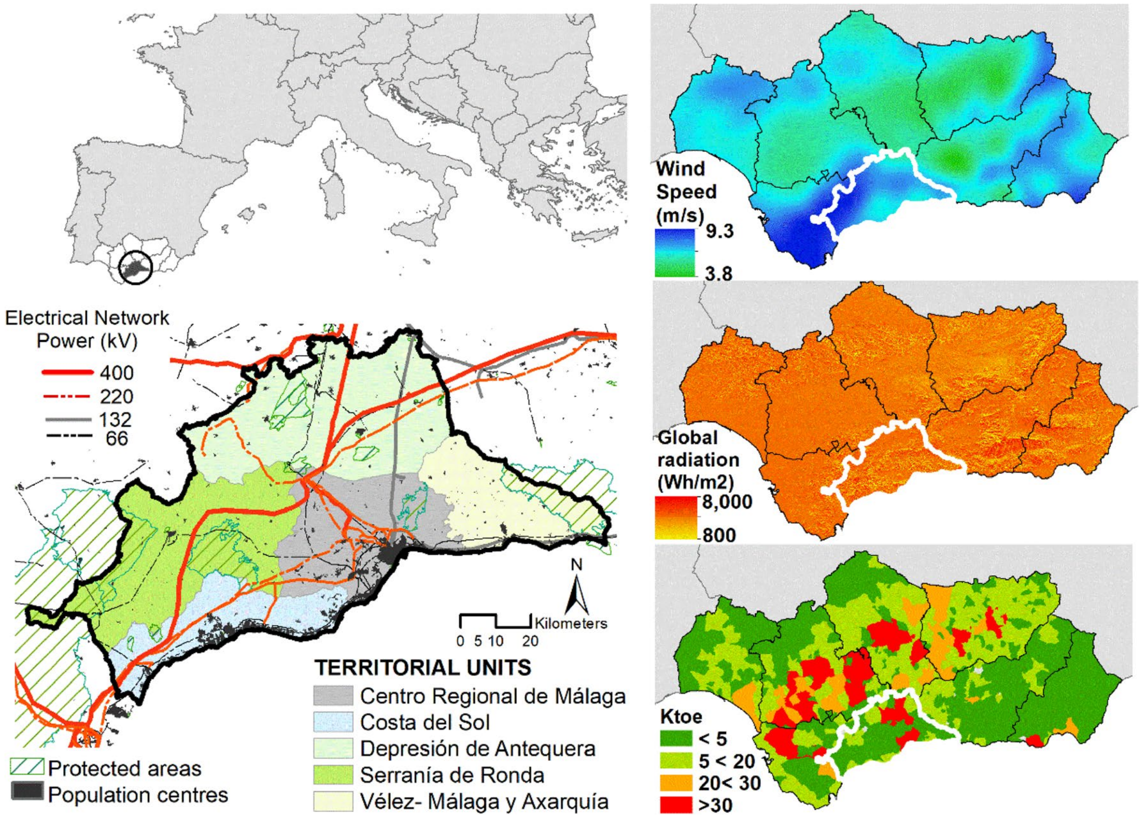


Fig. 1 Protected areas, population centres, electrical network and renewable energy resources (average annual wind speed at 120 m of altitude; global annual radiation; and annual biomass energy potential), in the study area

The province is divided into five territorial units, as follows, according to the Territorial Organization Plan (Consejería de Obras Públicas y Transportes, COPT 2006):

- Centro regional: This territorial unit includes the city of Malaga, capital of the province. It comprises 13 municipalities, with approximately 50% of the provincial total. Highly anthropised area, characterised by tertiary economic activities, especially towards the central and coastal areas. It also presents important protected natural spaces, such as the Parque Natural de Los Montes de Málaga.
- Costa del Sol: touristic area. Highly anthropised, owing to the large presence of tourists. One of the prime touristic destinations worldwide (Garcia et al. 2019).
- Depresión de Antequera: composed of middle-size population nuclei, this endorheic basin is rich in water and agriculturally prosperous. It includes several protected lagoons.
- Serranía de Ronda: characterised by forested and agricultural areas, this sector is very rich in terms of cultural and natural heritage. It hosts the Parque Natural Sierra de las Nieves and the Paraje Natural Los Reales de Sierra Bermeja. It comprises small population nuclei, characterised by slightly negative demographic dynamics.
- Veléz Malaga y Axarquía: highly anthropised environment, which presents the highest number of dispersed population nuclei in Andalusia (COPT 2006b). Historically, the economy of this hilly district has depended on arable and livestock farming; periods of economic crisis, however, have led to the exploitation of the coastline for touristic purposes and the introduction in recent years of subtropical crops. It also includes a number of highly valuable natural spaces, such as the Parque Natural Sierra de Tejera, Almijara y Granada.

Materials and methods

Material

In order to assist with the characterisation of the territories of Malaga according to their potential, spatial data are drawn from the Institute of Statistics and Cartography of Andalusia and the Environmental Information Network of Andalusia, the bodies in charge of elaborating and distributing socio-demographic and environmental information at the regional level. Concerning wind-energy resources, the wind speed 50-m-resolution grid (for a turbine height of 120 m) was based on results published by project Minieolica (Lorente et al. 2012), while solar radiation data were based on radiation maps published by the Environmental Information Network, which we have previously used to calculate solar energy potential in Andalusia (Díaz et al. 2018a, b). Finally, biomass potential data were taken from the Biomass Potential Map of Andalusia (AAE 2018c), published by the Andalusian Energy Agency. This variable is assessed by municipality, and it evaluates biomass resources (Ktoe/year) based on the biomass resources provided by agricultural, forestry-related, industrial, urban, animal and energy-related activities.

