RESEARCH ARTICLE

MCDM analysis of wind energy in Turkey: decision making based on environmental impact

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Abstract
Development of new wind energy projects require complex planning process involving many social, technical, economic, environmental, political concerns, and different agents such as investors, utilities, governmental agencies, or social groups. The aim of this study is to develop a tool combining Geographic Information System (GIS) and Multi-Criteria Decision-Making (MCDM) methodologies, and its application for Turkey as a case study. A variety of constraints and criteria were identified based on a literature review and regulations gathered from variety of agencies, use of which resulted in determination of infeasible sites. Then, pairwise comparisons were carried out using analytic hierarchy process as the MCDM method to estimate relative importance of the criteria, and to visualize a suitability map with three classes. As the final stage, decision making was carried out based on environmental impact where 45.5% of the Turkish territory was found as infeasible area. Sixty percent of the remaining area are covered by the moderate suitability class, followed by the highly suitable area (20.3%) and low suitable area (19.8%). The output of this study can be used by energy planners to estimate the extent that wind energy can be developed based on public perception, administrative, and environmental aspects.

Keywords Wind · Energy · Environmental impact · MCDM · AHP · GIS

Introduction

Electrical energy is required for economic growth and human populations. Although it is mainly obtained from conventional sources such as coal, oil, and natural gas, environmental impacts caused by conventional sources are much worse than those brought about by the use of renewable energy sources (RES) (Góralczyk 2003; Weisser

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2007; Kumar et al. 2016). Therefore, RES have become promising alternatives to non-renewable sources. RES include natural sources such as wind, solar, thermal, photovoltaic, hydro, wave, tidal, biofuels, ocean, and geothermal sources (Twidell and Weir 2015). Utilization of RES such as wind reduces emission of CO_2 and other greenhouse gases (GHG), and hazardous air pollutants, increases water conservation; provides domestic job creation; landowner revenue generation and rural tax revenue; and perhaps most importantly, reduce reliance on fossil fuels for electricity generation (AWEA 2008). Specifically, the impacts of wind energy are low, local, and manageable (Bilgili and Simsek 2012).

Turkey is one of the fastest growing power markets in the world and was positioned in the global wind energy market as the 10th largest annual market in 2015. Turkey's first commercial wind farm was commissioned in Alaçatı, Çeşme, in 1998 with a capacity of 1.5 MW (Ilkılıç et al. 2011). Even though the first wind farm started operation in Turkey as early as 1998, investments significantly increased after 2005 with the adoption of "The Renewable Energy Law of Turkey." The market has grown from 20 MW in 2006 to 4700 MW in 2016 (TWEA 2016). Turkey's primary energy reserves are not

enough to meet the rising energy demand. Currently, there are 3.144-GW acquired wind farm licenses waiting to be built.

Europe, specifically the EU states, has a goal of at least 27% renewable energy consumption in final energy consumption at European level until 2030 (EWEA 2015). Turkey has a similar target of increasing the installed capacity to 20 GW until 2023 (Dursun and Gokcol 2014). Since geographical limitations, public opposition, wildlife conservation, and electricity grid integration pose challenges for the investors, not much space is available for the implementation of wind farms. These factors make planning of wind power plants to become a complex procedure, involving the consideration of many different criteria and constraints. The most important consideration in site selection for wind turbines is the wind energy density, but technical, economic, environmental, social, and political requirements have started being considered efficaciously. Economic issues are associated with maximizing economic benefit, and environmental concerns aim to decrease the adverse effects of the wind farms. Environmental concerns include impacts on humans (e.g., noise, visual effect) and effects on ecosystems (e.g., the damage to the wildlife, especially birds and bats, and habitat loss). The acceptance of wind farms and socio-political parameters are two difficult points that have been imbedded in the Environmental Impact Constraints (EIC) and should be discussed by the developer and other parties involved, after the output of MCDM tools results are extracted.

The complex decision-making process requires a tool that can incorporate a set of decision alternatives and the decision maker's preferences effectively. In a Geographical Information System (GIS)-based decision-making process, the alternatives are evaluated by preferences of individuals (decision makers, managers, stakeholders, interest groups) with utilization of Multi-Criteria Decision-Making (MCDM) that contributes a methodology for guiding the decision maker, whereas GIS provides processing of the geographic data. Therefore, GIS and MCDM methods combine and transform geographic data and the decision maker's preferences into a resultant decision, and allow to reach optimal solutions for highly complex spatial decision-making problems (Malczewski 2010). The major advantages of using a GIS-based approach for siting is to reduce the time and cost of site selection, and also to provide a digital data bank for long-term monitoring of the site (Moeinaddini et al. 2010). Therefore, GIS is widely used in the decision and management situations such as environmental planning and management, transportation planning and management, urban and regional planning, waste management, hydrology and water resource, agriculture and forestry, geology and natural hazard, and real estate and industrial facility management (Malczewski 2010).

