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A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in Greece

D. Latinopoulos*, K. Kechagia

School of Spatial Planning and Development, Faculty of Engineering, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

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ABSTRACT

The present paper proposes and implements an integrated evaluation framework for selecting the most appropriate sites for wind-farm development projects. This framework focuses on the combined use of geographic information systems (GIS) and spatial multi-criteria decision analysis, aiming to provide a decision tool for wind-farm planning at the regional level. This procedure has been developed by means of various technological, economic, social, and environmental criteria (known as siting criteria), which were used either as constraints and/or as evaluation factors in order to identify first the potential/appropriate sites for wind farm installation and then to evaluate these sites using a composite Suitability Index (SI). The proposed decision tool is thus able to get the optimal locations for future projects, as well as the suitability score of the already licensed projects. The results of this paper support the potential role of planners in designating areas for wind farm development.

1. Introduction

As the effects of global warming and climate change become more pronounced, the need to increase the penetration of renewable energy resources in the energy mix is growing globally. Renewable energy resources (RES) are considered as clean sources of energy and their optimal use is likely to minimize environmental impacts, as well as to produce minimum secondary wastes [24]. For this reason, in 2007, EU Member States provided a road map for future renewable energy policy in Europe, according to which EU should reach a 20% share of energy from RES by 2020 by setting individual targets for all Member States [7]. Therefore, the evaluation of RES potentials is critical when planning the future energy development of a country.

More specifically, wind power is one of the most environmentally friendly RES, as well as one of the fastest-growing and most economical forms of renewable energy. Today wind generators can be considered as a mature, cost effective technology with reasonable efficiency rates, high reliability and availability values [25]. Besides, wind energy, compared to fossil fuels causes less environmental damage by significantly decreasing CO_2 emissions [4]. However, wind development projects are usually associated with several planning and environmental restrictions and conflicts [5]. The reason is that wind farm locations are crucial to the viability of wind turbine investments, while they are also associated with environmental impacts at the local level (e.g. visual impact, noise generation, wildlife impacts, electromagnetic interference, etc.) [2]. In other words, land planners face a double challenge as they must design projects/plans that will contribute to economic growth while minimizing environmental risks as well as reducing the opposition from local stakeholders [12,13]. Therefore a growing need is emerging for identifying (evaluating) suitable locations for wind farm developments. To be able to do that it is essential to establish a number of terms/rules that will evaluate different sites on the basis of several environmental and socio-economic factors (criteria) [11].

Geographic information systems (GIS) have emerged over the recent years as an essential tool for spatial planning and management. A main reason for this is that GIS can be used in the planning process by incorporating multiple criteria in decision-making about land-uses [6,16]. Therefore, their application can be particularly valuable not only for visualization and data management but also for the assessment of choice alternatives, based on spatially related criteria. Concerning the evaluation of suitable locations for wind farm developments, GIS may contribute as a decision support tool aiming to identify economically viable and environmental feasible sites, using a large amount of spatial data related to various technical, economic, social and environmental criteria. To deal with these often conflicting criteria, a spatial multi-criteria decision making (MCDM)

* Corresponding author. Tel.: +30 2310 994248.
E-mail address: dlatinop@plandevel.auth.gr (D. Latinopoulos).

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model should be integrated in a GIS environment in order to provide a powerful tool aiming at evaluating land suitability for wind farm locations. This decision support tool will be useful for assessing and managing a variety of spatial data, incorporating at the same time people's (i.e. decision makers, planners, stakeholders, policy makers, etc.) preferences within the decision making process [30].

Since early 2000s, a number of studies have been conducted in several countries aiming to evaluate land suitability for wind farm siting, by combining GIS with multi-criteria analysis [1,2,12,23,29,35]. In Greece, the most relevant studies were applied for in-shore and offshore wind farms in island regions [20,33,34,37] due to the high wind resource potential on these areas. On the contrary, the present study focuses on a mainland application, where the main advantage is not the wind potential – which is actually a major constraint over a large part of this area - but the close proximity to the mainland's national electricity grid and especially to the electric grid transmission centers of the Prefecture of Western Macedonia. In this context, the present paper presents a methodology for the systematic assessment of land suitability for wind farm development at the regional level, taking into consideration several planning and environmental criteria. This land suitability analysis can then be used in two ways. On the one hand, it can serve as a tool for the ex-ante evaluation of potential new wind farm investments, providing useful suggestions for spatial planning on the regional level. On the other hand, it can be used as an ex-post evaluation process aiming to appraise the already licensed sites. This process can provide useful insight into: (a) the relative importance of the factors that impact the regional planning decisions so far, as well as into (b) the overall suitability of the already licensed – but not yet built – projects.

2. Study area and legislative framework

The Regional Unit of Kozani, which is part of the Perfecture of Western Macedonia in Greece, was selected as the study area. This area – according to the National Census of 2011 [9] – has a population of 150.000 and a population density equal to 42.7 inhabitants/km^2. It is also part of the largest energy center of Greece (Western Macedonia), which generates about 50% of the country's total energy production. As already noted, this is the main reason for selecting this area, as the existing power transmission networks are able to absorb the wind power production from future wind farm developments. It should be also underlined that the existing electricity generation units in the study area are mainly based on the local lignite reserves, as the local six lignite-based power stations have an overall installed capacity around 4500 MW [14].

The study area is characterized by mountainous regions with high wind energy potential (i.e. potentially suitable sites for wind farm development) and a diverse natural and human environment that may cause significant conflicts between wind energy and environmental protection. It should be noted that according to the Greek Special Framework for Spatial Planning of Renewable Energy [32] the study area can be considered as a Wind Suitability Area (WSA) for RES development.[1] WSAs are actually the local authorities of the mainland that are not included in the Wind Priority Areas (WPA) but they may be characterized as energy efficient by the Greek Regulatory Authority for Energy [3]. It is also worth mentioning that according to the regional planning strategy – i.e. as listed in the Regional Framework of Spatial Planning and Sustainable Development of Western Macedonia – the strengthening of RES infrastructure and the mobilization of private RES investments are top priorities of the future (mid-term and long-term) energy policy.

Fig. 1 shows a map of the study area, indicating: (a) the sites of environmental interest (Natura 2000 areas and protected landscapes), (b) tourism attractions (archeological and historical sites) and facilities (hotels and guesthouses), (c) residential areas and road networks, as well as (d) the already licensed wind farm projects. Concerning the latter, it is noteworthy that 35 (production) licenses with a total capacity of 1203.9 MW have been granted in the study area, according to the dataset collected by the Greek Regulatory Authority for Energy [27]. Nevertheless, only two farm projects, with a total capacity of 38 MW, are currently operational (i.e. issued with an operational license), a fact that indicates that there are some barriers for the deployment of wind power in the study area, which are virtually the same as those encountered at the national level (according to Ref. [25] the two main difficulties concerning the current and future development of wind energy in Greece are the complicated licensing procedure[2] and the immaturity of investment plans).

