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ORIGINAL PAPER

Developing a wind energy potential map on a regional scale using GIS and multi-criteria decision methods: the case of Cadiz (south of Spain)

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Abstract

This paper focuses on the combined use of geographical information systems and multi-criteria decision methods when developing a decision support model in order to determine the most favourable sites for the installation of wind turbines on a regional scale. This study differs from others in three ways: (1) it analyses two distinct scenarios (depending on whether major or minor constraints, as defined in the existing literature, are applied); (2) the area under study, Cadiz, already has an extensive network of wind-generating facilities; and (3) this study analyses at length areas where installation is not suitable. The methodology is proven to be a valid and appropriate tool for identifying potential areas for wind-energy facilities on a regional scale for both planners and investors. The model is proved to be useful for planning and evaluating phases: for example, it helps to outline criteria which can be used to define sectors where the number of suitable areas for wind-energy facilities can be increased, as well as locations where repowering might be a suitable alternative.

Keywords Wind energy · GIS · MCDM · Repowering · Cadiz

Introduction

Renewable energy has become a priority for the EU, and it is intrinsically tied to climate change policies. As such, the EU has been promoting the use of renewable energy in all member states for a number of years (EC 2007a, b, 2010, 2011a, b, c). One of the most significant renewable energy resources is wind energy (Noorollahi et al. 2016). It is both a commercially viable means of generating electricity (Satking et al. 2014) and one of the safest and most environmental-friendly sources of renewable energy (Baban and Parry 2001; Latinopoulos and Kechagia 2015). Despite this, wind power is often controversial with regard to landscape and land use, generally concerning the location of wind turbines (Baban and Parry 2001; Prados 2010).

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The implementation of assessment protocols which can be used for the identification of suitable locations for wind energy facilities will minimise controversy and improve the public's perception of wind power (Rodman and Meentemeyer 2006; Ramírez-Rosado et al. 2008; Aydin et al. 2010). Energy actors should plan their actions within a general framework with the overarching aim of promoting and integrating renewable energy (Voivontas et al. 1998). Spatial planning provides a basis for a territorial framework strategy, which facilitates a new energy model that is based on the management of demand and the promotion of renewable energy sources (Díaz-Cuevas et al. 2016).

Geographical information systems (GIS), in combination with multi-criteria decision methods (MCDM), can support the territorial framework strategy. The extensive functionalities of this combination have led to it being used both in general analyses of renewable energy (Yue and Wang 2006; Domínguez and Amador 2007; Angelis-Dimakis et al. 2011; Resch et al. 2014; Uyan 2017 etc.) and in the selection of optimal sites for wind farms in particular.

Therefore, this paper presents a methodology capable of assessing the installation of wind farms on a regional scale. A location model using the analytical capabilities of GIS and MCDM has been built for this purpose. This model will determine the areas with the greatest potential for wind power development, as well as those areas in which wind energy is inadvisable or even incompatible with the existing activities and land use.

This paper contributes to our overall understanding in several ways:

1. In contrast to several previous studies, which focus on areas that do not yet have wind turbines, this study focuses on an area with greater wind potential and considerable experience of wind turbines being installed.
2. It constitutes a decision-making tool that may be of use to both public and private agencies. Two scenarios have been analysed. The first scenario, which takes into account minor constraints, examines the actual planning and legislation in force in the study area. The second, which takes into account major constraints, derives from the application of precautionary principle (COM/2000/0001 final).
3. Unlike previous studies, which tend to ignore unsuitable sites, this paper analyses them. As the following sections will make clear, this analysis may be of interest to regulatory and planning authorities and to investors, especially in regions which have enormous potential but do not currently have a large number of wind turbines. This analysis means that our work is of application not only during the planning phase but also when evaluating the existing wind projects and with regard to future decision-making.
4. No previous studies for locating suitable sites for wind farms covering the whole of the province of Cadiz have been found. The present research may be used as a reference point for future studies.

Literature review

Partly owing to its geographical dispersion and its sometimes conflicted relationship with the surrounding territory, renewable energy must be analysed from a variety of perspectives, e.g. social, environmental, economic and territorial. All of these perspectives can be studied by using GIS, which is a powerful geographical analysis tool capable of ordering and generating data for the systematic investigation of the territory; the system allows data to be captured, consulted, managed and analysed. In general, GIS are defined as 'tools for consulting, analysing and editing data, maps and spatial information' (Sánchez-Lozano et al. 2014: 546). In combination with GIS, MCDM methods are a common planning tool. MCDM methods are regarded as among the most efficient decision-making support tools for those entrusted with selecting optimal locations for services and infrastructure (Yazdani et al. 2018). These tools evaluate a number of alternatives according to multiple criteria and targets (Voogd 1983). None of the alternatives available satisfies every objective, and no optimal solutions exist; as a result, the most satisfactory option is to be preferred.

In the energy sector, the use of GIS and MCDM methods allows for the generation of spatial location models and the representation, integration and analysis of criteria for the location of renewable energy facilities (Domínguez-Bravo 2002; Aydin 2009; Díaz-Cuevas 2013). Table 1 presents an overview of wind farm site selection studies using GIS and MCDM methods. Several conclusions may be drawn from the table:

1. Different areas have been analysed, from islands to whole countries, especially in areas where exploiting the potential of wind energy is in its infancy.
2. Various MCDM methods have been used, e.g. elimination and choice translating reality (ELECTRE), analytical hierarchy process (AHP), fuzzy analytical hierarchy process (FAHP), technique for order preference by similarity to the ideal solution (TOPSIS), fuzzy logic ordered weighted operator (FLOWA), weighted linear combination (WLC) or weighted linear sum (WLS) among others. All techniques have certain pros and cons, which are summarised in Choudhary and Shankar (2012), Wu and Geng (2014) and Kumar et al. (2017). The most widely used MCDM method is AHP proposed by Saaty (1980). This method consists of several clearly differentiated analytical phases: the selection and standardisation of criteria, the assignation of relative weights to selected criteria, the determination of the internal consistence of weight assignation (through the calculation of the consistency ratio) and the calculation of the representative index of areas with the greatest potential. AHP is universally accepted as robust and easy to apply because it suits complex decision-making processes, allows for the incorporation of both qualitative and quantitative criteria and also tests the consistency of the weight assignation process. However, based on previous experience, some authors who use AHP do not provide consistency ratio and do not include pairwise comparison matrices.
3. In some cases in which criteria are evaluated, weights have been assigned by authors on the basis of previous experience or of questionnaires and interviews (involving experts, planners and students). According to Uyan (2017), collecting the opinion of experts is the best option for assigning relative weights. However, in order for the experts' opinion to be valuable, it is important that the experts are well acquainted with the area being studied.
4. Most previous works take local legislative and planning criteria into consideration, but others do not explain their sources or they base them entirely on published works, without taking local conditions and restrictions