One of the first studies regarding the evaluation of the wind energy potential has been carried out by Voivontas et al. (199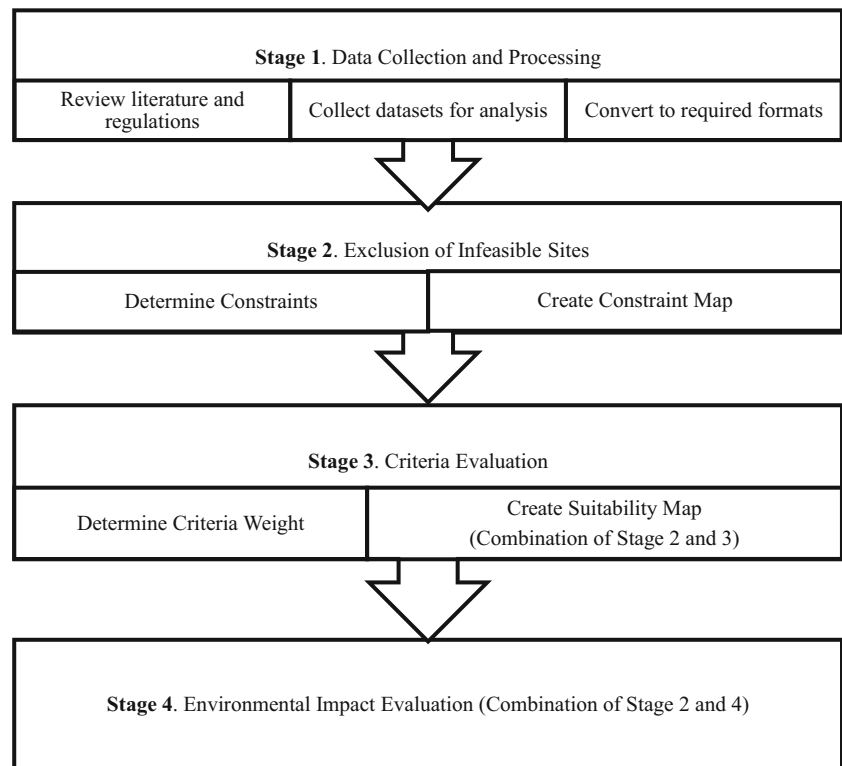8) for the island of Crete, Greece, using a 250-kW wind turbine. In recent years, there are several studies of GIS applied to site selection of wind farms around the world including Turkey. Studies differ from each other with respect to choice of the study area, the criteria, and the methodologies applied. Short list of studies compiled by the authors are from several countries such as Austria (Gass et al. 2013), Belgium (Lejeune and Feltz 2008), Cyprus (Georgiou et al. 2012), Denmark (Hansen 2005), Germany (Höfer et al. 2016), Greece (Tegou et al. 2010; Latinopoulos and Kechagia 2015), Iran (Noorollahi et al. 2016), Oman (Al-Yahyai et al. 2012), Poland (Sliz-Szkliniarz and Vogt 2011), Spain (Sánchez-Lozano et al. 2014; Schallenberg-Rodríguez and Notario-del Pino 2014), Thailand (Bennui et al. 2007), Turkey (Aydin et al. 2010; Atici et al. 2015), the UK (Baban and Parry 2001; Watson and Hudson 2015), and the USA (Van Haaren and Fthenakis 2011; Grassi et al. 2012; Gorsevski et al. 2013). While some of them focus on the national scale (Al-Yahyai et al. 2012; Gass et al. 2013), the others were conducted on regional scale. Parameters of interest vary from country to country, even sometimes region to region based on the legal framework enforced by governments. MCDM have been used by different methods like Elimination and Choice Translating Reality (Sánchez-Lozano et al. 2014; Atici et al. 2015), Stochastic Multiobjective Acceptability Analysis (Atici et al. 2015), Order Weighted Averaging (Baban and Parry 2001; Aydin et al. 2010; Al-Yahyai et al. 2012), Analytical Hierarchy Process (Baban and Parry 2001; Bennui et al. 2007; Tegou et al. 2010; Al-Yahyai et al. 2012; Georgiou et al. 2012; Latinopoulos and Kechagia 2015; Watson and Hudson 2015; Höfer et al. 2016), Simple Additive Weighting (Hansen 2005; Georgiou et al. 2012; Gorsevski et al. 2013), and Weighted Index Overlay (Noorollahi et al. 2016).

This study presents a GIS-based multi-criteria decision-making model applicable to diverse terrain and climatology conditions, that accounts air density for wind speed, that can be updated with changing regulations, that integrates environmental impact into the selection at the last stage among those remain after application of the technical/economic criteria, and that has been validated by comparing locations of > 100 in-operation wind farms, which all give form to a unique study with regard to the literature. Nevertheless, nationwide studies are scarce in the literature and Turkey has not been studied based on Turkish regulations or there is no such model in use in Turkey for wind farm planning.

Theory and method

The proposed methodology for site selection of wind power plant installation in Turkey, which is illustrated in Fig. 1, was handled under four stages. In the first stage, decision-making criteria associated with energy generation of wind turbines were identified