Bureaucratic constraints, public opposition of the local communities, improper grid structure and deficiencies in the national spatial planning are also some key obstacles to meeting the national/regional targets for wind farm development [19]. During the recent years, the Special Framework for Spatial Planning of Renewable Energy Sources [32] and the Law L3851/2010[3] are trying to address and tackle some of the above mentioned problems.

Under the assumption that these problems will be effectively solved in future, the following three questions should be addressed in the following sections:

Question 1: Can all the licensed farms in the study area meet a set of critical siting criteria?

Question 2: Are there any alternative locations where wind farms can be potentially built?

Question 3: Is it possible to apply a hierarchy process method for evaluating and then selecting the most suitable locations in the study area?

3. Methodology

3.1. Framework of land suitability decision making

The selection of sites for wind farm installation requires the consideration of multiple criteria, as well as a number of evaluation steps aiming to identify the most appropriate locations, minimizing (or even eliminating) at the same time the various environmental and social obstacles to wind power development [10]. In order to create a model that would be able to identify these locations, a set of technological (operational), economic, social and environmental criteria – also known as siting criteria – is selected and a GIS-based approach is developed to spatially represent and analyze the collected data. Criteria selection was based on literature data and on national legislation. Specifically, most of the analysis is performed according to the recommendations of the Greek Special Framework for Spatial Planning of Renewable Energy Sources [32], which attempts, among others, to establish a set of criteria for the installation of wind farms in WSAs.

[1] According to the SFSPRE [32]; the national mainland territory is divided into two major categories based on the exploitable wind potential, as well as on spatial and environmental characteristics: Wind Priority Areas (WPA) and Wind Suitability Areas (WSA).

[2] Some of the licenses required include: the electricity generation license, installation and operating permits, environmental permit, planning license, connection agreement with the Utility and power purchase contract with the grid operator [18].

[3] Law3851/2010, 2010: Accelerating the development of Renewable Energy Sources to deal with climate change and other regulations addressing issues under the authority of the Ministry of Environment, Energy and Climate Change.

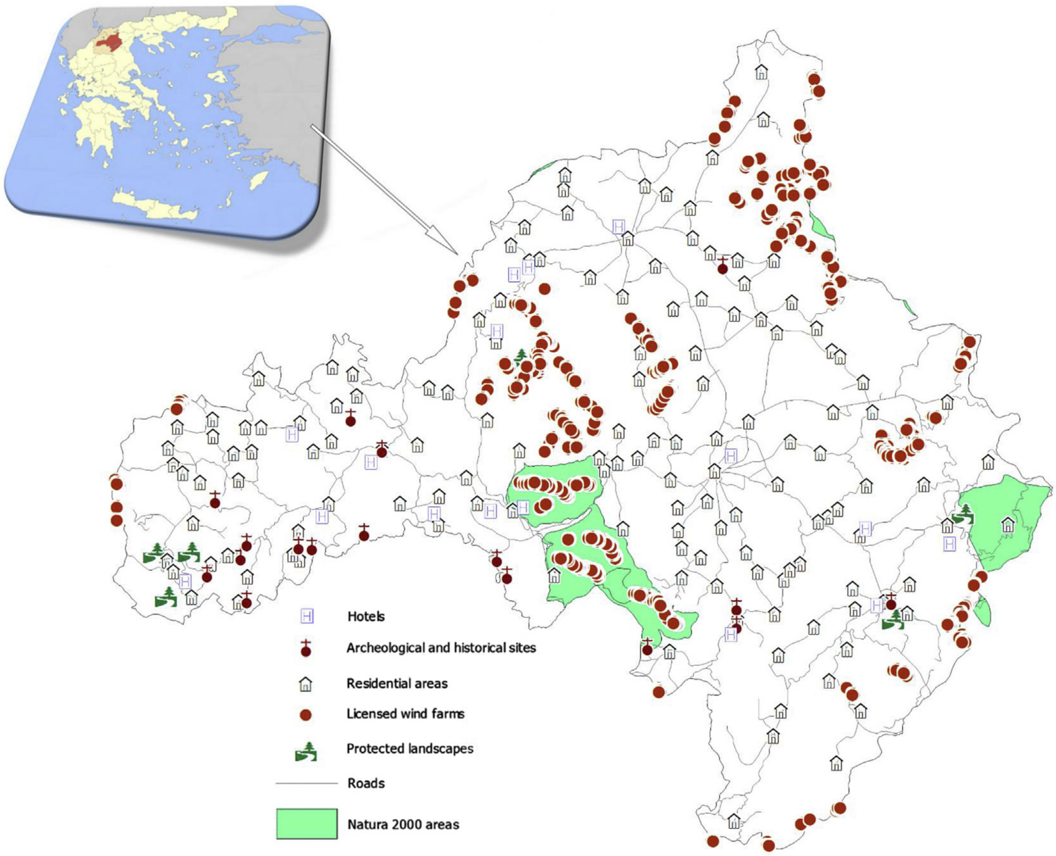

Fig. 1. Study area.

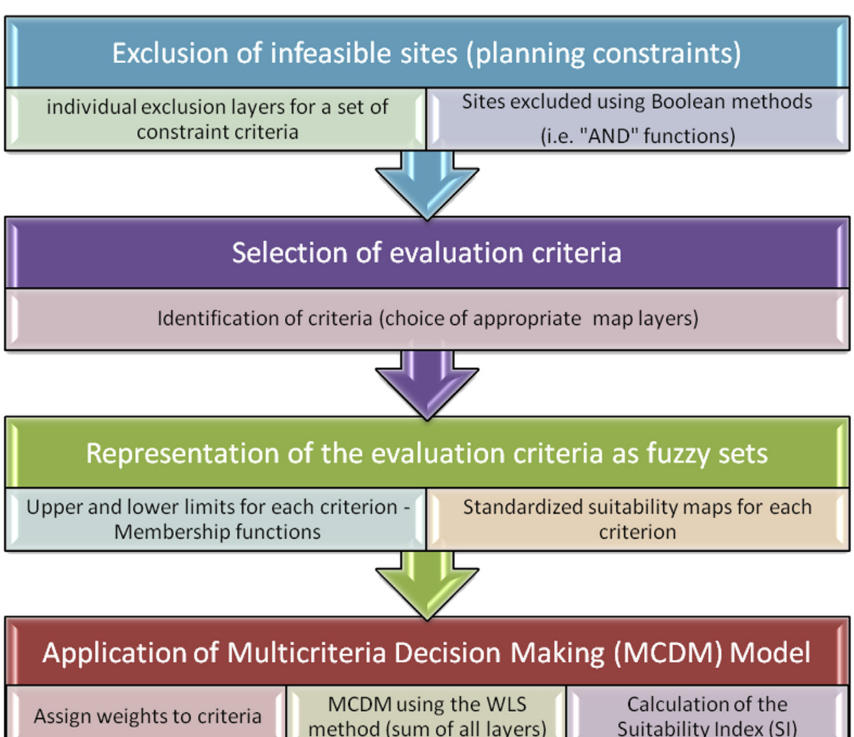

Fig. 2. Methodology of the study.