The digitalisation (*x*, *y*) of wind turbines and of polygons occupied by solar energy plants was carried out using 2017 aerial orthophoto data stored in the Infrastructure for Spatial Data in Andalusia (Díaz et al. 2018a, b). This infrastructure uses international standards to integrate interoperable geoservices, following the guidelines delineated in the Infrastructure for Spatial Information in Europe (INSPIRE) Directive (Council Directive 2007/2/EC).

The coordinate system used was the European Terrestrial Reference System 1989 (ETRS89), projected in (EPSG25830), in accordance with the regional legislation (Royal Decree 1071/2007) with a 100 m^2 resolution.

Finally, the ArcGIS 10.3 software was used, owing to its ample spatial analysis capabilities.

Methods

The methodology used was based on the construction of a locational model though GIS and MCDM. The methodological sequence comprised four steps.

- *Step 1* Construction of a simple binary (0–1) locational sub-model for the identification of areas incompatible with the construction of renewable energy plants. This was based on incompatibility criteria and restrictions. Afterwards, criteria and restrictions were mapped, aggregated and reclassified, incompatible areas receiving a value of 0 and compatible areas a value of 1.
- *Step 2* Construction of a weighted locational sub-model for the classification of compatible areas according to their suitability. For this, suitability factors were weighed using analytic hierarchy process—AHP—(Saaty 1980, 1989). Afterwards, these criteria were aggregated and reclassified in order to evaluate the territory in terms of suitability, from 10 (most suitable areas) to 1 (least suitable areas).
- *Step 3* Calculation of wind power, solar power and biomass potential. Wind power potential was estimated according to the annual wind-speed map; solar power potential was estimated according to the solar radiation map, weighted for different orientations; and biomass energy potential was estimated according to the biomass potential map.
- *Step 4* Combination of results—incompatible areas; compatible areas according to suitability; and wind, solar and biomass potential—for the classification of areas in terms of their potential. Results were divided into four tiers: areas with the highest potential received a value of 3, and incompatible areas a value of 0. Individual potential values (wind, solar and biomass) were put together in order to calculate the potential for hybrid or combined systems (wind and solar, wind and biomass, biomass and solar, etc.).

Finally, a cluster analysis was undertaken in order to define a typology of municipalities based on the percentage of the municipality area which is regarded as being moderately to highly suitable for the construction of wind farms, solar plants and biomass energy generation facilities, or combinations thereof.

Each of the phases is explained in detail in the following sections.

Identification of incompatible areas

The first step was to establish incompatibility criteria and restrictions to the construction of renewable energy facilities (Table 1), based on local planning and legislation. Where legal or planning-based restrictions could not themselves determine these criteria, those established in the existing literature were used. These criteria are designed to protect, among other things, cultural and natural heritage, and to ensure energy efficiency and, thus, economic and territorial efficiency of energy facilities.

After the criteria were defined, incompatible (0 value) and compatible (1 value) areas were mapped.

Availability assessment

Availability was determined by means of a Delphi panel composed of three experts (two renewable energy plant planning and management experts and a geographer with extensive knowledge of the study area). The experts identified four common factors to be considered for the construction of renewable energy facilities. These factors have to do with energy saving and efficiency, economic and territorial efficiency, and the avoidance of negative environmental impact.

This allowed for the identification of available areas for the construction of renewable energy plants in terms of distance to the electric grid and population nuclei, and also of orography. One aim is to avoid the need to build new energy transport and road networks, which would negatively

Table 1 Criteria and restrictions applied

Criteria	Wind	Solar	Biomass
Settlements	Cities and main population nuclei < 500 m Rural villages and buildings < 250 m Yue and Wang (2006), Ramírez et al. (2008) and Sliz-Szkliniarz and Vogt (2011) Watson and Hudson (2015)	Incompatible, except in industrial districts Sánchez et al. (2013, 2014) and Uyan (2013, 2017)	Incompatible, except in industrial districts
Tourism facilities (hotels, golf courses, etc.)	< 100 m Sliz-Szkliniarz and Vogt (2011)	Incompatible Uyan (2013, 2017)	Incompatible
Road network	< 140 m from motorways and highways Combination of Act 8/2001 and Act 37/2015, which aims to establish clear boundaries for and secure perimeter around areas in the public domain 100 m from roads and footpaths		
Scenic roads, green roads, etc.	Areas located within 175 m of cattle tracks, within 135 m of restricted byways, within 20 m of lanes and within 100 m of other green paths *Act 3/1995,* which aims to establish clear boundaries for and a secure perimeter around areas in the public domain		
Rail network	< 110 m *Act 9/2006,* which aims to establish clear boundaries for and a secure perimeter around areas in the public domain		
Antennae and military areas	<600 m Lejeune and Feltz (2008) and Atici et al. (2015)	Incompatible Sánchez et al. (2013, 2014) and Uyan (2013, 2017)	
Natural areas, protected landscapes, environmental protected areas	Incompatible Nature reserves and national parks: as established for each park in its Natural Resources Management Plan; other regional protected areas: entire extent of these spaces according to functionality established by Act 2/89 and Act 4/1989 RAMSAR areas: entire extent, Biosphere reserves: not the core of these areas		
Rivers, water public domain, lagoons and wetlands	< 50 m which aims to establish clear boundaries for and a secure perimeter around areas in the public domain. Royal Decree 9/2008		
Cultural heritage	< 100 m from cultural assets Sliz-Szkliniarz and Vogt (2011) and Sánchez et al. (2013, 2014)		
Forested areas	< 250 m Yue and Wang (2006)	Incompatible	
Faults	< 200 m Atici et al. (2015) and Díaz et al.(2018a)		Incompatible Davtalab and Alesheik (2018)
Electric grid	< 100 m > 10 km Sunak et al. (2015) Díaz et al. (2018a, b)		
Slope	> 30% Sunak et al. (2015)	Areas with steepest slopes Sánchez et al. (2013), Uyan (2013, 2017) and Díaz et al. (2018b)	Incompatible Davtalab and Alesheik (2018)
High-potential agricultural areas		Incompatible areas Sánchez et al. (2013) and Uyan (2013, 2017) and Díaz et al. (2018b)	
Areas already occupied by any renewable energy facility	Incompatible areas Díaz et al. (2018a, b)		
< 500 m shoreline	Incompatible areas Noorollahi et al. (2016)		
Fluvial inundation areas over period of 100 years	Incompatible areas Villacreses et al. (2017) and Davtalab and Alesheik (2018)		

impact facilities' energy, economic and territorial efficiency; new energy transport networks involve energy loss, and their construction is costly, as well as resulting in further environmental impact.