Table 1 Overview of wind farm site selection studies

Authors	Study area; approach adopted
Baban and Parry (2001)	UK; GIS and MCDM Criteria based on questionnaires and literature review Weights based on questionnaires
Hansen (2005)	Northern Jutland, Denmark; GIS, fuzzy logic and WLC Criteria based on interviews with specialists on spatial planning Weights assigned by authors
Rodman and Meentemeyer (2006)	Northern California; rule-based GIS Criteria based on three models: physical, environmental and human impact Models combined by ascribing same weight to all layers
Yue and Wang (2006)	Chigu, south-western Taiwan; GIS Criteria based on reports and literature review Two developmental scenarios (renewable energy prioritised and wildlife prioritised) No weights assigned
Bennui et al. (2007)	Five provinces in Thailand; GIS and AHP After exclusion areas defined, suitability analyses carried out Criteria based on planning documents and legislation Unclear who assigned weights Pairwise comparison matrix presented but not the consistency ratio
Lejeune and Feltz (2008)	Walloon Region, southern Belgium; rule-based GIS Criteria validated by software application designers and regional planning experts No weights assigned
Ramírez-Rosado et al. (2008)	La Rioja, Spain; GIS and AHP in combination with Chu's method Criteria defined by economic and environmental stakeholders Pairwise weights based on experience and professional points of view No pairwise comparison matrix or consistency ratio provided
Janke (2010)	Colorado, USA; GIS and WLS After unsuitable areas defined, suitability analyses carried out Unclear who defined criteria and weights
Tegou et al. (2010)	Island of Lesvos, Greece; GIS and AHP Environmental, economic, social and technical constraints, based on legislation Study considers already existing wind energy installations With exclusion areas defined, remaining areas evaluated Unclear who assigned weights Pairwise comparison matrix and consistency ratio presented
Aydin et al. (2010)	Provinces in Western Turkey; GIS and FLOWA Wind energy installations already exist Criteria based on bibliography review and environmental laws
Sliz-Szkliniarz and Vogt (2011)	Kujawsko–Pomorskie Voivodeship, Poland; GIS and MCDM Study takes into consideration already existing wind energy installations Begins by defining unsuitable areas, based on legal constraints and precautionary principle, followed by evaluating different areas according to wind strength No weights assigned
Van Haaren and Fthenakis (2011)	New York State, USA, GIS and WLC Some wind turbines already exist in area under consideration Default values of constraints based on literature review Firstly exclude sites deemed infeasible based on land use and geological constraints. Secondly identify best feasible sites based on expected net present value from major cost and revenue categories. Thirdly assess ecological impacts on birds and their habitats. Finally, priority map is calculated No weights assigned
Al-Yahyai et al. (2012)	Oman; GIS and AHP-OWA Study identifies different socioeconomic and environmental factors Considered wind turbines of different height Included energy demand matching, percentage of sustainable wind and turbulence intensity Unclear how criteria defined and who assigned weights Pairwise comparison matrix provided
Gorsevski et al. (2013)	North-west Ohio, USA; GIS and WLC and Borda Count Unclear how criteria defined Three alternative suitability principles defined: environmental, economic and combination of both Weights assigned according to interviews with 30 students

Table 1 (continued)

Authors	Study area; approach adopted
Effat (2014)	Red Sea Governorate, Egypt; GIS and AHP Differences between wind power and environmental criteria defined Ecological and social criteria excluded areas from the analysis Unclear who defined criteria, restrictions and weights Pairwise comparison matrix provided, but not consistency ratio
Höfer et al. (2014)	Städteregion Aachen, Germany; GIS and AHP model Wind turbines already exist in area under consideration Study begins by excluding areas on the basis of legislation, establishing nine evaluation criteria for remainder Weights assigned according to opinion of experts Pairwise comparison matrix and consistency ratio provided
Miller and Li (2014)	Two counties, Nebraska, USA; GIS in order to overlay weighted layers Criteria from literature review narrowed down to those deemed relevant and critical to suitability of wind farm installation in Nebraska Study takes into consideration already in-place wind turbines Study begins by calculating potential of different areas and continues by defining exclusion criteria Weights based on Janke (2010) and the evaluation of the relative importance of different criteria for the study area.
Sánchez-Lozano et al. (2014)	Murcia, Spain; GIS and ELEctri; Criteria and restrictions based on the existing legal framework Differences established between environmental, orographic, location and climatic criteria Most suitable sites defined according to series of interviews with experts
Schallenberg- Rodríguez and Notario-del Pino (2014)	Canary Islands, Spain; GIS Territorial constraints based on the existing literature and regulatory framework Determined the wind farm configuration, the placement of the wind turbines and the wind production No weights assigned
Szurek et al. (2014)	Prusice Commune, Lower Silesia, south-west Poland; GIS, AHP, OWA and WLC Criteria and constraints based on national legislation and on review of the existing literature Unclear who assigned weights Pairwise comparison matrix and consistency ratio presented
Baris et al. (2015)	Two neighbouring districts in western Turkey; GIS with different MCDM techniques (AHP, ELECTRE III, ELECTRE-TRI and SMAA-TRI) Study begins by excluding unsuitable areas, continues by evaluating remainder Criteria based on literature review, technical reports and report of external consultancy firm Three main groups taken into consideration (regulators, investors, public) Weights assigned on basis of expert opinion
Latinopoulos and Kechagia (2015)	Regional Unit of Kozani, Greece; GIS, FAHP and WLC Two wind farms already exist in the area under consideration Criteria based on the existing legislation and literature review Study begins by excluding unsuitable areas, continues by analysing remainder Three scenarios taken into consideration (no weights assigned/environmental factors assigned greatest weight/economic–technical criteria assigned the greatest weight) Unclear who assigned weights Pairwise comparison matrix and consistency ratio provided
Sunak et al. (2015)	Städteregion Aachen, Germany; GIS and AHP Several wind farms already exist in area under consideration Study begins with site selection (a spatial AHP modelling approach) and continues with Micrositing (gradient-based algorithm approach) Exclusion and constraints defined on practical grounds and legal regulations Weights based on expert opinion Pairwise comparison matrix and consistency ratio provided
Al-Shabeeb et al. (2016)	North-west Jordan; GIS and AHP The five criteria defined in the literature review Weights based on interviews and questionnaires with five experts Pairwise comparison matrix and consistency ratio provided
Noorollahi et al. (2016)	Markazi Province, western Iran; GIS and MCDM Study begins by identifying exclusion areas, based on physiographic and environmental criteria defined in previous studies, continues by establishing suitability ranking Unclear who assigned weights

Table 1 (continued)

Authors	Study area; approach adopted
Panagiotidou et al. (2016)	Dodecanese Islands, Greece; GIS and AHP Several wind farms already exist in area under consideration Exclusion and evaluation criteria selected on basis of environmental protection principles and based on current legislation and literature review Weights established by authors Pairwise comparison matrix and consistency ratio provided
Sánchez-Lozano et al. (2016)	Murcia, Spain; GIS, FAHP and FTOPSIS Study begins by defining exclusion areas, continues by evaluating remainder Restrictions defined according to legislative framework of study area Evaluation criteria identified on basis of the existing bibliography and reviewed by experts Weights based on opinion of three experts
Sadegui and Karimi (2017)	Tehran, Iran; GIS and AHP Selected environmental and economic factors based on expert opinion Unclear how weights defined No pairwise comparison matrix or consistency ratio provided
Villacreses et al. (2017)	Andean region of Ecuador; GIS, AHP, OWA, OCRA, VIKOR and TOPSIS Study begins by identifying exclusion areas and classifies remainder according to suitability Criteria weights obtained from the literature No pairwise comparison matrix or consistency ratio provided

into consideration. According to Höfer et al. (2014) and Uyan (2017), using the same criteria and restrictions for different areas is a mistake, since while some criteria may apply in all cases, others depend on local conditions.