Fig. 2 shows the methodology of the decision process followed in this paper. The overall approach is actually a procedure that combines spatially referenced data (inputs) into a common decision map. It consists of four steps: (a) the exclusion of infeasible sites (planning constraints), using individual exclusion layers and Boolean criteria (true/false), (b) the selection (identification) of evaluation criteria, (c) the representation of the evaluation criteria as fuzzy sets in order to generate a set of standardized maps for each criterion, and (d) the application of a multi-criteria decision making (MCDM) model, aiming to calculate a composite suitability index (SI) and the associated land suitability maps.

3.2. Exclusion of infeasible sites

During this first step we tried to identify those criteria that are capable to describe various constraints related to wind farm development, and then to create individual map layers corresponding to each constraint criterion. In this context the study area was divided into 150 m × 150 m grid cells, each cell representing an alternative location for a wind turbine. Different map sources (vector files) were used including: study area boundaries, settlement areas, roads, slopes, Corine land-cover, Natura 2000, wind energy potential, etc.[4] The vector database was organized into a number of map layers (layered structure) and map algebra was used to define the suitability of each location [17]. It should be noted that constraints criteria are expressed on a Boolean scale (true/false) and their aim was to exclude those areas where the constraints were not met [12]. Using this classification, a given threshold is determined for each criterion, according to which the land units (cells) were defined as excluded/unacceptable (when exceeding the threshold value) or as potential/acceptable sites for wind farm development. Threshold values are set according to the recommendations of the Special Framework for Spatial Planning of Renewable Energy Sources [32], taking though into consideration the levels used in other recent applications (e.g. Refs. [1,2,12,15,21,29,36,38]). Ten constraints criteria, shown in Table 1, were finally selected to define/identify the “wind-farms exclusion zones”:

- The social implications of wind farms, including visual impact, noise impact and aesthetics are usually considered as very important constraints. For this reason all urban areas are excluded, while various distances (buffer zones) from settlements were also adopted, by using the following SFSPRE recommendations (*Criterion 4*):
  - 1000 m from the boundaries of settlements with over 2000 inhabitants,
  - 1500 m from the boundaries of traditional settlements,
  - 500 m from the boundaries of settlements with less than 2000 inhabitants.
- To preserve the esthetic value of natural environment, the wind-farms should not be sited on or within 1000 m from protected landscapes (*Criterion C1*).
- To preserve cultural environment and cultural heritage buffer zones of 1000 m radius around all archeological (*Criterion C2*) and historical sites (*Criterion C3*) were created.
- To minimize the impacts on local tourism (*Criterion C5*), wind farms should be located at least 1000 m from all tourism facilities (hotels and guesthouses).[5]

Table 1
Description of constraints criteria.

	Categories	Buffer zones/exclusion zones
C1	Protected landscapes	1000 m
C2	Archeological sites	1000 m
C3	Historical sites	1000 m
C4	Urban areas & Traditional settlements	[Population > 2000 inhabitants]: 1000 m [Population < 2000 inhabitants]: 500 m [Traditional settlements]: 1500 m
C5	Tourism facilities (hotels and guesthouses)	1000 m
C6	Distance from roads (minimum distance)	150 m
C7	Land use restrictions (no buffer)	Artificial surfaces (CLC: 111, 112) Industrial, commercial and transport units (CLC: 121,122, 124) Mine, dump and construction sites (CLC: 131, 132,133) Irrigated agricultural land. (CLC: 212) Wetlands (CLC: 411, 412)
C8	Wind speed (no buffer)	Areas where average wind speed is lower than 4.5 m/s
C9	Proximity to airports	3000 m
C10	Slope (no buffer)	>25%

- Both environmental and cost constraints determine a set of land restrictions, which are applied using the CORINE 2006 land-cover raster data-set (*Criterion C7*). In particular, the following land-cover classes were excluded: artificial surfaces, industrial, commercial and transport units, mine, dumb and construction sites, irrigated agricultural land, as well as wetland areas.
- In physical terms the wind farms should be located on suitable windy sites avoiding great slopes. The average wind speed is a crucial economic factor determining the economic viability of a wind farm project in a specific location. In this context, regional wind-speed maps (with cell size: 150 m × 150) were used and the threshold for the average wind speed was set at 4.5 m/s (*Criterion C8*). In addition, sites with slope higher than 25% were considered as problematic and for this reason they were excluded (*Criterion C10*).
- Finally, for safety reasons wind farm projects must also be located:
  - at a minimum distance of 150 m from the road network (*Criterion C6*).
  - at a minimum distance of 3000 m from the airport areas (*Criterion C9*)

All the above mentioned criteria were represented by criterion maps, which were produced with the MapInfo Professional software package [26]. Elevation grids and slope gradient values were further generated using the Vertical Mapper ver.3 software [22]. Map layers were converted from vector to grid-based data models and Boolean intersection operations, using the logical “AND” were applied to all constraint criteria (0 = unacceptable site, 1 = acceptable site). Hence, in a composite constraint map layer only locations that are characterized as suitable on all maps were considered as potential sites for wind farms development [12]. Fig. 3 illustrates the outcome of this procedure, showing the exclusionary zones and the potential sites for wind farms in the study area.

3.3. Evaluation criteria

In the next step of analysis, the remaining (not-excluded) sites are being ranked according to specific suitability factors. Contrary to the constraints (criteria), which are expressed in a Boolean form and their aim was to restrict the alternative sites, factors

[4] Initial datasets have been retrieved from geodata.gov.gr, which is an open-access portal for Greek government's geospatial data.

[5] The buffer distance of C1, C2 and C5 was selected to be consistent with previous studies and at the same time to be uniform over the three criteria. The reasoning for this uniform buffer is that these criteria will be merged into a single evaluation factor, which will use the selected distance (1000 m) as the lower threshold value.

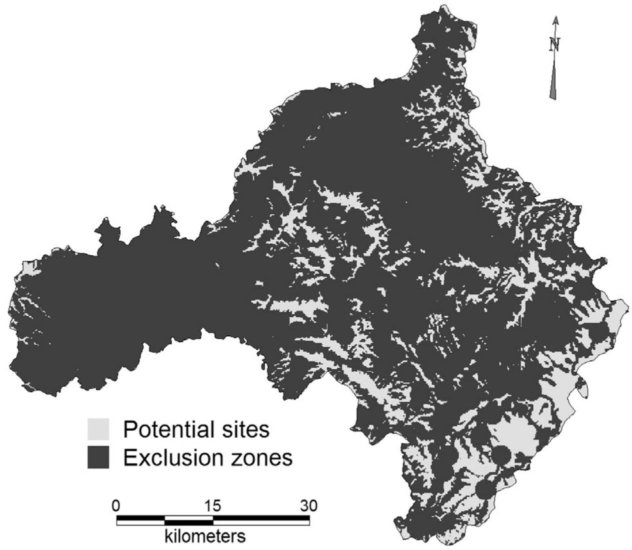

Fig. 3. Exclusion zones and potential sites.