Fig. 1 Overview of the methodology

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┌─────────────────────────────────────────────────────────────┐
│              Stage 1. Data Collection and Processing          │
├──────────────────┬──────────────────┬───────────────────────┤
│ Review literature│ Collect datasets │ Convert to required    │
│ and regulations  │ for analysis     │ formats                │
└──────────────────┴──────────────────┴───────────────────────┘
                            ↓
┌─────────────────────────────────────────────────────────────┐
│               Stage 2. Exclusion of Infeasible Sites          │
├────────────────────────────┬────────────────────────────────┤
│   Determine Constraints     │      Create Constraint Map      │
└────────────────────────────┴────────────────────────────────┘
                            ↓
┌─────────────────────────────────────────────────────────────┐
│                   Stage 3. Criteria Evaluation                │
├────────────────────────────┬────────────────────────────────┤
│  Determine Criteria Weight  │   Create Suitability Map        │
│                             │  (Combination of Stage 2 and 3) │
└────────────────────────────┴────────────────────────────────┘
                            ↓
┌─────────────────────────────────────────────────────────────┐
│  Stage 4. Environmental Impact Evaluation (Combination of     │
│                        Stage 2 and 4)                         │
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based on a review of the literature and the regulations. Then, boundaries and geographical coordinates of these factors were collected and processed in GIS. In the next step, infeasible sites were excluded depending on regulations and planning constraints. In the third stage, the remaining sites were evaluated based on the economical and technical characteristics of the study area. The evaluation at this stage was conducted with a multiple-criteria decision-making method. In the last stage, the areas were evaluated with the environmental objectives adopting a conservative approach (i.e., implementing exclusion areas) to show potentially problematic sites and suitable locations for wind turbines.

Study area: Turkish territory

Turkey, located between 36º–42º North latitude and 26º–45º East longitude, is a large peninsula that bridges the continents of Europe and Asia. The country has a small part in Europe and a large area in Asia called Thrace and Anatolia, respectively. Turkey is surrounded by sea on three sides: the Black Sea, the Mediterranean Sea, and the Aegean Sea. Turkey is divided into 81 provinces in seven geographical regions. All the provinces and regions might apply different cost and/or environmental criteria. Its total area is 78 million hectares of which 21.7 million hectares are designated as forest area (TUIK 2014).

Multi-criteria decision-making methods and AHP

The application of MCDM techniques is gaining popularity in renewable energy management (Pohekar and Ramachandran 2004). The aim of traditional single criteria decision making in energy investments was maximization of net benefits, in monetary terms. As the energy management problems are getting more complex, economic considerations are complemented with environmental and social considerations, leading to multiple-criteria decision making being used to deal with conflicting decision problems.

There is a wide range of MCDM methodologies, based on their goals and application steps, and how the alternatives are ranked. For energy planning applications, the Analytical Hierarchy Process (AHP) is popular and recommended (Pohekar and Ramachandran 2004) because of its simplicity, flexibility, and especially its ability to mix qualitative as well as quantitative criteria in the same decision framework, which was followed in this study. The basic principles can be summarized as follows; however, a detailed description of the methodology employed in this study is provided in Supporting Document–1: AHP, a hierarchy is a MDCM approach where criteria are organized in a hierarchic structure in such a way that each level may represent a different section at the problem. Once each of the levels is defined, the method derives priority scales or weights through a series of pairwise comparisons (Saaty 1980). The pairwise comparisons are the core of

the AHP process and they determine the relative importance of one criterion over another (Saaty 2008). Evaluations can be based on measurable quantities or people's perceptions and preferences, in which case the need and purpose of the decision and the effects on various stakeholders come strongly into play. Finally, the alternatives are ranked in terms of combination of the criteria scores. Additionally, the method has a special provision for the consistency in the judgements of each individual evaluator assigning scores.

Data collection and processing

All land with adequate or optimum wind energy resources may not be equally suitable for wind energy development. For example, certain areas may be declared as protected land by the governmental regulations, or they may be located at a significant distance from available roads, which significantly increases construction costs. Therefore, all objectives/possible factors associated with site selection for wind turbines were identified based on national legislation related to wind turbine development and literature research. A set of factors were finally selected and the boundaries and geographical coordinates of those factors were collected from government agencies, web-based datasets, scientific studies, and a voluntary agency (Table 1) which were then processed in GIS. Factors were classified into three categories, based on a logical sequence of application (schematic diagram).

- Exclusion Parameters (political concern)
- Evaluation Criteria (economical and technical concern)
- Environmental Impact Constraints (environmental and social concern)

Data sources (and other information) are presented for each factor in Table 1.

In addition, a detailed description of the rationale for the inclusion of each factor and the definitions of elements/classes/thresholds are given in the Supporting Document–2. It should be emphasized here that the inclusion of further factors in the site suitability analysis was also considered, such as location of protected forests, world heritage sites, natural sites, military districts, bat habitats, and bird migration routes. However, these