Similar criteria apply to proximity to the road network. Concerning biomass, the proximity of biomass power generating facilities to roads reduces transportation costs, construction and maintenance costs, etc. (Davtalab and Alesheik 2018).

Concerning the proximity of population nuclei, the key factor is the principle of distributed generation (DG); according to this principle, energy should be generated near where it is consumed. This minimises the transmission lines that need to be built and maintained, as well as also energy losses during transmission.

Finally, steep slopes are avoided in order to reduce construction costs together with the geomorphological impact of construction.

In order to assess the availability of different areas, distances to the electric grid, road network and population nuclei were calculated, while taking orography into account with the aid of an existing digital elevation model that has a 100 m resolution. Each of these factors received a value (1–10) based on ten distance intervals. The most suitable areas received a score of 10 in this variable (see Fig. 2).

After standardising values according to this 1–10 scale, other less important factors were weighted and applied. Weights were assigned by the expert panel using Analytic Hierarchy Process (Saaty 1980; 1989; Ilbahar et al. 2019) in order to ensure their consistency. This method examines each expert's opinion regarding the relevance of each criterion. Delphi software (eDelphi.org), which compares criteria with one another by means of questions such as "which of the two is more important?—and by how much?" was used. The results are expressed on a semantic scale (Table 2), which determines the degree to which one criterion is relatively more important than another in assessing an area's suitability for the construction of renewable energy plants.

This process generates an auxiliary matrix "*A*", where if the relative importance of the factor 1 over the factor 2, *F*12, is judge to be 5 "strong importance" in Saaty scale—see

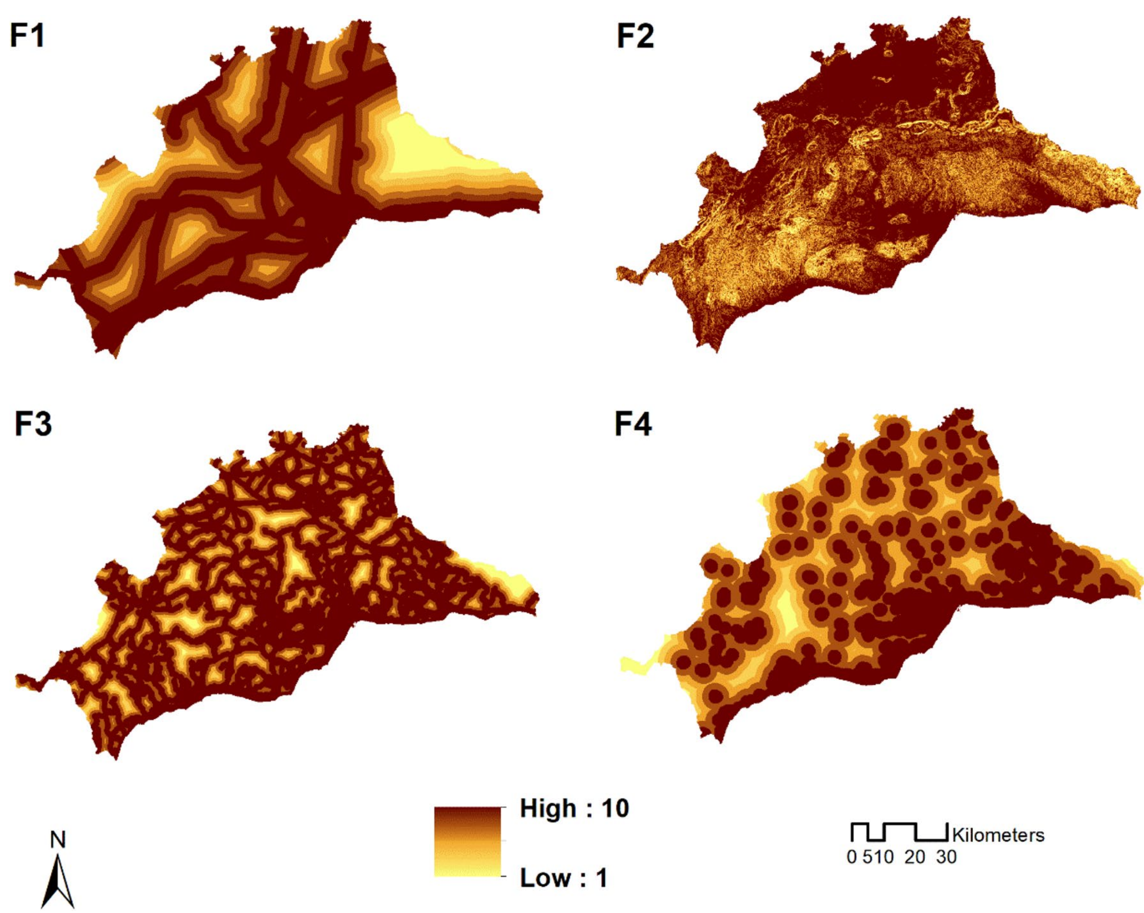


Fig. 2 Normalised area maps for each factor. *F*1 (Distance to the electric grid); *F*2 (slope); *F*3 (distance to the road network); *F*4 (distance to population nuclei)

Table 2 Saaty scale

	1	3	5	7	9
Definition	Equal importance	Moderate importance	Strong importance	Very strong importance	Extreme importance