(evaluation criteria) are usually measured on a continuous scale and their aim is to enhance or to detract from the suitability of a specific alternative location [6]. There are two types of factors: (a) benefit criteria contributing positively to the site selection and (b) cost criteria contributing negatively to site selection (i.e. lower values are more preferable than higher ones).

In this framework, six factors are introduced aiming to examine/evaluate the overall suitability of each site (grid cell), according to certain aspects of the decision making process (Table 2). These factors are listed in Table 2, indicating their policy relevance (technical, economic, environmental or social), as well as their type (benefit or cost). As shown in this table, the selected evaluation criteria are not necessarily different from the constraint ones, as given in Table 1. For example a constraint (C8) was used to exclude all sites with average wind speed lower than 4.5 m/s, as the economic feasibility of those sites was considered extremely low. The Boolean approach followed in that case was seeking for a completely non-compensatory decision rule; resulting to nil (0) performance value in the composite constraint map. Nevertheless, locations with average wind speed higher than 4.5 m/s should be evaluated using a continuous function that will be able to represent the decision maker's preferences (i.e. higher preference for higher wind speed values). In this context, all the preference functions – as estimated for each grid cell – can be combined in order to specify a compensatory decision tool, according to which a poor performance in one criterion (e.g. wind speed values lower than 5.5 m/s) can be compensated by a good performance of another criterion (see Section 3.5).

It is worth noting that the only factor that was not previously used as a constraint criterion is the distance from Natura 2000 areas (S5). According to the European Commission's guidance document on "Wind energy development and Natura 2000", wind farm development in and around Natura 2000 sites is not prohibited but it: "has to undergo a step-by-step Appropriate Assessment procedure and, where necessary, apply the relevant safeguards for the species and habitat types of Community interest [8]. For this reason, Natura 2000 sites were not initially considered as exclusion zones. However, in order to take into account during the evaluation process the preservation of natural and ecological values (i.e. to eliminate bird collisions, to reduce noise affecting wildlife, etc), wind-farms should be ideally located outside the Natura 2000 and at a sufficient distance from these areas.

3.4. Representation of criteria as fuzzy sets

In this step, the selected evaluation criteria are represented as fuzzy sets, using the fuzzy sets theory, which was introduced by [39].[6] The membership functions of these fuzzy sets are used to estimate the individual satisfaction degree for a specific factor for each potential site (grid cell). These are actually functions that define the grade of membership of an element z in the fuzzy set, taking values between zero (0 = not satisfied) and one (1 = fully satisfied). Various types of membership functions can be used to describe these fuzzy sets. In this study, a linear function was used so that individual satisfaction degrees can be mathematically expressed according to Eq. (1) (benefit criteria) or Eq. (2) (cost criteria). It should be noted that for each factor there is a lower threshold value (control point) q indicating its least suitable value and an upper threshold value p indicating that all values beyond this point are the most suitable ones.

$$\text{Increasing fuzzy function}: \overline{MF}(z_i) = \begin{cases} 0 & \text{for} \quad z_i < q_i \\ \dfrac{z_i - q_i}{p_i - q_i} & \text{for} \quad q_i \le z_i \le p_i \\ 1 & \text{for} \quad z_i > p_i \end{cases} \tag{1}$$

$$\text{Decreasing fuzzy function}: \underline{MF}(z_i) = \begin{cases} 1 & \text{for} \quad z_i < p_i \\ \dfrac{z_i - q_i}{p_i - q_i} & \text{for} \quad p_i \le z_i \le q_i \\ 0 & \text{for} \quad z_i > q_i \end{cases} \tag{2}$$

Linear decreasing functions were used for the factors of slope (S1) and the distance from the road network (S4). On the contrary, linear increasing functions were used for the wind speed (S2) and the distance from specific sites (S6). Concerning the distance from Nature 2000 areas (S5) the following mixed function (mF_5) was used, in order to combine both fuzzy (linear increasing distance from the boundaries of Natura 2000 areas) and Boolean (potential sites should be outside the Natura 2000 areas) logic.

$$mF_5 = \overline{MF}(z_5)^*\widehat{B}_5 \tag{3}$$

where

$$\widehat{B}_5 = \begin{cases} 1 & \text{site (grid cell) lies outside the Natura 2000 boundaries} \\ 0 & \text{site (grid cell) lies inside the Natura 2000 boundaries} \end{cases}$$

Finally, concerning the land use criterion (S3) a set of membership values was assigned to each CORINE land-cover class, according to the most valuable (in both economic and environmental terms) land uses. It should be pointed out that those areas excluded in the previous section were the only land-cover classes assigned with a zero value. On the other hand, shrub and/or herbaceous vegetation, as well as open spaces with little or no vegetation were considered as the most suitable areas (membership value equal to 1). Table 3 analytically presents the fuzzy set memberships and membership functions, as well as the control points used for all factors determining the wind farm suitability. Furthermore, the membership functions for the fuzzy representation of (a) wind

[6] The main advantage of using the fuzzy set theory is that it provides a framework for representing and treating uncertainty in the sense of vagueness, imprecision and lack of information ([16,39]).

Table 2
Description of the evaluation criteria (factors) used for wind site selection.

	Criterion	Policy relevance	Type
S1	Slope (%)	Technical/Economic	Cost
S2	Wind speed (m/s)	Technical/Economic	Benefit
S3	Current land uses (qualitative variable): Five point Likert-type scale where higher scales indicate more valuable land uses (in both environmental and economic terms)	Environmental/ Economic	Benefit
S4	Distance from road network (m)	Economic	Cost
S5	Distance from Natura 2000 areas (m)	Environmental	Benefit
S6	Distance from specific sites (archeological sites, tourism facilities, historical sites, protected landscapes)	Social/Economic/ Environmental	Benefit

speed and (b) the distance from road network are indicatively illustrated in Fig. 4.

The next step in this analysis is to convert the membership functions/values to corresponding map layers, i.e. to individual suitability maps. In this framework, the spatial data from each factor were represented as a fuzzy set by applying the membership functions/values in each grid cell, using the MapInfo software. The outcome of this procedure is to associate each grid cell with a "degree of satisfaction" for each evaluation criterion and then to represent these values on a corresponding standardized map layer (individual suitability map). Fig. 5 shows the individual suitability maps for: (a) the slope gradient, (b) the wind speed, (c) the land uses, and (d) the distance from the road network.