5. Finally, another weakness of these examples is the omission of relevant criteria (Sunak et al. 2015). It is worth mentioning that certain important criteria cannot be represented spatially, which makes it difficult to include them in the analysis. This is, for example, the case with the ecological, visual or aesthetic value of different areas. Landscape value, which must take into account the social perceptions (Council of Europe 2000), should be evaluated in detail; one of the main problems of regional scale approaches is that they make the participation of local actors operationally difficult.

Materials and methods

Study area

The study area is the province of Cadiz (in Andalusia, southern Spain), Fig. 1. According to the most recent Municipal Population Census which was updated in January 2017, the population of Cadiz province is 1,239,109 (approximately 15% of Andalusia). The province comprises 44 municipalities, with a total area of 7412 km^2. The province of Cadiz leads wind power rankings in Andalusia, with 67 wind farms (44% of the regional total). More than half of the wind turbines in the region (900) are located in the province of Cadiz (Díaz-Cuevas et al. 2016).

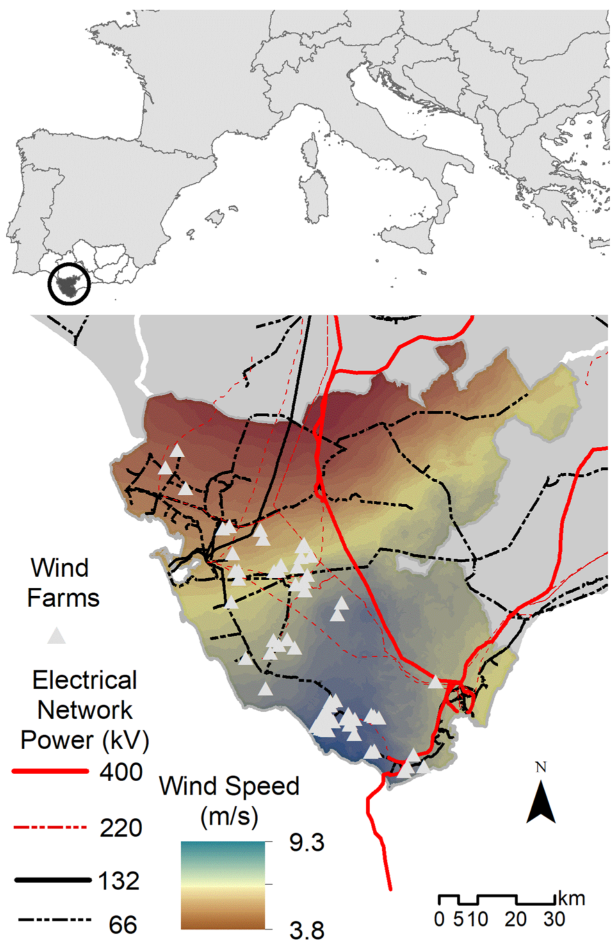

Fig. 1 Wind speed for a turbine height of 120 m; wind farms and electrical network in Cadiz

As such, the province has significant wind potential, and a substantial number of wind farms already exist, as well as an important electric network.

Owing to the large number of wind turbines in the area under study, and given the ambitious targets that have been set for the wind energy sector, we aim to answer the following questions:

1. Are there suitable unused sites for wind farms in the province?
2. How restrictive has the implementation of wind energy been in the area?
3. Is the repowering of the existing wind turbines a good alternative for helping to reach the targets?

Data source

GIS data sets were provided by the Institute of Statistics and Cartography of Andalusia, and the Environmental Information Catalogue has been used to collect spatial data for outlining suitability criteria. In addition, aerial orthophotos collected by the Spatial Data Infrastructure of Andalusia (http://www.ideandalucia.es/portal/web/ideandalucia/), including different batches of photographs, have also been used in the analysis. The locations of wind turbines (x, y) in the province of Cadiz have been digitised using photographs dated to 1998, 2002, 2004, 2006, 2009 and 2011.

Concerning wind energy resources, a 50-m resolution grid of wind speed (for a turbine height of 120 m) was based on results published by project MINIEOLICA (Lorente-Plazas et al. 2012). MINIEOLICA is one of the wind source evaluation projects which have generated the greatest amount of data for modelling and simulation, including the longest times series.

Proposed referential framework

This study combines GIS and MCDM methods to identify potentially suitable and unsuitable areas for wind farms. The proposed methodology is divided into three stages, Fig. 2. During the first stage, unsuitable sites were identified. Criteria and constraints were selected for two different scenarios: Scenario A, with minor constraints, and Scenario B, with major constraints. In the second stage, suitable areas were classified according to their suitability. Subsequently, a suitability index was calculated by aggregating three precalculated sub-indices (environmental and cultural protection, population protection and territorial energy efficiency). Finally, during the third stage, the suitability index was combined with wind power density, and the areas ranked according to potential. Each of these stages were described in detail in the following sections.