Table 1 Spatial analysis layers

Step	Layer	Source of data
Exclusion Parameters (political concern)	Radars	Turkish Republic Official Journal (Number: 29033) (Legistration on Prelicence of Wind and Solar Power 2014)
	Airports	CORINE 2002 Seamless Vector Data (CLC: 124), Energy Market Regulatory Authority Announcement in 12th of May, 2016
	Fault lines	Kandilli Observatory and Earthquake Research Institute (KOERI 2015)
	Urban areas	CORINE 2002 Seamless Vector Data (CLC: 111, 112)
	Protected areas	Directorate of Nature Conservation and National Parks (Coordinates of Special Environmentally Protected Areas 1990, 2000, 2004, 2007, 2010, 2013; Law on Wildlife Protection and Development Areas 2004), UNESCO (UNESCO 2016a, b)
	Altitude	SRTM 4.1 DEM (Jarvis et al. 2008)
Evaluation Criteria (economical and technical concern)	Air density	'Adaptation of Uniform Wind Atlases' (Bingöl 2016)
	Wind speed	Global Wind Atlas (DTU 2016)
	Frozen period	WorldClim (Hijmans et al. 2005)
	Land cost	The Revenue Administration (Turkey 2014)
	Roads	OpenStreetMap (OpenStreetMap 2015)
	Grid capacities	TEİAŞ (TEIAS 2015)
	terrain Complexity	'Adaptation of Uniform Wind Atlases' (Bingöl 2016)
Evaluation Criteria and Environmental Impact Constraints (economical and environmental concern)	Forest	CORINE 2002 Seamless Vector Data (CLC: 311, 312 and 313), (Regulation for Article 18 of the 17/3 of the Forest Law 2014)
Environmental Impact Constraints (environmental and social concern)	Agricultural lands	CORINE 2002 Seamless Vector Data (CLC: 212)
	Bird habitat	Doğa Derneği (KusBank Veritabanı, Doğa Derneği 2016)
	Visual impact	The study of 'Identification of Visual Influence Zones of Wind Farms in Lithuania' (Abromas and Kamičaitytė-Virbašienė 2014)
	Noise	Regulation on Assessment and Management of Environmental Noise (Regulation on Assessment and Management of Environmental Noise 2008)
To validate results	Farms areas	Energy Market Regulatory Authority (EMRA 2015)

datasets were either not accessible or not available, due to security regulations or were simply not shared with the public by the authorities.

Generic wind turbines

An additional consideration in our study pertains to the different wind potential calculation for different wind turbine models (criterion "Wind potential" of step 2–Technical and economical evaluation criteria). Given that more than 50 wind turbine models have been developed over the last decade, it was deemed impractical to create a separate evaluation/decision-making tool for each of them. Additionally, environmental impacts of bigger and smaller turbines differ from each other (Tremeac and Meunier 2009). Therefore two different wind turbines representing the 900-kW (50-m hub height) and 2.1-MW (100-m hub height) classes, which are frequently used, were chosen for this study (Table 2). Capacity factors of the defined turbines were acquired from Hughes (2012) who collected onshore wind datasets on substantial installations. Capacities were calculated by taking the averages of lifetime efficiency of the turbines that have the same power rate with the generic turbines and found as 22% for 900 kW and 31% for 2.1 MW.

Data analysis

The data analysis was performed following the step-wise processing algorithm described in the "Theory and method" section. In the first step (Exclusion of Infeasible Sites), layers representing exclusion zones for wind farms were collated, merged, and dissolved. In the second step (Criteria Evaluation), technical and economical criteria were assigned weights through pairwise comparisons, the values of the GIS layers were scaled and used in the calculation of coefficients for the final decision-making atlas. Finally, when the user reaches the last step, a very few number of places are left

Table 2 Properties of the generic wind turbines

Characteristic	Generic turbine 1	Generic turbine 2
Hub height (m)	50	100
Diameter (m)	45	80
Swept area (m^2)	1590.4	5026.5
Power (kw)	900	2100
Capacity factor (%)	0.22	0.31
Total turbine cost (€)	680,000	1.580.000
O&M cost (€)	680,000	1.580.000
Gross yearly income from electric sale (€)	125.000	375.000
Net income annually (€)	25.000	175.000

which can be compared among each other. Now, the user can choose one against other (maybe between top two best locations) based on environmental impact criteria to finalize the case study.

An exclusion zone is an unsuitable zone for wind turbine installation based on legal regulations and literature review. In some cases, buffer zones are also taken into account to define the minimum distance around those areas. The raw data, in the form of GIS vector layers, were used to create exclusion zones by adding buffers. Any site that is outside the below listed buffers is assumed to be "a technically feasible site".

- Radar locations with 5-km buffer zones around them (Legistration on Prelicence of Wind and Solar Power 2014),
- Airports with 3-km buffer zones around them (According to the Turkish legislation prior to 2016 (Legislation for Construction Criteria Around the Airports 2012))
- 2- and 15-km buffer zones around aeronautical stations and navigational aids, respectively (Energy Market Regulatory Authority announcement on 12th of May, 2016)
- Fault lines with 150-m buffer zones around them (Demirtaş 2005)
- Urban areas with 1-km buffer zones areas around them (applicable to cities only) (Regulation on the Technical Assessment of Applications related to Wind Power Generation 2015)
- Protected areas (Forest Law 1956; Law on National Parks 1983; Law on Protection of Cultural and Natural Properties 1983; Coordinates of Special Environmentally Protected Areas 2004; Law on Wildlife Protection and Development Areas 2004)
- Areas with an elevation above 1500 m (REPA 2007)

Each vector layer created in order to define the exclusion zones was subtracted from the borders of Turkey. As the regulation regarding airports was changed during the study, two different suitability maps with the new and old regulation were developed to illustrate the suitability levels within the feasible sites.

After assessing the technically feasible sites, economically optimum sites were obtained in the next step using the pairwise comparisons of criteria weights in combination with scaled numerical values of each criterion/variable. Firstly, data of each layer were converted from vector format to a raster format and resampled to $^1/_{120°}$ cell sizes (around 700 × 900 m) to obtain raw data of all criteria in grid format, and each of these grid cells was considered as a potential location for installation of wind farms. Secondly, the numerical values for each criterion were scaled from 0 to 100 based on their maxima and minima. The calculation for wind power was repeated for two generic wind turbines defined in Table 2. The scaling factor is applied to criteria as

100 being the most positive and 0 is being the most negative effect to the decision-making steps. Therefore; wind power, roads density, and grid capacities were scaled as a positive impact, and the factors of land cost and frozen periods were scaled as negative impact (Table 3). The forested terrains warranted a special consideration. In order to visualize forested terrain areas, non-vegetated areas were taken from CORINE 2002. Seamless Vector Data were combined with the rental agreement regional prices (Regulation for Article 18 of the 17/3 of the Forest Law 2014). Although these areas were classified according to their fees and the regions having lowest prices represented high preferability, the non-vegetated areas were defined with the highest score in order to minimize any forest loss.