Values 2, 4, 6 and 8 on the Saaty scale correspond to intermediate situations

Table 3 Pairwise comparison of factors

	I_F1	I_F2	I_F3	I_F4
I_F1	1	1	4	7
I_F2	1	1	4	5
I_F3	1/4	1/4	1	2
I_F4	1/7	1/5	1/2	1
SUM1	2.39	2.45	9.5	15

I_F1 = electrical network; I_F2 = slope; I_F3 = road network; I_F4 = population centres

Table 2—the relative importance of the factor 2 with regard to the factor 1, $F21$, has the reciprocal value, which is 1/5

$$A = \begin{matrix} \mathbf{F11=1} & F12=5 & F13=3 \\ F21=1/5 & \mathbf{F22=1} & F23=2 \\ F31=1/3 & F32=1/2 & \mathbf{F33=1} \end{matrix} \quad (1)$$

Once the judgments have been established by the experts, Table 3, the matrix has been normalised. This process involves dividing the elements of each column by the sum of the elements of the same column (SUM1). Subsequently, the values of the rows of the normalised matrix (Table 4, SUM2) are summed and divided by the number of factors (in this case 4), to obtain the relative importance of the compared factors (W).

As such, the experts considered that areas closest to the electricity grid, followed by those with lesser slopes, are better fits in terms of territorial and economic efficiency (weight values 42.8 and 39.6). This is followed by proximity to the road network (weight value 11.1), and proximity to population nuclei (weight value 6.5).

The comparison matrix measures robustness in expert bias in terms of the consistency ratio, Cr (Saaty and Ozdemir 2003; Ho et al. 2005). If $Cr < 0.1$, the ratio indicates a reasonable level of consistency in pairwise comparisons; if, however, $Cr > 0.1$, then the ratio is indicative of inconsistency, and therefore requires the weighting of variables to be revised. Cr is calculated from the consistency index, Ci Eq. (3), and random index, Ri, as follows:

$$\mathrm{Cr} = \frac{\mathrm{Ci}}{\mathrm{Ri}} \quad (2)$$

$$\mathrm{Ci} = \frac{(\lambda - n)}{(n-1)} \quad (3)$$

where n is the number of factors in the comparison matrix and λ is the principal eigenvalue of the matrix that can be defined as the product of the original matrix and the weights (Saaty 1977; Tahri et al. 2015).

The random index, Ri is the average Ci of the randomly generated comparisons (Saaty, 1980). The value of random index for a matrix of order 4 is 0.9. Therefore:

$$\mathrm{Cr} = \frac{\mathrm{Ci}}{\mathrm{Ri}} = \frac{0.076}{0.9} = 0.08 \quad \mathrm{Ci} = \frac{(4.022-4)}{(4-1)} = 0.0076$$

After determining the weight of each criterion, suitability was calculated by means of a weighted linear sum (Eq. 4), a widely used and simple methodology with the available software that uses either map algebra or the weighted linear sum itself

$$A_{\mathrm{p}} = \sum_{i=1}^{n} w_i x_{\mathrm{ip}} \quad (4)$$

where A_p value for the cell p; w_i the relative weight of the factor i; and X_{ip} normalised value of the cell p for the factor i.

Afterwards, the result was divided into 10 tiers, value 10 being assigned to the areas with the highest scores, and value 1 to areas with the lowest scores.

Table 4 Normalised pairwise comparison and weighting of suitability factors

	I_F1	I_F2	I_F3	I_F4	SUM2	W
I_F1	0.42	0.41	0.42	0.47	1.72	0.4281
I_F2	0.42	0.41	0.42	0.33	1.58	0.3959
I_F3	0.10	0.10	0.11	0.13	0.44	0.1110
I_F4	0.06	0.08	0.05	0.07	0.26	0.0648

I_F1 = electrical network; I_F2 = slope; I_F3 = road network; I_F4 = population centres

Determination of potential by area

The determination of potential area combined wind, solar and biomass energy potential with suitability criteria.

Wind resource was obtained from wind-speed maps for 120 m turbines (Lorente et al. 2012).

Concerning solar potential, a global average solar radiation map (Wh/m^2/year) is available in Andalusia, but following Arán et al. (2008), Sánchez et al. (2013), Al Garni and Awasthi (2017) and Díaz et al. (2018b), it was also considered advisable to regard orientation. In the northern hemisphere, areas facing south, south-east and south-west are more productive, as they are exposed to radiation all year round, especially during the middle hours of the day, when radiation is most intense. As a result, a solar potential map which takes orientation into account was generated. Orientation was calculated with the aid of the existing digital elevation model of the study area, which has a 100 m resolution. Afterwards, following the experts' opinion, the values corresponding to SE/S/SW-facing cells were multiplied by 10.

Finally, biomass potential (in Ktoe/year) was obtained with the aid of the biomass potential map of Andalusia, published by the Andalusian Energy Agency (AAE 2018c).

Figure 3 shows the wind, solar and biomass maps. Following cells were homogenised to 1–10 scores and multiplied by suitability and availability values. The results were then divided into four tiers, indicating potential: 0 (incompatible), 1 (low), 2 (medium) and 3 (high).