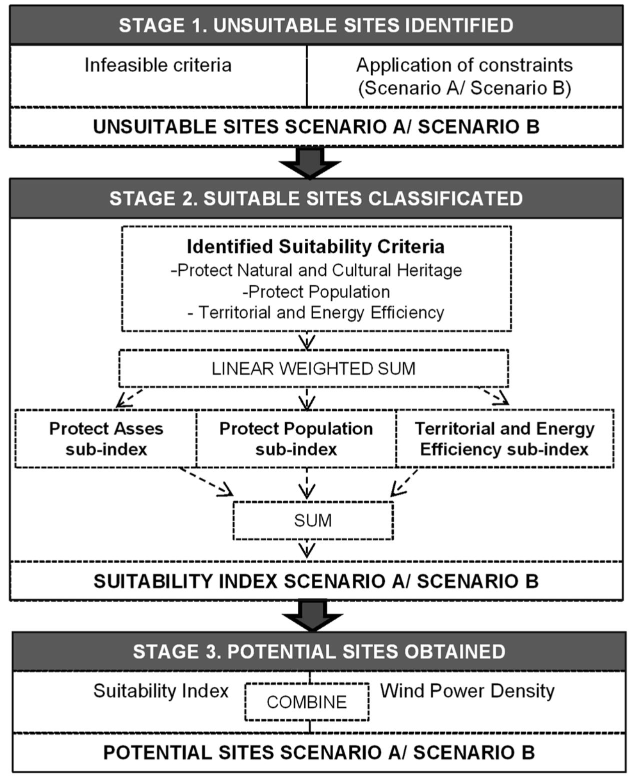

Fig. 2 Methodology workflow

Identifying unsuitable sites

In order to identify areas which are incompatible with wind generated energy, criteria and constraints have been formulated primarily to ensure that the environment and the local population are not negatively affected, as well as to assess the energy efficiency of potential facilities (Table 2). These criteria and restrictions are based on the existing literature, the targets and objectives of this study, the characteristics of the region under study and accessibility to the geo-referenced database. Taking into account that criteria and constraints cannot always be entirely objective and regardless of decision-making processes among both planners and investors, two spatial scenarios were established in the present work: The first scenario is based primarily on the implementation of the legal framework. In this scenario, when no mandatory recommendations concerning the assessment of potential wind farm sites apply, minor restrictions, based on the existing literature, have been incorporated into the analysis; the second scenario is linked to the application of precautionary principle specifications (EC 2001 -COM (2000) 1 final-), through the application of the major constraints defined in the existing literature (Díaz-Cuevas 2013).

It is important to clarify the thought process behind wind speed—one of the energy efficiency criteria. There is common agreement that wind speed must be regarded as

Table 2 Criteria and constraints both scenarios

	Criterion	Constraints			
		Minor restrictive scenario		Major restrictive scenario	
Population protection	Cities, villages and rural buildings	< 500 m from major cities	Yue and Wang (2006), Ramírez-Rosado et al. (2008), Sliz-Szkliniarz and Vogt (2011)	< 2.5 km from major cities	Baban and Parry (2001), Aydin et al. (2010), Al-Yahyai et al. (2012), Effat (2014), Noorollahi et al. (2016)
		< 250 m from villages and rural buildings	Yue and Wang (2006)	< 1000 m from villages and rural buildings	Bennui et al. (2007), Aydin et al. (2010)
	Population public facilities (hotels, golf courses…)	< 450 m from public facilities	Sliz-Szkliniarz and Vogt (2011)	< 1000 from public facilities	Bennui et al. (2007), Latinopoulos and Kechagia (2015)
	Industrial, agri-food and productive lands	Not in these areas	Lejeune and Feltz (2008)	< 250 m from these areas	Sliz-Szkliniarz and Vogt (2011)
	Motorways, footpaths and railways	< 140 m from motorways and highways; 100 m from foot paths	Ley 8/(2001) de carreteras and Ley 9/(2006), de Servicios Ferroviarios de Andalucía	< 500 m from motorways and highways, other roads and footpaths	Bennui et al. (2007), Al-Yahyai et al. (2012), Effat (2014), Baris et al. (2015), Noorollahi et al. (2016)
		< 110 m from other roads or railways		< 300 m from railways	Noorollahi et al. (2016)
	Airports, aerodromes, antennas and military areas	2 km from airports	Aydin et al. (2010)	25 km from airports	Effat (2014)
		< 2 km from aerodromes	Lejeune and Feltz (2008), Noorollahi et al. (2016)	600 m from radio and television antennae	Lejeune and Feltz (2008)
		< 600 m from radio and TV antennae	Lejeune and Feltz (2008), Baris et al. (2015)	< 600 m from military areas	Lejeune and Feltz (2008), Baris et al. (2015)
		< 600 m from military areas	Lejeune and Feltz (2008)	600 m from radio and television antennae	Lejeune and Feltz (2008)

Table 2 (continued)

	Criterion	Constraints			
		Minor restrictive scenario		Major restrictive scenario	
Environmental protection	Natural and national parks	As established for each Park in its Natural Resources Management Plan		The entire surface and 2000 m distance from these areas	Al-Yahyai et al. (2012), Baris et al. (2015)
	Rest of protected areas	The entire surface according to the functionality of these spaces, as stipulated in the Ley 2/(1989a) and Ley 4/(1989b)			
	Natural areas (LIC and Z ECs)	–			
	Ramsar and biosphere reserve areas	Not in RAMSAR areas Not in biosphere core areas			
	Birds and bats	Considerations regarding birds and bats shall be taken into account at sub-regional and local levels due to the fact that impacts dependents on the exact disposition of each wind turbine (de Lucas et al. 2007)		The entire surface of ZEPAS, ZIAES and IBA and 5000 m distance from them	Sliz-Szkliniarz and Vogt (2011), Gorsevski et al. (2013)
	Assessment of cultural interest	< 100 m from Assest of Cultural Interest	Sliz-Szkliniarz and Vogt (2011)	< 1000 m from Assest of Cultural Interest	Baban and Parry (2001), Effat (2014)
	Water courses, lakes…	< 50 m	Sunak et al. (2015)	< 3000 m	Baris et al. (2015)
	Flooding areas	Not in fluvial inundation areas for a period of 100 years	Villacreses et al. (2017)	<200 m	Sliz-Szkliniarz and Vogt (2011)
	Coastline	< 500 m	Noorollahi et al. (2016)	< 4000 m	Effat (2014)
Energy and territorial efficiency	Forest areas	< 250 m	Yue and Wang (2006)	<500 m	Baban and Parry (2001)
	Slope	> 30%	Sunak et al. (2015)	> 10%	Baban and Parry, (2001), van Haaren and Fthenakis (2011)
	Electrical network	< 100 m	Sunak et al. (2015)	< 250 m	Effat (2014), Baris et al. (2015), Noorollahi et al. (2016)
		> 10 km	Baban and Parry (2001)	> 10 km	Baban and Parry (2001)
	Fault lines	< 200 m	Baris et al. (2015)	< 500 m	Noorollahi et al. (2016)
	Height	–		> 1500 m	Baris et al. (2015)
	Soil erosion	Not on severely eroded areas			

a major criterion of unfeasibility for economic reasons. In this regard, the applied constraints range from 4 m/s (Yue and Wang 2006; van Haaren and Fthenakis 2011) to 7 m/s (Rodman and Meentemeyer 2006).

In the framework of this study, however, wind speed will be considered a potential factor and not a criterion of unfeasibility. This decision was made for several reasons. The first is that, according to Izquierdo (2008), the accurate assessment of wind resources requires rigorous on-site testing to be carried out over a period of at least a year, followed by rigorous analysis of the data. Second, given recent improvements in the efficiency of wind turbines, including increased height and capacity, turbines may now be placed in areas that were previously considered unsuitable because of wind speed. Taller towers and hubs mean higher wind speed (Patel 1999; Schallenberg-Rodríguez and Notario-del Pino 2014), but also greater costs and wider intervals between wind turbines. Schallenberg-Rodríguez and Notario-del Pino (2014) further suggest that micrositing analysis is necessary for determining the optimal height of wind turbines. However, this level of analysis is well beyond a large-scale study such as the one presented here.