Subsequently, the relative importance of each layer was assigned by an expert group. The relevant priorities for the pairwise comparisons were provided by the expert group comprised of two academicians, one manager of a company, one project engineer, and two graduate students, utilizing a preference scale of 1 to 9 as recommended by Saaty (Saaty 2008). Please see Supporting Document–1 for details. Since there is a lack of expertise regarding the ruggedness index calculation and usage, the weight of altitude was assigned by only one expert from the group to avoid inconsistencies. For the other parameters, mean values were used. A Consistency Index (CI) was also calculated to evaluate the consistency in the judgement of each expert (see Supporting Document–1).

To obtain the priority vector for each criterion, the nth root value method was applied with $n = 7$ for this study. Dividing each row to sum of the nth root column in gives the priority vector. The suitability scores per criterion per grid cell were calculated by multiplying the priority vector with the scaled values for each criterion, and then summing across criteria to obtain the overall suitability index. Then, the map thus created was divided into three classes according to the overall suitability score. The classes having higher score represent better suitability: low suitable (scores between 2000 and 4000), moderately suitable (scores between 4000 and 6000), and highly suitable (scores > 6000).

Although comprehensive studies should be conducted for the Environmental Impact Assessment (EIA), our work in the third stage aims to provide a preliminary step for the detection of

Table 3 Scaling rules for the raw data of the evaluation criteria

	Factors	Type (min/max)
1	Wind power	Max
2	Frozen period	Min
3	Land cost	Min
4	Roads	Max
5	Forest	Special consideration
6	Grid capacities	Max
7	Terrain complexity	Min

adverse environmental effects of wind power plants. The objective of this stage was to evaluate the project sites in terms of primary environmental aspects and the potential for environmental concerns to arise. The primary environmental issues were classified as forests, agricultural areas, important bird areas, noise, and visual impact. With respect to the first two constraints, removal of vegetation for the construction of power plants can cause fragmentation and loss of habitat. It has been estimated that approximately 1.23 ha of vegetation is removed per wind turbine (Zimmerling et al. 2013). The road and grid infrastructure are added up to habitat loss.

Although actual habitat loss changes based on local circumstances, the predicted habitat loss for Turkey based on this average loss per turbine and the number of turbines constructed in Turkey according to previous studies was approximately 2063 ha (TWEA 2015). Moreover, habitats in the vicinity of wind farms may not be preferred for foraging, nesting, and roosting during their construction activities and operation by some bird species depending on their life history, behavior, and habitat requirements (Zimmerling et al. 2013).

For the purposes of this particular step, all forest and agricultural areas were considered as areas of concern. Visual impacts were explored with two buffer zones, 20 km from wind turbines, a distance that eliminates visual impact on humans completely (Abromas and Kamičaitytė-Virbašienė 2014), and 5 km away, whereby wind turbines become landscape accents (Abromas and Kamičaitytė-Virbašienė 2014).

Current license permitting authorities do not require a comprehensive study for important bird species, which causes opposition at the courts after the construction of wind farms. Therefore, despite the lack of legal requirement, it was considered essential to analyze important bird areas. Two periodical bird observation datasets (2011–2015 and 2013–2015) were taken into consideration, covering 32.2 and 20.6% of the country, respectively. Since wind farm licensing takes nearly 5 years, it was deemed appropriate to include sightings reported from 2011 through 2015 in this study. Based on the focal bird habitats for 20 species (center of habitat) and the radius of distribution, areas of concern were created with an additional 100-m buffer (see Supporting Document–2).

Finally, noise does not constitute any constraint for further evaluation, since the average distance needed to ensure compliance with government regulations regarding acceptable noise levels (Supporting Document–2) is well within the mandatory 1-km buffer zone around urban areas (Stage 1 of the Analysis).

Additionally, the results of the final site suitability map were compared to the locations of existing wind farms in Turkey to examine the compatibility of the existing wind farms with the suitable areas and test the validity of our assumptions. However, this comparison did not include environmental criteria since they are not quantitative but more importantly because the majority of the wind farms used in the analysis had already been erected

before environmental considerations were introduced with relevant legislation.

Results

Exclusion of infeasible areas

The aim of this step in the analysis was to remove unsuitable areas from the geographic extent of the study based on the constraints and their associated buffers. Any site that failed to satisfy even one of the exclusion criteria was excluded from further investigation (Fig. 2). Based on the calculation, 10.7% of the country is covered by urban areas: 6% by airports, 4% by protected areas, 0.6% by faults lines, and 0.2% by radars can be seen in Fig. 2a to Fig. 2f. The percentage sums up to 21.5% that corresponds to 17 million ha of the total 78 million ha of Turkey (Fig. 2g). An additional 24% of the area is not usable for wind energy due to the high altitude (> 1500 m). The remaining 54.5% is considered suitable at this stage.