After this, areas which could potentially host hybrid-combined power generation facilities (wind–solar;

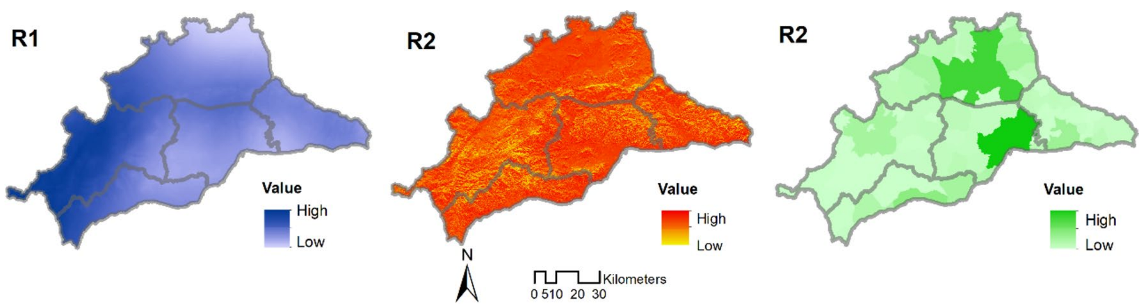
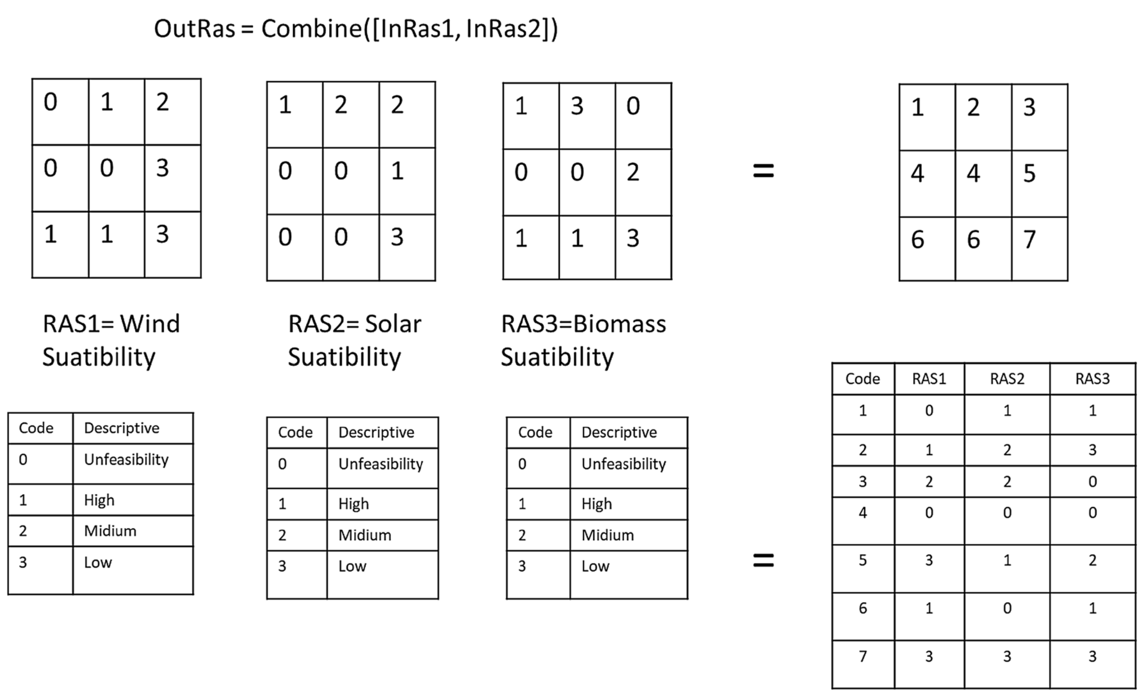


Fig. 3 Wind power (*R*1), solar power (*R*2) and biomass (*R*3) estimates for the province of Malaga



0	1	2
0	0	3
1	1	3

1	2	2
0	0	1
0	0	3

1	3	0
0	0	2
1	1	3

1	2	3
4	4	5
6	6	7

Code	Descriptive
0	Unfeasibility
1	High
2	Midium
3	Low

Code	Descriptive
0	Unfeasibility
1	High
2	Midium
3	Low

Code	Descriptive
0	Unfeasibility
1	High
2	Midium
3	Low

Code	RAS1	RAS2	RAS3
1	0	1	1
2	1	2	3
3	2	2	0
4	0	0	0
5	3	1	2
6	1	0	1
7	3	3	3

Fig. 4 Combination of wind potential (RAS1), solar potential (RAS2) and biomass potential (RAS3) by means of the COMBINE tool for the province of Malaga

wind–biomass, etc.) were identified. This was done by means of the ArcGIS COMBINE tool, which combines different rasters and provides a single exit value to each combination of data entered (Fig. 4).

Typology of municipalities

After the combined values were calculated, a typology of municipalities was undertaken. This typology reflects what percentage of a municipality's area can be regarded as having a medium-to-high potential for the installation of single- or combined wind, solar and biomass energy generation facilities. This was carried out through a non-hierarchical *K*-means cluster analysis with the aid of statistical programme SPSS, using Euclidean distance-squared as expression of distance.

Results and discussion

Incompatible areas

Incompatible areas for renewable energy facilities are illustrated in Fig. 5; 74.6% of the province is considered incompatible with the construction of wind farms; 79.4% is considered incompatible with the installation of solar energy plants; 63.4% is considered incompatible for the construction of biomass plants; and 83.3% of the territory is incompatible for combine power plant consisting of the three types.

By territorial units, Velez-Málaga presents the highest proportion of incompatible areas, owing largely to two factors: the abundance of wooded, steep slopes and the fact that a large proportion of the territory is 10 km or more distant from the electricity grid.

Costa del Sol also presents a high proportion of incompatible areas, owing chiefly to the existence of numerous population nuclei and other settlements and their associated infrastructures (dense road and electrical networks), as well as the existence of numerous wooded areas in the mountainous territory that characterises the northern sectors of the territory.

The abundance of wooded and steep slopes also explains why most of Sierra de las Nieves is regarded as incompatible. This is in addition to the fact that the construction of generation plants is prohibited in wide sectors of Parque Natural de Sierra de Grazalema and Parque Natural Sierra de las Nieves due to relevant planning and management regulations.