Classifying suitable sites according to their suitability level: implementation of the AHP

According to the existing literature, the most suitable areas for the construction of wind farms are those in which the protection of the population is assured; natural and cultural heritage is not badly impacted; and the existing territorial assets are used as efficiently as possible. For these reasons, the most suitable areas are defined by the aggregation of three pre-calculated sub-indices (environmental and cultural protection, territorial and energy efficiency and population protection).

Concerning the population, although wind facilities are usually not dangerous, some risks exist due to parts breaking off, as well as noise, fire and electromagnetic interference.

Concerning natural and cultural heritage, areas that are located farther away from natural and cultural protected areas provide better conditions for wind energy facilities. As such, areas that are located farther away from watercourses are considered more suitable, as they do not intrude on hydrodynamic systems and help to protect wildlife.

Finally, the need to ensure that territorial assets are efficiently used is justified by the targets set out in European, national and regional energy saving and efficiency frameworks. Thus, sites which meet the following conditions are understood to be the most suitable locations for wind farms:

- Areas closest to the existing electrical network, due to the need to distribute the energy generated by the turbines; furthermore, the development of new electrical networks might have a negative environmental impact;
- Areas closest to settlements, in order to facilitate distributed generation (DG);
- Areas closest to the road network, as this will facilitate installation and reduce future impacts, such as those caused by the building of new roads;
- Areas with the gentlest slopes, as steep slopes can affect wind conditions, leading to extra infrastructural investments.

After the criteria are selected, they are normalised and relative weights are assigned. The weights are based on the decision-maker's preferences, which are articulated by means of a pairwise comparison process that compares the relative importance of each criterion using the values of the Saaty scale (Saaty 1989). In the present study, weights have been assigned by a group of experts comprising three PhD holders, two engineers and a geographer specialised in energy planning in the study area. The experts compared pairs of criteria by answering the following questions: 'Which of the two criteria is more important?' and 'By how much?' This assessment is expressed on the Saaty semantic scale (Table 3), which determines to what extent a given criterion is relatively more important than another. (Values 2, 4, 6 and 8 on the scale correspond to intermediate situations.) For instance, if the relative importance of attribute A over attribute B is judged to be 3 ('moderate importance' on the Saaty scale), then the reciprocal judgement, the relative importance of attribute B with regard to attribute A, has the reciprocal value, that is 1/3.

Tables 4, 5 and 6 present the pairwise comparison matrices. The pairwise comparison yields value '$W1$', which represents the order of priority of factors, calculated by aggregating the values obtained on the previous scale, determining the weight to be assigned to each criterion. Finally, the table also includes the main normalised eigenvector 'W', which indicates the value of the weights, in this case normalised to 1.

Once the weights have been calculated, the next step is to determine the internal coherence of the decision-maker's

Table 3 Saaty scale

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

Table 4 Criteria and weights for population protection level of suitability

	S1	S2	S3	S4	W1	W
S1	1	5	3	8	17	0.55
S2	1/5	1	1/2	2	3.7	0.11
S3	1/3	2	1	5	8.3	0.26
S4	1/8	1/2	1/5	1	1.8	0.06

S1 (population facilities); S2 (airports and aerodromes); S3 (road and railway networks); S4 (military areas). $\lambda = 4.11$; $C_i = 0.036$; $C_r = 0.04$

Table 5 Criteria and weights for environmental protection level of suitability

	S1	S2	S3	W1	W
S1	1	1/3	1/3	1.6	0.13
S2	3	1	2	6	0.49
S3	3	1/2	1	4.5	0.37

S1 (natural protected areas); S2 (cultural areas); S3 (waterlines). $\lambda = 3.03$; $C_i = 0.015$; $C_r = 0.02$

judgements by calculating the consistency ratio (C_r) Eq. 1. This is calculated using the consistency index (C_i) –Eq. 2— and the random index (R_i) by applying the following formulas:

$$C_r = \frac{C_i}{R_i} \quad (1)$$

$$C_i = \frac{(\lambda - n)}{(n - 1)} \quad (2)$$

where n is the number of variables in the comparison matrix and λ is the value of the main normalised eigenvector 'W' multiplied by the pairwise comparison matrix.

The random index (R_i) is the C_i of a randomly generated pairwise comparison matrix of order 1–10, obtained by approximating random indices using a sample size of 500 (Saaty 1980). In Table 7, the value R_i sorted is by the order of the matrix.

If $C_r < 0.10$, the ratio indicates a reasonable level of consistency in the pairwise comparisons; if, however, $C_r > 0.10$, then the values of the ratio are indicative of inconsistent judgments.

For a consistency ratio < 0.10, the analysis derived from expert evaluation determines that areas which are most distant from settlements, roads and railway lines score the highest, with regard to the population protection index (0.8). Areas which are furthest from cultural heritage sites/waterlines score the highest with regard to the environmental protection index (0.86). Finally, areas which are closest to the electric grid/on less steep slopes score the highest with regard to the energy efficiency index (0.36 and 0.30, respectively).

Once weights have been assigned and their consistency has been estimated, the three sub-indices can be calculated (protection of natural and cultural heritage, territorial and energy efficiency and population protection) using the *linear weighted sum* (Eq. 3).

$$SI_p = \sum_{i=1}^{n} w_i x_{ip} \quad (3)$$

where SI_p = suitability partial index; w_i = the weight of the criterion i; x_{ip} = normalised value of the cell p for the criterion i.

Table 6 Criteria and weights for energy and territorial efficiency level of suitability

	S1	S2	S3	S4	S5	W1	W
S1	1	1/5	1	1/2	1/5	2.9	0.07
S2	5	1	5	1	2	14	0.36
S3	1	1/5	1	1/2	1/3	3.0	0.07
S4	2	1	2	1	1/2	6.5	0.17
S5	5	1/2	3	2	1	11.5	0.30

S1 (population facilities); S2 (electrical network); S3 (road network); S4 (forest areas); S5 (slope). $\lambda = 5.16$; $C_i = 0.04$; $C_r = 0.03$

Table 7 Value of random index

Order matrix	1	2	3	4	5	6	7	8	9	10
Definition	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Finally, by the sum of the three partial indices, a map reflecting levels of suitability may be generated (Eq. 4). This map incorporated unsuitable areas by multiplying the values of unsuitable areas. (Value of 0 was applied to unsuitable.)

$$SI = \left[SI_{pa} + SI_{po} + SI_{pe}\right] \times Z_0 \quad (4)$$

where SI = level of suitability index; SI_{pa} = suitability environmental partial index; SI_{po} = suitability population partial index; SI_{pe} = suitability energy and territorial partial index; Z_0 = unsuitable areas.