3.5. Multi-criteria decision making and site selection

The multi-criteria decision rules are introduced in order to define a relationship between the input maps and the final output map [16]. In this context, all the individual satisfaction degrees of the selected factors (standardized suitability maps) should be aggregated using spatial multi-criteria decision making, so that an overall Suitability Index (SI) will be generated (composite map layer). The aim of this procedure in the present work is to associate each grid cell with a composite degree of satisfaction for the "wind farm site selection" and to locate the main "priority sites" in the study area. A weighted linear combination (WLC) method was selected for the multi-criteria evaluation. According to this method, each factor is multiplied by a weight and the results are summed – using map algebra – to produce the final suitability index [6]. The following mathematical expression was used to combine the evaluation criteria (factors) according to the weighted linear combination method:

$$SI_j = \sum_{i=1}^{n} w_i x_{i,j} \tag{4}$$

Table 3
Membership values/functions and control points.

	Map Layer	Unit	Function type/membership	q	p
S1	Slope	%	$\underline{MF}$	20	5
S2	Wind speed	m/s	$\overline{MF}$	5	7.5
S3	**Current land uses (Corine classes)**	–	0		
	111, 112, 121, 122, 124,		0.2		
	131, 212, 411, 412		0.4		
	222, 223		0.6		
	211, 213, 221, 241, 243		0.8		
	311, 312, 313		1.0		
	231, 241, 242, 243, 244				
	321, 323, 324, 333				
S4	Distance from road network	m	$\underline{MF}$	5000	200
S5	Distance from Natura 2000 areas	m	$\overline{MF} \cdot \widehat{B}$	0	3000
S6	Distance from specific sites	m	$\overline{MF}$	1000	3000

where SI is the suitability index for cell j, w_i is the relative importance (weight) of factor i (i = 1,..,6) and $x_{i,j}$ is the standardize score of cell j for factor i (as estimated in the previous section). In order to take also into consideration the exclusion criteria it is necessary to include in Eq. (4) the Boolean constraints that may apply in each cell. The product of these constraints is first estimated, so that only locations that are characterized as suitable ($\widehat{B}_{i,j} = 1, \quad \forall i = 1, .., n$) on all maps – i.e. locations without any siting issue – will be qualified for further evaluation. Therefore, Eq. (4) is actually transformed as follows:

$$SI_j = \prod_{i=1}^{n} \widehat{B}_{i,j} \sum_{i=1}^{n} w_i x_{i,j} \tag{5}$$

Concerning the estimation of the weight of factors w_i three different policy scenarios were examined. The first scenario (Scenario 1) assumes that all factors are of equal importance, carrying thus the same weight in the WLC function (Eq. (5)). In the other two scenarios, the weights are allocated to the decision factors by trying to depict two different policy orientations: a policy focusing on environmental and social criteria (Scenario 2) and a policy focusing on technical and economic criteria (Scenario 3). Simple pair-wise comparisons were applied, by implementing the analytic hierarchy process (AHP) [31]. The pair-wise comparisons are based on a nine-point continuous scale, which is used in order to rate the relative importance of two decision factors. For simplicity the factors are compared according to authors' expertise and experience by taking into consideration the relevance of each factor to the predetermined policy objectives. Tables 4 and 5 present the Saaty matrices and the associated eigenvectors (i.e. relative weights) for the two policy-oriented scenarios.[7]

4. Results and discussion

The three maps in Fig. 6 compose the final result of the GIS-based MCDM analysis. These maps present the varying levels of land suitability for siting wind farm development projects in the study area. The grid layers once again take values between 0 (unacceptable location) and 1 (ideal location), showing the overall SI score, according to the decision factors (criteria) and the weights chosen in each policy scenario. This index enables us to deal with Question 3 (see Section 2) by applying a hierarchy process method (i.e. a spatial suitability assessment) for evaluating and then selecting the most suitable locations.

As shown in Fig. 6, a significant part of the study area (17% of the Regional Unit –corresponding to about 55,000 ha) satisfies the constraint objectives and has a value greater than 0 on at least one factor (i.e. a cell j with $SI_j > 0$). It should be mentioned that the SFSPRE [32] suggests that the maximum land coverage from wind farms in each primary local authority in the study area (i.e. in any Wind Suitability Area) should not exceed the 5% of the municipal area.[8] According to recent data from the Regulatory Authority for Energy [28], the wind energy projects with a production license in the study area are well below the carrying capacity of the area. Namely, on average, only 24% of the actual capacity is reached,[9] which corresponds to about 3700 ha. This means that

[7] According to the self-valuation methodology followed, all pair-wise judgments were consistent (CR = 0.00).

[8] However this constraint is not binding, as the total land coverage may increase up to 50% with the consent of the Municipal Council that is provided for the entire life cycle of the wind farm and for a time period at least equal to the period of the relevant power production license [3].

[9] This percentage varies significantly among the different municipal units in the study area (from 1.1% in the municipal unit of Mourikiou up to 99.7% in the municipal unit of Vlasti) [28].

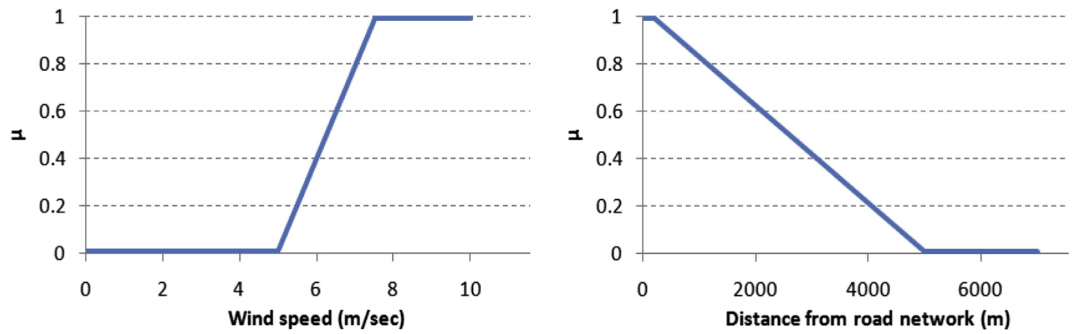

Fig. 4. Fuzzy set for wind speed and distance from road network.