Depresión de Antequera presents the highest proportion of territory compatible with the construction of these facilities. The territory is relatively flat and has few wooded areas. However, the presence of wide tracts of cultivated

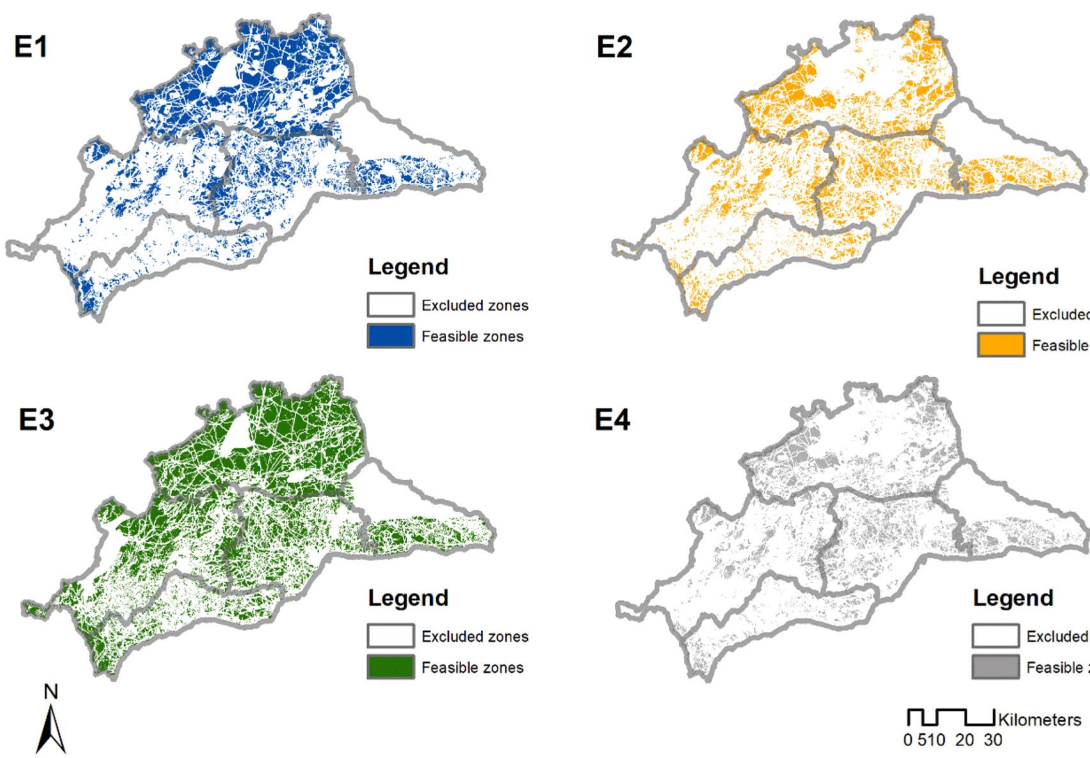


Fig. 5 Incompatible areas. *E*1 (Wind energy); *E*2 (solar energy); *E*3 (biomass); *E*4 (combined power plants)

land renders a large proportion of this territory incompatible with the construction of solar energy plants.

Finally, Centro Regional de Malaga includes the most densely urbanised areas, and the road and rail networks are accordingly dense, especially near the coast.

Potential areas

Figure 6 illustrates the areas with the highest potential for renewable energy plants in the province of Malaga. The highest wind-energy values are found in Depresión de Antequera and some sectors of Serranía de Ronda, where 18 and 2 (respectively) of the 23 wind farms currently extant in the province are located (AAE 2018b). To an extent, the areas with the highest solar energy values overlap with these; these two territorial units host 12 of the 18 solar energy plants currently extant in the province, although all territorial units present significant proportions of areas with a high solar energy potential.

Concerning biomass, high potential values are only to be found in Depresión de Antequera, owing to the abundance of agricultural residue, and Centro Regional de Malaga, owing to the abundance of urban residue. Some areas in Costa del Sol present medium values.

Despite the high potential for biomass energy generation outlined, only two biomass energy generation facilities are currently in existence in Depresión de Antequera (AAE 2018b), with two more in Centro Regional de Malaga. Despite the high potential of these units, however, before further plants are installed it will be necessary to analyse the use of resources by the existing facilities, in order to determine if the resources' availability justifies the construction of new plants.

Figure 7 illustrates that nearly 78% of compatible areas present high potential for the installation of single- or combined wind and solar energy generation plants, while 7.47% and 2.79% present high potential for the installation of hybrid-combined wind–biomass and solar–biomass plants, respectively.

Finally, 3.38% of the compatible territory presents high potential for the installation of plants in which all three types of energy generation are combined.

Typology of municipalities according to their potential

Municipalities were divided into eight groups according to their potential, as illustrated in Fig. 8 and Table 5. Each