Subsequently, the resulting values have been reclassified at five levels through the relevant quintiles, enabling the classification of the lowest 20% of the values as 'very low suitability' and the highest 20% of the values as 'very high suitability'.

Determining the areas with highest potential for wind turbines

The level of suitability index (SI) and wind resource availability were combined to determine areas where the construction of wind turbines is more advisable (Eq. 5).

$$P = \mathrm{SI}U\mathrm{wpd} \quad (5)$$

where P = wind energy potential index; SI—level of suitability index; wpd = wind power density.

Wind power density is an important factor because it provides information on the most suitable and profitable areas in the region as far as the construction of wind farms is concerned (Baban and Parry 2001). In the study area, the wind power density was calculated using Eq. 6 (see Hughes 2000; Manwell et al. 2009; Effat 2014; Schallenberg-Rodríguez and Notario del-Pino 2014). Wind energy potential based on the average wind speed for 120 m height turbines, a height attainable for current turbines.

$$\mathrm{wpd} = \frac{1}{2}\rho V^3 \quad (6)$$

where V = average wind speed (m/s); ρ = air density (kg/m^3); wpd = wind power density (W/m^2).

According to Hughes (2000), Söder and Ackermann (2012) and Busby (2012), air density may be estimated with reasonable precision by examining the relation between turbine height, air temperature and pressure. If pressure data are not available (they are generally difficult to attain), but air temperature data are available, air density at a given height and a given temperature can be calculated using Eq. 7.

$$p = \left(\frac{\mathrm{Po}}{RT}\right)\exp^{\left(\frac{-gz}{RT}\right)} \quad (7)$$

where Po = standard sea level atmospheric pressure (101,325 Pa); R = the specific gas constant (287 Jkg^{-1} K^{-1}); T = the air temperature in K; g = the gravitational constant (9.8 m/s); and z = the region's elevation above sea level in metres. In this case, the value of z is the sum of the altitude (as reflected in the Digital Elevation Model) plus the height of the wind turbine (120 m).

The wind potential for 120 m turbines is illustrated in Fig. 3.

The Digital Elevation Model and the temperature raster map (refers to the average temperature recorded during the period 1971–2000) provide by the Andalusian Environmental Information Catalogue.

Results and discussion

Unsuitable areas

The main results of identifying and analysing suitable areas include:

- In the scenario which takes into consideration minor constraints, a total of 4681 km^2 (63% of the study area) is considered unsuitable for wind energy development (Fig. 4a). In the scenario which takes into consideration greater constraints (Fig. 4c), the unsuitable territories encompass 6756 km^2 (91% of the study area).
- In the less restrictive scenario, almost 80% of unsuitable areas failed to meet between one and three criteria: one—47.2%; two—31.9%; three—13.6% (Table 8). The remainder fail to meet multiple criteria (between 3

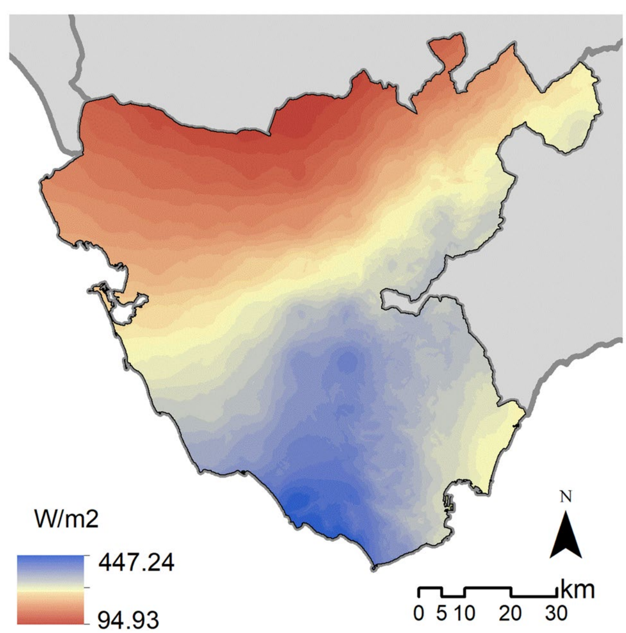

Fig. 3 Wind power density in the study area

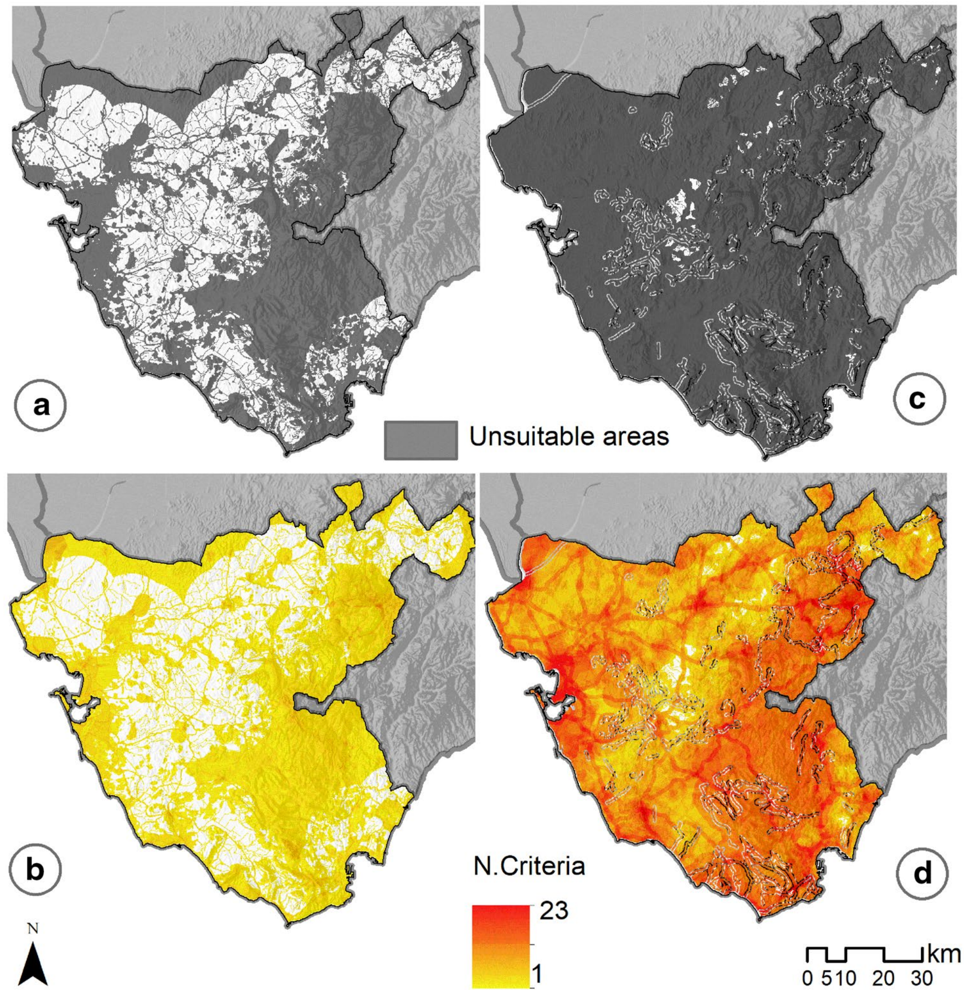

Fig. 4 Unsuitable areas (**a**) and unsuitable areas according to the unmet criteria (**b**) in both scenarios

or 12) (Fig. 4b). In the scenario with major constraints, the number of unmet criteria increases from 12 to 23 (Fig. 4d). Contrary to scenario A, only 19% of the territory receives this classification from the failure to meet one, two or three criteria.