Criteria evaluation

After assessing the technically feasible sites, economically optimum sites were obtained in this section using the pairwise comparisons of the evaluation criteria (Table 3). As a measure of the

consistency in the experts' judgment, a consistency ratio (CR) value of < 0.1 indicates a consistent matrix (Saaty 2008), and with a value of CR = 0.0974, the evaluations of the present study are considered acceptable.

Table 4 presents pairwise matrix for group decision and priority vectors of criteria, in which values higher than 1 in the upper triangular part of the matrix indicate that the criterion in the row is considered more important than the criterion in the column, while the opposite is true for values lower than 1. The lower triangular part of the matrix is simply the reciprocal of the upper part, while the last column includes the overall priority values for the criteria. The wind power is at the top of the priority list of criteria. It is followed by the importance of flat terrain and the presence of forest. The land cost is at the bottom of the list. The raw data and scaled distribution of each criterion are illustrated in Fig. 3a–h. With respect to the wind power criterion, it was seen that differentiation in suitability maps between the two generic turbines was insignificant ($R^2 =$ 0.9959); therefore, the generic turbine (2.1 MW) was used for the remaining calculations. Moreover, as the regulation regarding airports was changed during the study, two different suitability maps with the new and old regulation were developed to illustrate the suitability levels within the feasible sites (Figs. 4 and 5). Figure 8 shows the statistics of suitability classes at 100-m hub heights over Turkey. Following the classification of pixels into classes of low, moderate, and high suitability as
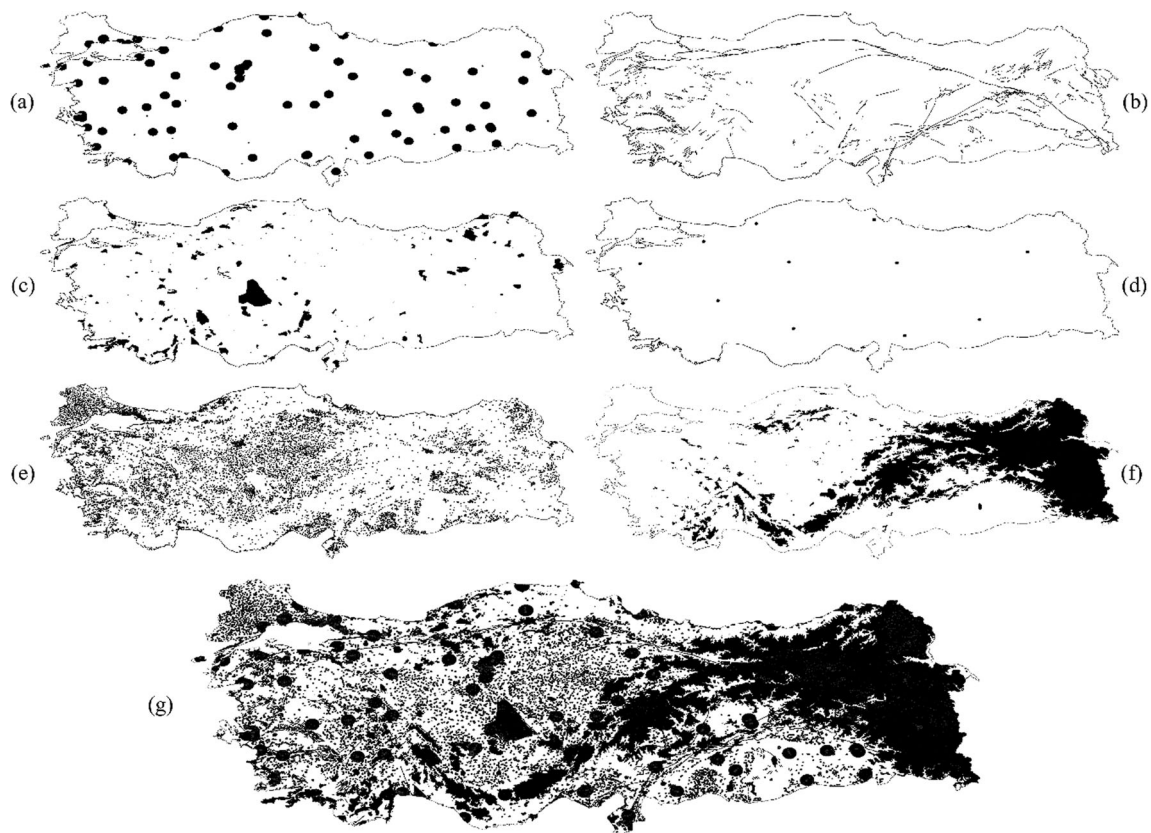

Fig. 2 Excluded zone of **a** airport, **b** fault lines, **c** protected area, **d** radar, **e** urban, **f** elevation above 1500 m, and **g** the total excluded area

Table 4 Pairwise matrix for group decision and priority vectors of criteria

	Power	Frozen period	Land cost	Roads	Forest	Grid capacity	Terrain complexity	Priority vector
Power	*1.00*	1.31	2.17	1.31	0.88	1.85	4.00	*0.21*
Frozen period	0.76	*1.00*	1.94	1.48	0.87	1.68	0.50	*0.14*
Land cost	0.46	0.52	*1.00*	0.91	0.37	1.25	0.25	*0.08*
Roads	0.76	0.67	1.10	*1.00*	0.73	1.53	0.33	*0.11*
Forest	1.13	1.15	2.69	1.37	*1.00*	0.93	2.00	*0.18*
Grid capacity	0.54	0.60	0.80	0.65	1.08	*1.00*	0.50	*0.10*
Terrain complexity	0.30	2.00	4.00	3.00	0.50	2.00	*1.00*	*0.2*

The diagonal values (all 1.0) were written in italic

described in the "Theory and method" section, it was observed that the majority of the land available for wind farm development is covered by the moderate suitability class (59.9%), followed by almost equal areas of highly suitable conditions (20.3%) and low suitability (19.8%) (Figs. 6 and 7).