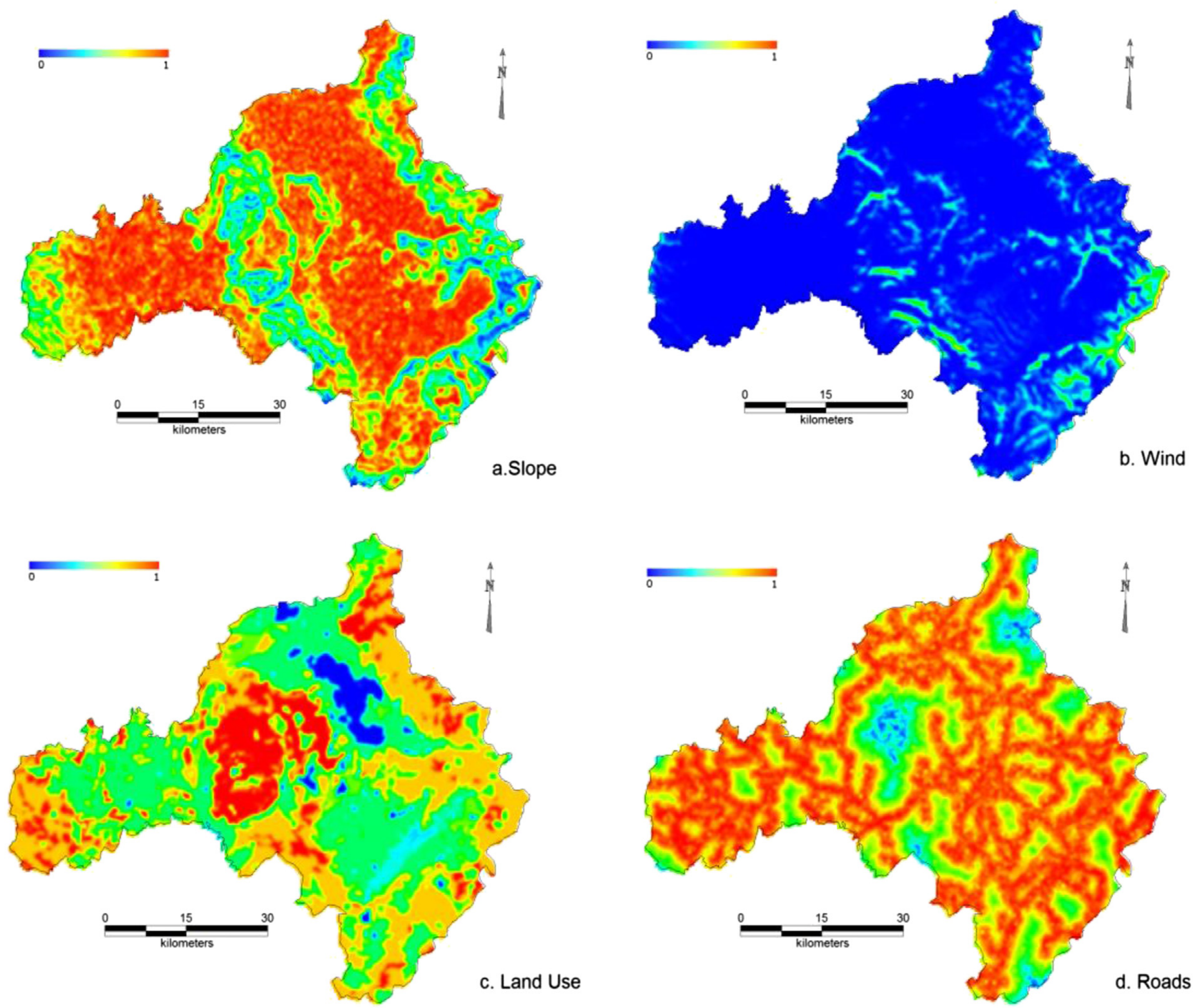

Fig. 5. Standardized suitability maps for the factors of: (a) slope gradient, (b) wind speed, (c) land uses (land cover), and (d) distance from road network.

some 10,000 ha are still available for wind energy development. Therefore, the appropriate choice of sites for new farm projects can be very crucial, especially in municipalities (e.g. the Municipality of Servia-Velventos) where a significant part of their territory seems to generate SI scores higher than a certain value (e.g. SI > 0.5).

Therefore, the answer to Question 2 (see Section 2) is affirmative (i.e. there are quite a few alternative locations where wind farms can be potentially built). The most suitable areas are those located along the eastern borders of the study area, where most factors exhibit high satisfaction degrees. The output maps also show that the total area with SI > 0.5 ranges from 12.9% (Scenario 3) up to 14.7% (Scenario 2). The differences between the policy scenarios become more apparent when examining the potential sites with high SI scores (SI > 0.7). In that case, the total area ranges from 2.2% (Scenario 3) up to 11.8% (Scenario 2).[10] These findings, which are

[10] Under policy Scenario 1, 14.5% of the total area is classified with SI > 0.5 and 3.9% with SI > 0.7.

Table 4
Saaty matrix and weights of factors under Scenario 2.

	S1	S2	S3	S4	S5	S6	Weight
S1	1.000	0.666	0.333	1.000	0.167	0.167	0.056
S2		1.000	0.666	2.000	0.333	0.333	0.102
S3			1.000	3.000	0.666	0.666	0.177
S4				1.000	0.167	0.167	0.053
S5					1.000	1.000	0.306
S6						1.000	0.306

Table 5
Saaty matrix and weights of factors under Scenario 3.

	S1	S2	S3	S4	S5	S6	Weight
S1	1.000	0.333	1.000	1.000	3.000	3.000	0.157
S2		1.000	3.000	3.000	6.000	6.000	0.416
S3			1.000	1.000	3.000	3.000	0.157
S4				1.000	3.000	3.000	0.157
S5					1.000	1.000	0.056
S6						1.000	0.056

quite similar to those found by Gorsevski et al. [10]; indicate that the selected economic and technical criteria are more difficult to met, especially for values that are close to the upper threshold limit. Besides, when considering the individual criterion/factor of wind energy potential, we can see that only 0.1% of the study area satisfies the upper threshold value (i.e. $z_2 > 7.5$ m/s). This may be a reason why the spatial patterns of the SI strongly reflect the influence of the wind energy potential. On the other hand, the influence of factors, such as the urban areas and different land cover types, is also apparent but not as important as in other case studies (e.g. Refs. [2,10]).

According to these results, wind speed is the dominant factor of land suitability in the study area. This conclusion can be easily drawn by comparing Fig. 6 with Figs. 3 and 5. However, future spatial planning policy should also take into consideration all the aforementioned evaluation factors because they may play a substantial role in prioritizing the potential locations for wind farm development. As shown in Fig. 7, notable differences can be detected between Scenario 2 and Scenario 3 (i.e. under two policy scenarios that differ significantly) concerning the higher ranked (not yet licensed) sites in the study area. This result indicates that wind speed is not the only important factor and that policy orientation (i.e. weight allocation) may play a crucial role in the final selection of the most appropriate sites. On the other hand, it can be also concluded that the final findings (rankings) may not vary greatly when the weight allocation is quite similar (as is the case of Scenarios 1 and 2), indicating that the determination of weights should be considered as a more general policy strategy and not as a detailed and in-depth evaluation process.