This information regarding unsuitable sites and unmet criteria is useful for stakeholders. Indeed, investors and regulatory authorities will benefit from a decision-making support system that not only designates areas in which the defence of the territory must be prioritised, but also provides specific information on the number and type of criteria that the site does not meet. Such a tool would be useful as a means of, for example, expediting assessing and authorising these infrastructures. This has major implications for the process, as the construction of this type of infrastructure generally entails a long process, and it is possible that authorisation will not be granted. Therefore, this analysis will ensure not only that these infrastructures cause have a smaller territorial and environmental

Table 8 Unsuitable territories according to number of unmet criteria in each scenario

	Scenario A (minor constraints) (km^2 %)		Scenario B (major constraints) (km^2 %)	
1	2210.9	47.22	198.09	2.93
2	1495.4	31.95	446.76	6.61
3	639.01	13.65	684.4	10.13
4	227.7	4.87	698.1	10.33
5	83.8	1.79	663.7	9.82
6	17.8	0.38	742.02	10.98
7	4.1	0.09	932.8	13.81
8	1.3	0.03	905.4	13.40
9	0.6	0.01	620.8	9.19
10	0.2	0.00	348.4	5.16
11	0.2	0.00	212.7	3.15
12	0.4	0.01	132.7	1.96
13–23			170.06	2.53
Total	4681	100	6756	100

impact, but also that they will become a powerful tool for decision-making and for reducing time and financial costs.

- The model also provides answers about how restrictive the installation of wind energy has been in the study area to date. In 2011, a total of 900 wind turbines were in operation in the province of Cadiz, of which 122 (13% study area) are in operation in areas that, according to the model, are unsuitable (Table 9). Most of them are located too close to highways, roads or watercourses. None of these turbines violate the protection of cultural heritage sites criterion. In contrast, the scenario which takes major constraints into consideration revealed that only 151 wind turbines are located in suitable areas, meaning that most of the existing wind turbines (749) are located in unsuitable areas. Although many of these turbines also violate the criteria associated with the less restrictive scenario, the greatest violations in Scenario B relate to asset protection (protected natural spaces, birds and bats, natural areas and watercourses). In addition, a significant number of the existing wind turbines do not meet the criteria related to the protection of the population, mainly owing to extensive restrictions regarding population centres, airports and military areas.

Based on these results, it may be said that the development of wind energy in the province of Cadiz to date has been more in line with less restrictive scenario. These results do not imply that the environment or the population has been negatively affected. In order to reach that conclusion, however, a detailed analysis of each wind turbine would need to be carried out, which is beyond the scope of the present paper.

Table 9 Wind turbines and number of unmet criteria in both scenarios

N. criteria	Minor constraints scenario	Major constraints scenario
1	65	29
2	45	84
3	12	78
4		46
5		153
6		88
7		129
8		70
9		37
10		35
Total	122	749

Suitable areas

Regarding the suitability of different areas for the construction of wind farms, the following results may be highlighted:

- While 37% of the study area is considered feasible in the less constraint scenario (2731 km^2), the feasible territory decreases significantly in the major constraint scenario (656 km^2). These areas have been classified according to their level of suitability (Fig. 5).
- Suitability values have been combined with wind power density values in order to define the most suitable areas for the construction of wind farms in both scenarios, see Table 10 and Fig. 6. For example, a value of 11 corresponds to areas which combine minimum suitability and wind power density values (1 and 1); conversely, a value of 55 corresponds to areas which combine maximum suitability and wind power density values (5 and 5). The results suggest that 399 km^2 of the suitable territory presents the highest potentiality values (44, 45, 54, 55) in Scenario A, whereas only 41.3 km^2 does so in Scenario B. If cells where wind turbines are already in operation are excluded from these results, these areas will decrease to 154 and 11 km^2, respectively. Furthermore, wind farms require a lot of space. If the fact that the space between turbines should be three times the diameter of the rotor (Yue and Wang 2006; Tegou et al. 2010) for 2 MW wind turbines (114 m of rotor) is taken into consideration, this involves a radius of 342 m around each turbine, or, in other words, 367,442 m^2 (0.37 km^2). This implies that there is room for the installation of a substantial number of extra turbines in the most suitable areas: 416 wind turbines—a total of 832 MW—in Scenario A, and 30 wind turbines—a total of 60 MW—in Scenario B.

The data can vary for several reasons. Improvements concerning any of the variables (roads, power lines, natural areas, etc.) may increase or decrease the amount of unsuitable areas. For instance, most of the existing literature agrees that turbines should not be installed near forested areas, but many turbines are, in fact, currently in operation near forested areas (Bergström et al. 2013).

- An analysis of the wind turbines currently in operation suggests that most wind turbines (502) are located in high and very high potentiality areas according to Scenario A (55, 54, 44 or 45). Of those, 393 (a total of 282.8 MW) were installed before 2004. Therefore, the capacity of the average wind turbine is 0.76 MW, which is far below the potential of more modern turbines. This means that large high or very high potentiality areas are currently occupied by obsolete wind turbines (most of which are