The predominance of the moderately suitable class is owed to the fact that Turkey has an abundance of flat terrain, short frozen periods, areas of low land cost, and moderate wind power potential. This is also reflected in the results of the validation analysis, whereby it was identified that 59.2% of the existing wind farms are located in moderately suitable areas based on the classification of this study, whereas the minority are placed on low (23.7%) and highly suitable (17.1%) areas (Fig. 8), a distribution that matches rather well the proportions of the three classes.

Fig. 3 Priority maps for **a** power for first generic turbine [kWh], **b** power for second generic turbine [kWh], **c** frozen periods [months], **d** land costs [million €/ha], **e** roads [0/1], **f** forest [million €/ha/20 years], **g** grid capacity[%] (relative to the local availability), and **h** terrain complexity [RIX]. Top legend values are scaled 0 to 100 after, and bottom legends are raw data values
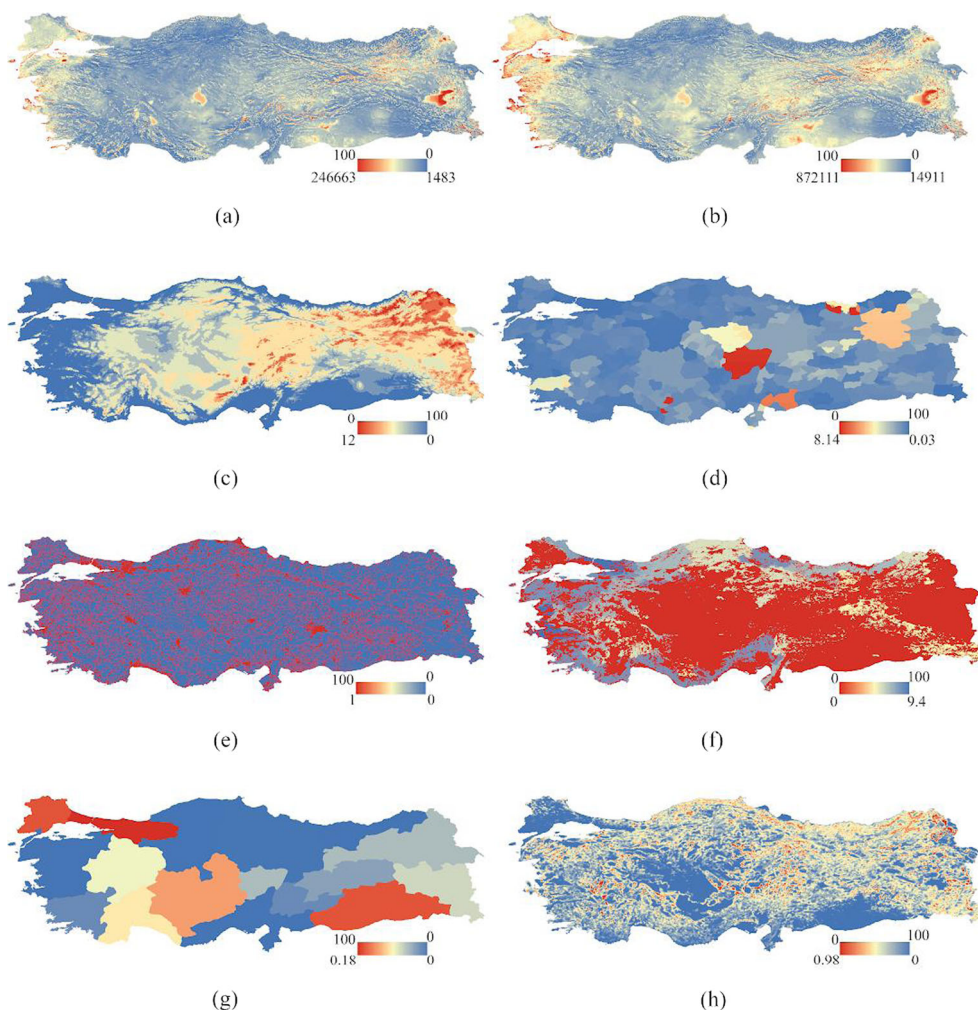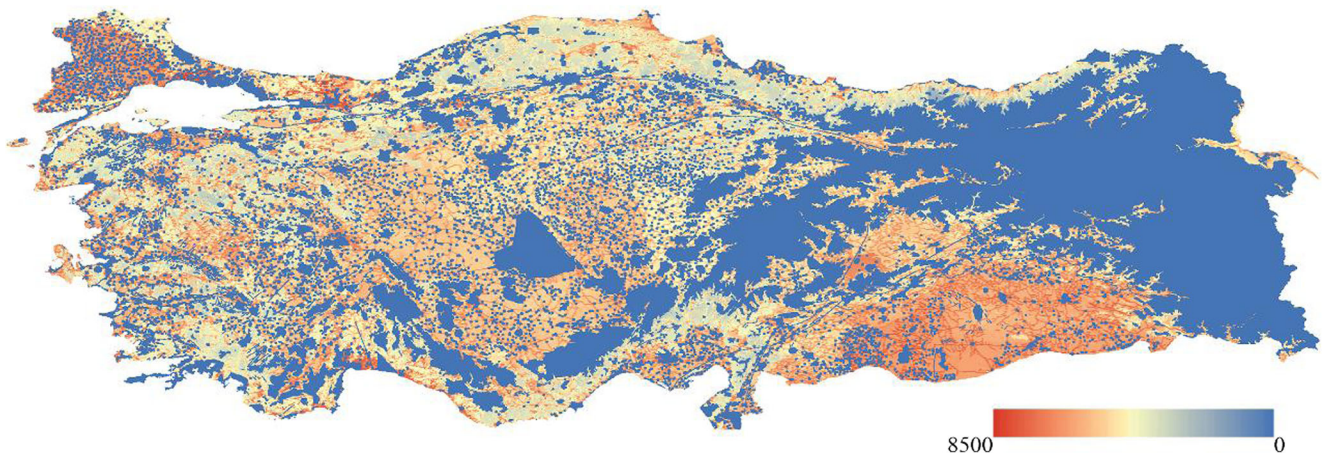
Fig. 4 Overall suitability index with the old airport regulation (2012)