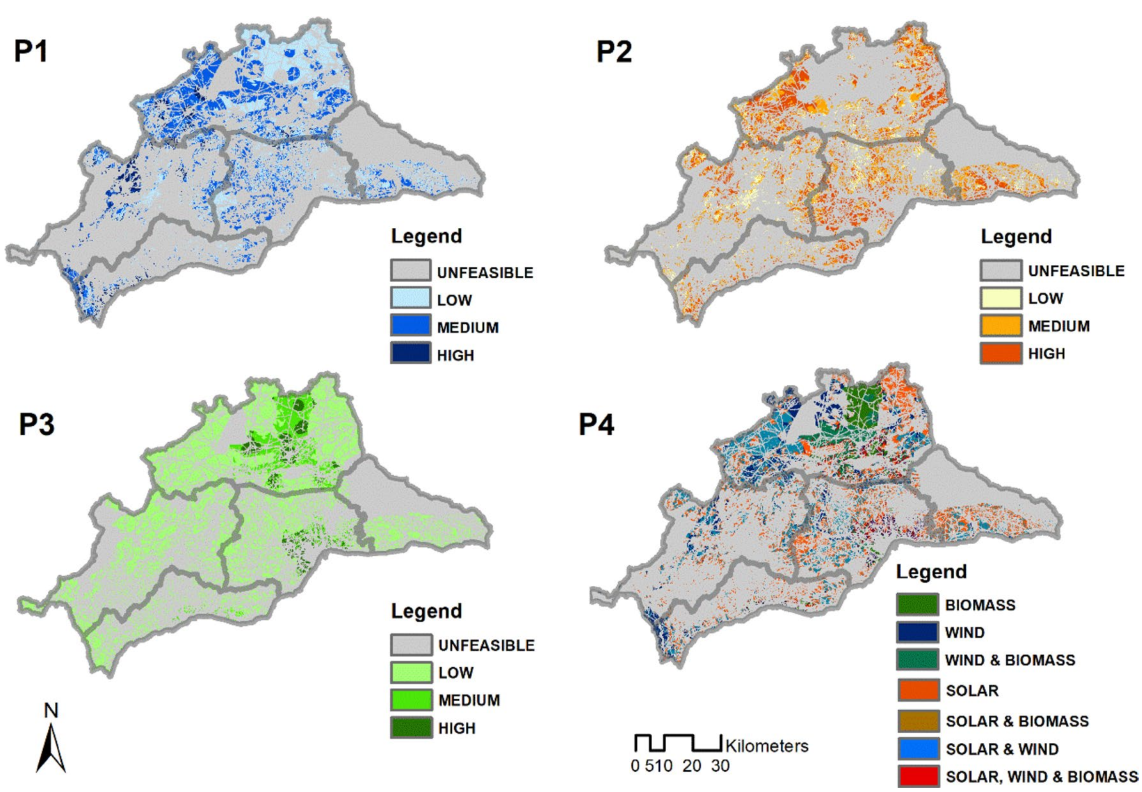


Fig. 6 Potential for the construction of renewable energy plants. *P*1 (Wind energy); *P*2 (solar energy); 3 (biomass); *P*4 (individual and combined plants)

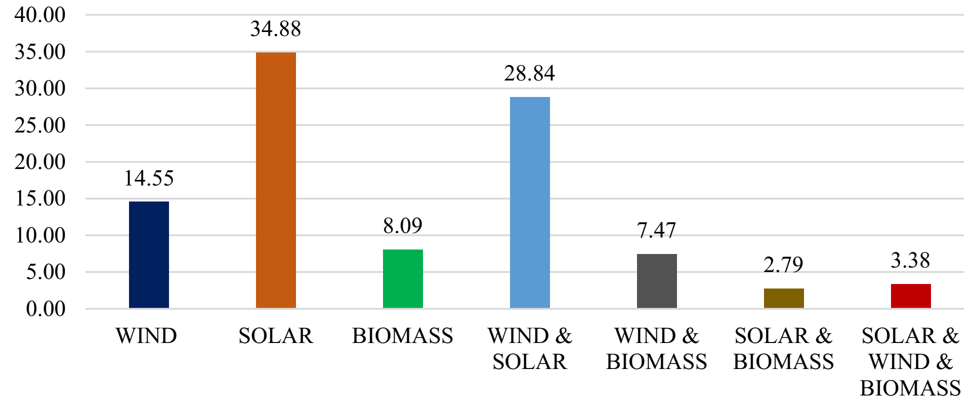


Fig. 7 Compatible territory (%) according to its potential for the installation of renewable energy generation plants

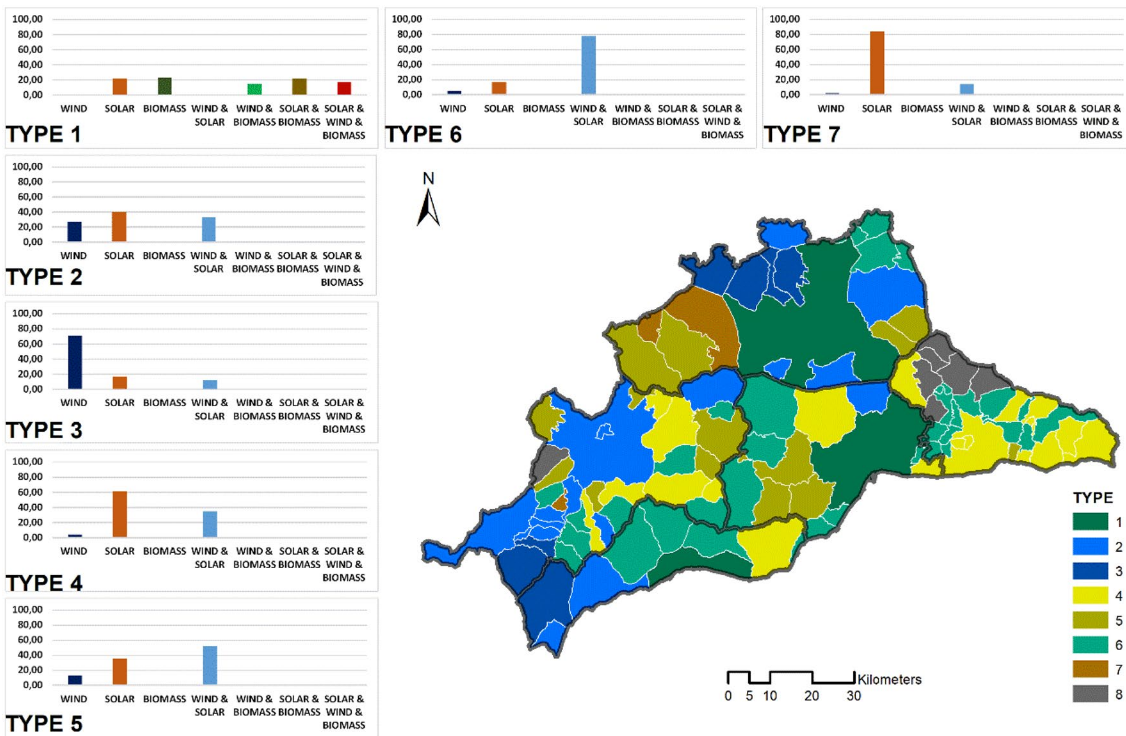


Fig. 8 Typology of municipality according to percentage of territory which presents medium–high potential values for the installation of renewable energy plants

Table 5 Groups

Group	Number of municipalities	Percentage of municipalities
1	3	3
2	16	16
3	7	7
4	19	18
5	14	14
6	34	33
7	3	3
8	7	7

group was characterised by a bar chart illustrating the average value, expressed as a percentage, of each energy source in each group (wind, solar, biomass or the combination thereof).