Next, a correlation analysis was performed in Vertical Mapper in order to examine the relationship between the grid layer of the

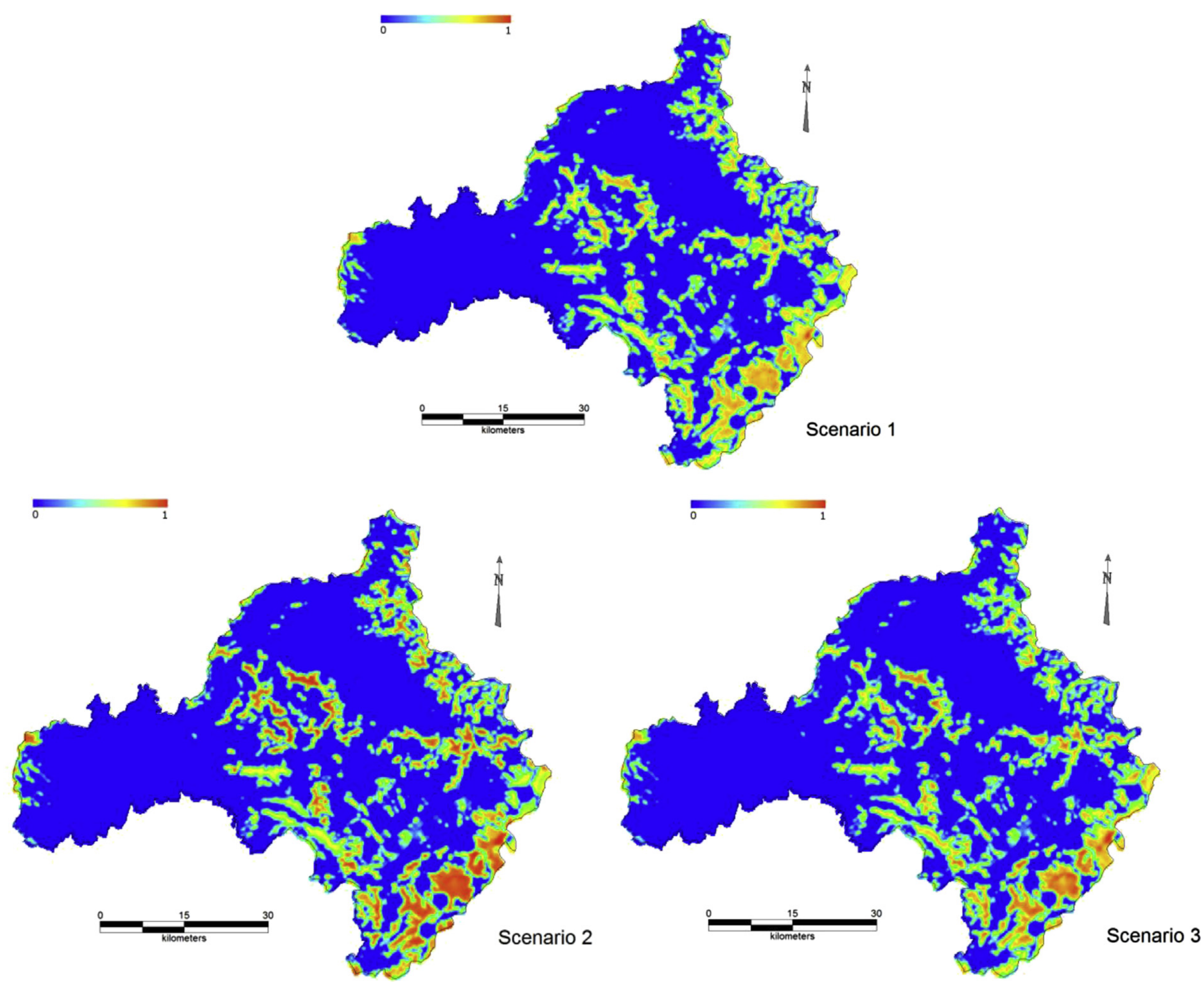

Fig. 6. Land suitability maps.

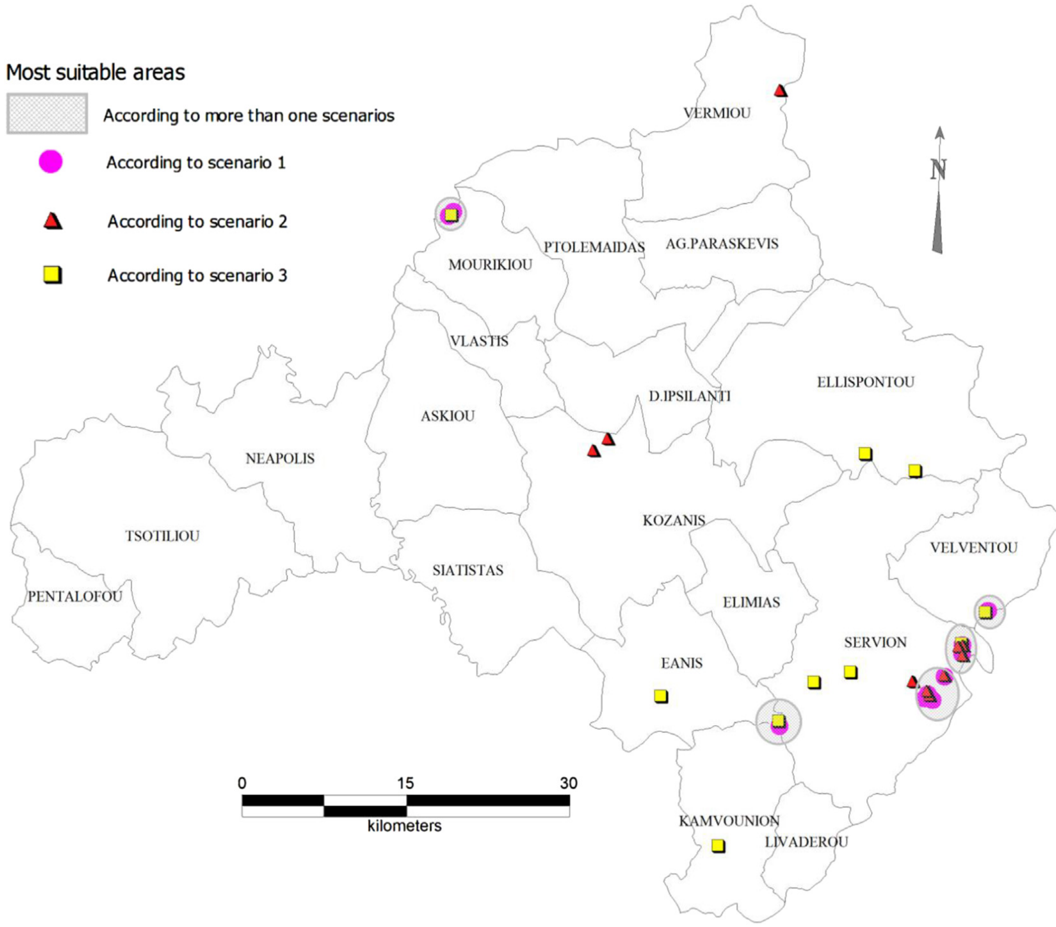

Fig. 7. Ex-ante evaluation of wind farm suitability – Top 10 non-licensed sites ranked according to their suitability index, as applied to all multi-criteria scenarios.

already licensed sites and the grid layers of all the individual suitability maps. In order to test the significance of the resulted correlation coefficients (r-values) the analysis was also carried out using the SPSS statistical package (version 16.0 for Windows, SPSS Inc.). According to the results, all the correlation coefficients were statistical significant with $p < 0.01$ and have the expected signs for all factors (as considered in the membership functions in Table 3). Their r-values are presented in the first row of Table 6, while the second row represents the normalized r-values, which can be considered as a vector of weights representing the actual preferences of wind farm developers and local authorities (with respect to the locations selected so far in the study area). This vector of weights, which is quite close to Scenario 3 (i.e. giving priority to technical and economic factors), can be further used as a prediction tool for future wind farm site selection, assuming no changes in local/regional or national (spatial) planning policy for wind power.