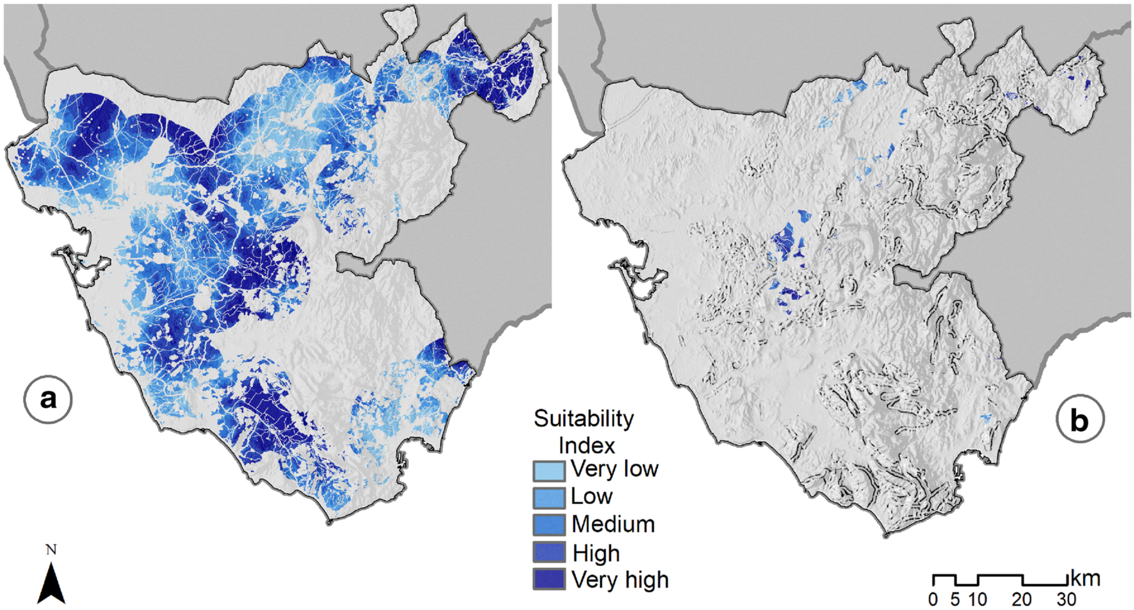

Fig. 5 Potential for wind farming sites in Scenario A (minor constraints; **a**) and in Scenario B (major constraints; **b**)

Table 10 Combined values of suitability index and wind power density in Scenario A (minor constraints; a) and in Scenario B (major constraints; b)

Suitability	Wind power density									
	1		2		3		4		5	
	A	B	A	B	A	B	A	B	A	B
1	167.66	73.6	107.72	52	80.54	47.1	69.73	18.3	18.32	8.3
2	141.96	73.2	210.5	23.6	172.5	18.1	52.02	32.5	44.07	20.1
3	145.7	37.8	239.2	95.6	148.3	14.4	58.7	18	76.73	12.3
4	139.31	20	132.55	12.97	131.5	8.31	**104.06**	**12.9**	**108.55**	**12**
5	39.98	0	32.58	20	122.22	8.49	**83.34**	**11.4**	**103.21**	**5**

Bold has been used to emphasize the best values

to be found in the municipality of Tarifa). These results emphasise the need to consider upgrading and replacing obsolete wind turbines. According to Colmenar-Santos et al. (2015), repowering is a profitable alternative for Spain and is often better than the construction of new wind farms, as it allows for the more efficient use of wind resources. This would also decrease the density of the existing wind turbines, which could lead to an improvement in the social perception of these facilities whilst simultaneously increasing their energy and territorial efficiency.

Conclusions

This paper develops an integrated methodology for determining the most appropriate sites for the installation of wind turbines on a regional level. To this end, a decision support model has been developed using GIS and MCDM methods in a region with long experience in installing wind energy facilities: the province of Cadiz (Andalusia).

The main conclusions of this work may be highlighted:

- The decision support model is relevant for planners and investors, as well as for the planning and evaluation phases. In this way, unsuitable locations could be vetoed more quickly, and the different stakeholders could focus on a more detailed analysis of the best scoring areas. Therefore, the model is useful in selecting consensual locations for wind farms even if different stakeholders initially hold conflicting views and can make these processes faster and more effective, resulting in acceptable solutions for all stakeholders. At the same time, the model allows for the identification of areas where public and private actions may lead to

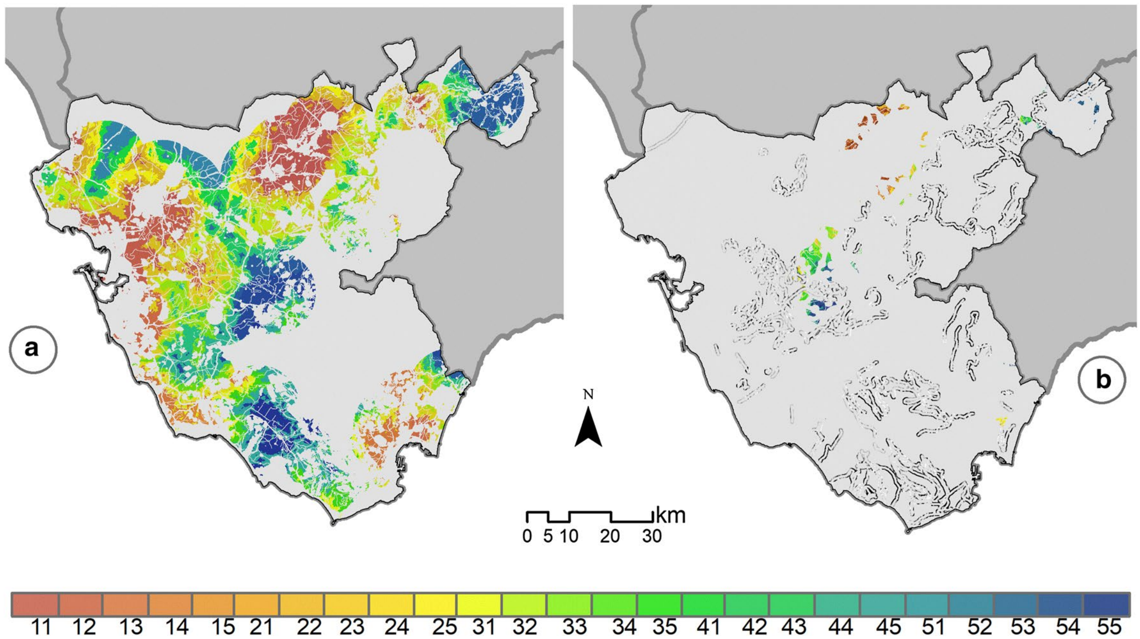

Fig. 6 Combined values for suitability and wind power density in Scenario A (minor constraints; **a**) and in Scenario B (major constraints; **b**)

improved scores, as well as the identification of other areas where repowering may be a profitable option.

- The definition of two different scenarios allows for results to be filtered through more and less restrictive conditions, as well as for the comparison of the two. This model is conceived as a dynamic tool that can be updated on an ongoing basis, following changes to the regulatory framework. This also opens up the possibility of adapting the methodology to territorial or institutional contexts that may differ from the present study area. Therefore, the method itself is well suited for application in other study areas.
- The combination of GIS and MCDM methods involves the generation of added value, which results from the possibility of changing localisation methods, adding or removing criteria and reassessing the relative value of criteria, both easily and on an ongoing basis. As such, should the criteria change in any way, the model can be updated to present an entirely new perspective of the territory, a feature that can be applied in numerous other fields.
- No previous studies for locating suitable sites for wind farms covering the whole of the province of Cadiz have been found. The present research may be used as a reference point for future studies.

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