Group 1 comprises three municipalities (Antequera, Marbella and Malaga), which are the only municipalities in the province in which medium–high potential areas for combined (wind–solar–biomass) generation plants are found. In addition, these are the only municipalities which present high potential values for the installation of biomass plants.

Group 2 comprises 16 municipalities. It is characterised by the fact that a significant proportion of their territory presents medium–high potential values for the installation of solar plants, wind farms or the combination thereof.

Group 3 is a composite category, which comprises seven municipalities that are characterised by a predominance of areas with medium–high potential values for the installation of wind farms.

Group 4 comprises 19 municipalities that are characterised by the predominance of areas with high-to-very high potential values for the installation of solar plants.

Groups 5 (14 municipalities) and 6 (34 municipalities) are similar. They are characterised by the fact that a significant proportion of their territories presents high potential values for the installation of wind–solar plants. Potential values in Group 6 are higher than in Group 5.

Group 7 comprises three municipalities. It is characterised by the fact that a significant proportion of their territories presents high potential values for the installation of solar plants.

Finally, Group 8 comprises seven municipalities, which are devoid of any areas that present high–medium values for the construction of any analysed form of renewable energy generation plant.

As a result, we may conclude that most municipalities in the province present high potential values for the installation of wind and solar energy plants. However, since the percentages have been calculated on the basis of compatible areas, in order to express the real potential of each municipality, these values need to be expressed in absolute terms (km^2), as illustrated in Fig. 9.

These results suggest that 14 of the 103 municipalities possess less than 1 km^2 of medium-to-high potential territory for the construction of renewable energy plants. While seven municipalities possess no potential for the installation of this sort of plant, others, such as Fuengirola, are densely populated while hosting a large amount of touristic accommodation (Sistema de Información Multiterritorial de Andalucía 2018) and hence demanding, now and in the future, a large supply of electricity. In these municipalities, it will be necessary to explore the installation of rooftop solar panels to promote self-sufficiency. A further 50 municipalities possess between 1 and 10 km^2 of high potential territory; Benalmádena, Torremolinos and Nerja, in Costa del Sol, which are densely populated and host a large amount of touristic accommodation, are within this category.

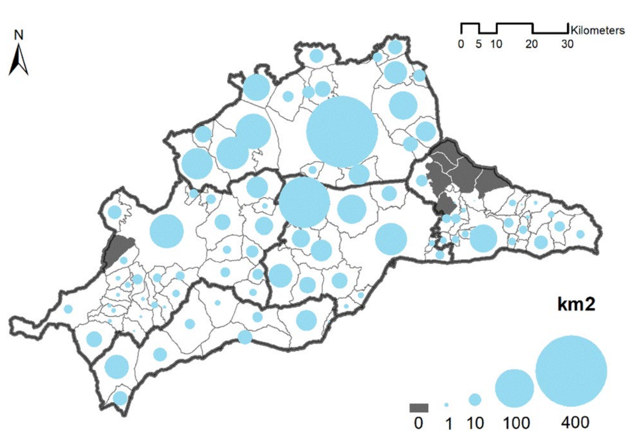


Fig. 9 Extent of compatible territory (km^2) presenting medium-to-high potential for the construction of renewable energy plants

Finally, 28 municipalities possess between 10 and 50 km^2 of high potential territory, with 9 over 50 km^2; two municipalities stand out in this regard: Antequera (340 km^2) and Álora (185 km^2).

Conclusions

Renewable energy sources are a key factor in the transition towards a new, more diversified and efficient energy model. In Spain and specifically in Andalusia, the high energy dependence rate along with the availability of plentiful renewable resources is leading to an increase in renewables-based energy generation, with the active support of public agencies. As a result, the energy model is moving towards a new scenario characterised by distributed generation and a more intensive use of renewables.

For these plants to be correctly sited, a full assessment of the territory must be carried out which evaluates the need for such a facility and the availability of the resource, and which identifies the best technology; the facility must adapt to the territory, and different implementation strategies must be considered. The construction of these facilities, therefore, is a complex endeavour in which spatial and energy planning are jointly considered.

The current paper has applied a methodology based on the combination of GIS and multi-criteria evaluation techniques in order to analyse the potential (in terms of medium-to-high potential areas) of a given territory for the construction of renewable energy generation plants. Three types of energy plants were taken into consideration (solar, wind and biomass) in the province of Malaga, which has a large population and which hosts 35% of touristic accommodation in Andalusia, posing both currently and in the future a substantial electricity demand.

GIS and MCDM are a useful tool for renewable energy planning, and in high-resolution decision-making processes, although evaluations must also take into consideration other criteria (social approval, landscape integration, load hours, among others), that can only be measured at detailed scales.

In addition, the model can be of use to both promoters and public agencies entrusted with territorial management, for it helps prevent the construction of ill-sited plants. The method can also be used to choose between various alternative implementation strategies and could speed up assessment processes; often, this sort of project involves a lengthy evaluation process, and there is always the risk of it not being authorised. The method is, therefore, a powerful territorial planning tool which allows for expedient and cost-effective decision-making processes.

Finally, it is necessary to mention that although the results are interesting and significant on the renewable energy planning process, this model is a simplification of reality, but by generalising the components of a complex system, relationships between salient factors in these systems can be explored. It should be use as guide, knowing that it is a result of a model and not a factual picture of reality.

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Compliance with ethical standards

Conflict of interest All authors declare that they have no conflict of interest.

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