Another purpose of the ex-post evaluation process is to use the SI in order to estimate the overall suitability of the already licensed – but not yet built – projects in the study area. In this context, Fig. 8 shows the SI scores, as calculated for those sites with a production license for wind farm development. It is interesting to note that all

Table 6
Correlation coefficients between wind farm site-selection and factors' actual values.

	S1	S2	S3	S4	S5	S6
r-values	−0.034	0.231	0.124	−0.138	0.088	0.029
Normalized r-values (weights)	0.053	0.361	0.189	0.215	0.137	0.045

these sites were found to meet the constraint criteria, while their suitability index is always higher than 0.3. Furthermore, according to Table 7, the mean values of SI range between 0.59 and 0.73, while their maximum values are close to unity. It is also noteworthy that only in a small fraction of licensed sites (less than 25% in all weight assessments) the SI is lower than 0.5. Therefore, it can be concluded that the locations of these projects are acceptable with respect to the methodology followed in this study and that the answer to Question 1 is again an affirmative one (i.e. all the licensed farms can meet the critical siting criteria).

5. Conclusions

The aim of this paper was to design, apply and evaluate an integrate framework for selecting, at the regional level, the most appropriate sites for wind-farm projects' development. For this aim, a GIS-based multi-criteria decision analysis procedure has been developed and then applied to the Regional Unit of Kozani, in Greece. This system is able to handle the multiple and usually conflicting planning objectives that need to be considered when selecting a location for a new wind farm. The siting analysis was performed at a high resolution (150 m × 150 m) following the cell size of the available wind resource map. An overall constraint map and a land suitability map were constructed. The latter uses a fuzzy approach in order to represent the evaluation criteria with continuous decision functions.

The results identified the optimal locations for wind projects as well as the suitability score of the already licensed (but not yet

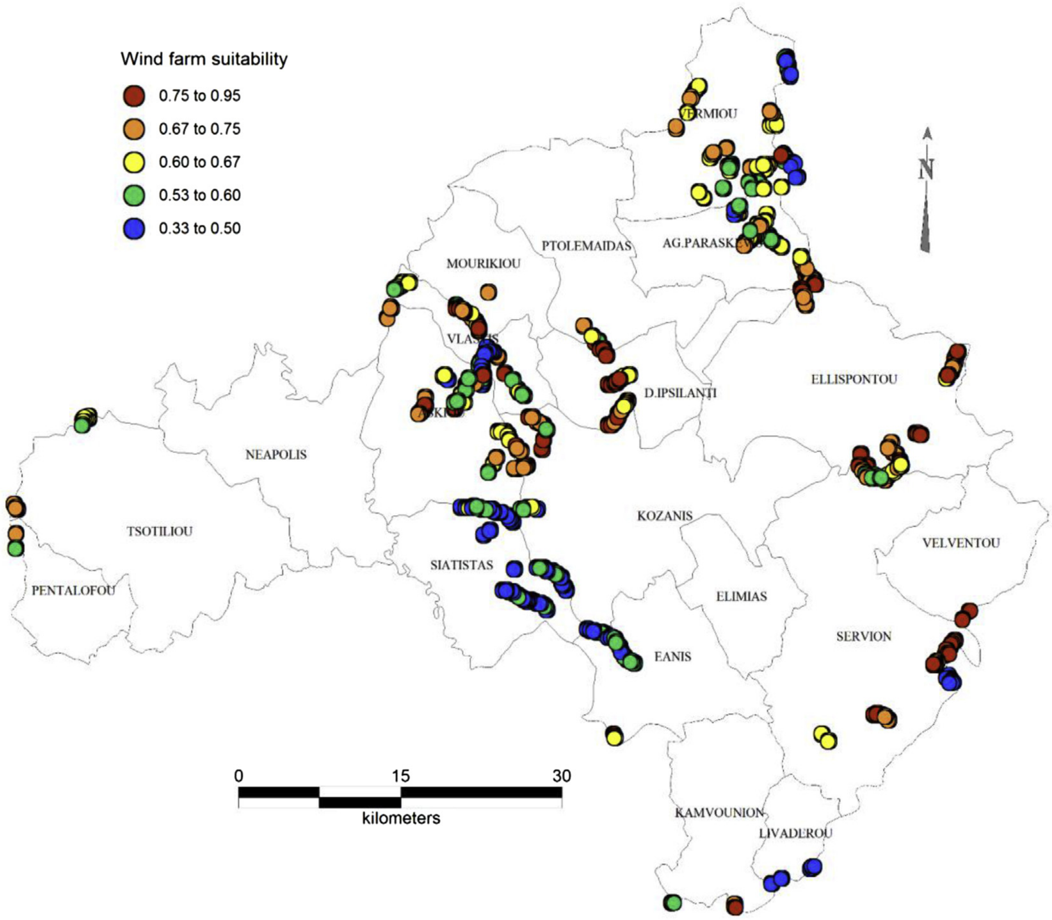

Fig. 8. Ex-post evaluation of wind farm suitability - Suitability of sites with production license (under Scenario 1).

built) projects. According to these findings the locations of the already licensed wind-farms were all characterized as acceptable ones, while the majority of these projects achieved a satisfactory score in their overall suitability assessment. Furthermore, the results of this paper indicate that more than 12% of the study area has an acceptable SI score ($SI > 0.5$). This outcome, in conjunction with the fact that the current number of projects is well below the carrying capacity of the study area, supports the potential role of planners in designating more areas as appropriate for wind farm development.

A number of extensions to the present investigation could be considered, including the incorporation of multiple perspectives in the AHP, through a survey of stakeholders and/or experts. Although in the present paper we applied the decision tool at the regional level, it could be also applied at the national level or scaled down to the local decision-making level (e.g. at the level of municipalities), depending on data availability and policy needs. The tool is also applicable to other study areas and particularly in the mainland of Greece where most of the selected criteria are virtually similar.

Table 7
Descriptive statistics for the SI scores in the licensed areas.

	Scenario 1	Scenario 2	Scenario 3
Minimum value	0.329	0.390	0.300
Maximum value	0.922	0.944	0.917
Mean value	0.629	0.728	0.591
Standard deviation	0.114	0.148	0.114
Range of SI			
$SI \leq 0.5$	12.9%	15.0%	23.5%
$0.5 < SI < 0.7$	60.0%	10.0%	54.1%
$SI \geq 0.7$	27.1%	75.0%	22.4%

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