Environmental impact evaluation

Figure 9a–d shows the areas where environmental issues regarding forests, agricultural land, visual impacts, and important bird areas may arise. The application of a 20-km buffer around urban areas left very little space available for unequivocal wind farm development due to the density of human settlements. It was considered overly conservative/unrealistic and incompatible with the national planning targets for wind energy production. Hence, only the results for the 5-km buffer for urban areas are presented. The resulting area of concern covers 43 million ha (Fig. 9c).

The combined map illustrating areas where any of the primary environmental issues examined in this study is displayed in Fig. 10, which covers an area of 57.6 million ha.

Discussion

The main output of this study is the developed GIS-based MCDM model which can provide support on effective decision making by relative comparison of wind farm sites. We collected data listed in Table 1 which are to our knowledge is the largest list of factors made for Turkey. Another novelty of our study is the more elaborate processing of some of the factors. For example, in previous MCDM studies (Al-Yahyai et al. 2012; Höfer et al. 2016), wind speed was considered as the main criterion for the wind power calculation. However, the power is also related to air density and the height or the capacity of wind turbines, which we took into account in our calculations to produce a more accurate estimation of wind power potential. Furthermore, the extent of the frost period was also used for the first time in Turkey for site suitability evaluation. For the estimation of the technical and economical suitability, we employed an AHP approach with an expert group with a varied set of backgrounds, striving for a judgement as balanced as possible for the prioritization of the importance of factors. The results of the suitability analysis demonstrate that Turkey is a country rich in wind energy potential. The fact that the distribution of existing wind farms (Fig. 8) among the different suitability classes matches so well, their availability according to our analysis not only validates our choice of factors and weights, but also raises a number of issues. One would expect areas of high suitability to have been
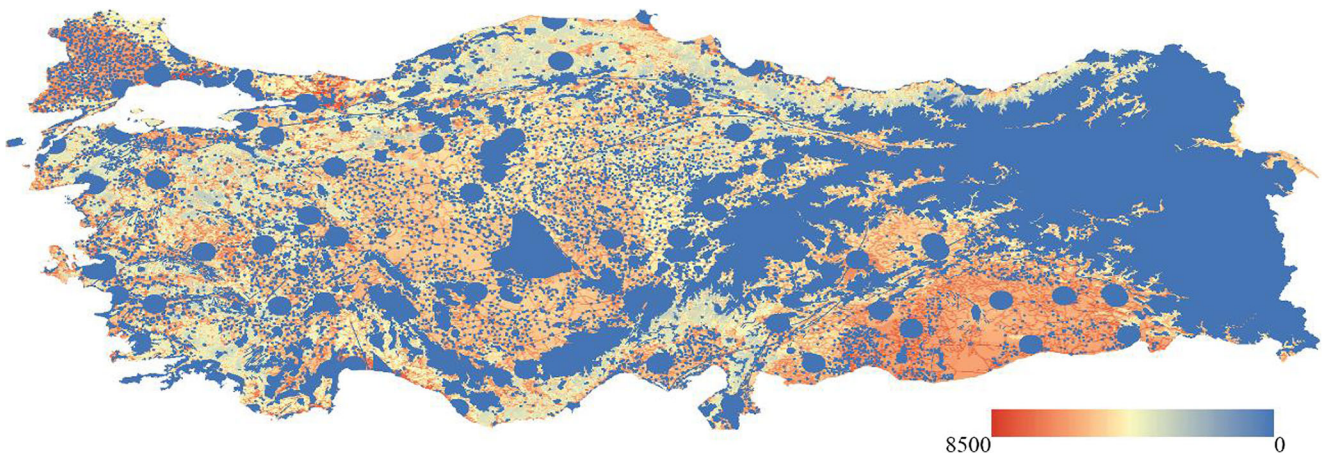

Fig. 5 Overall suitability index with the updated airport regulation (2016)
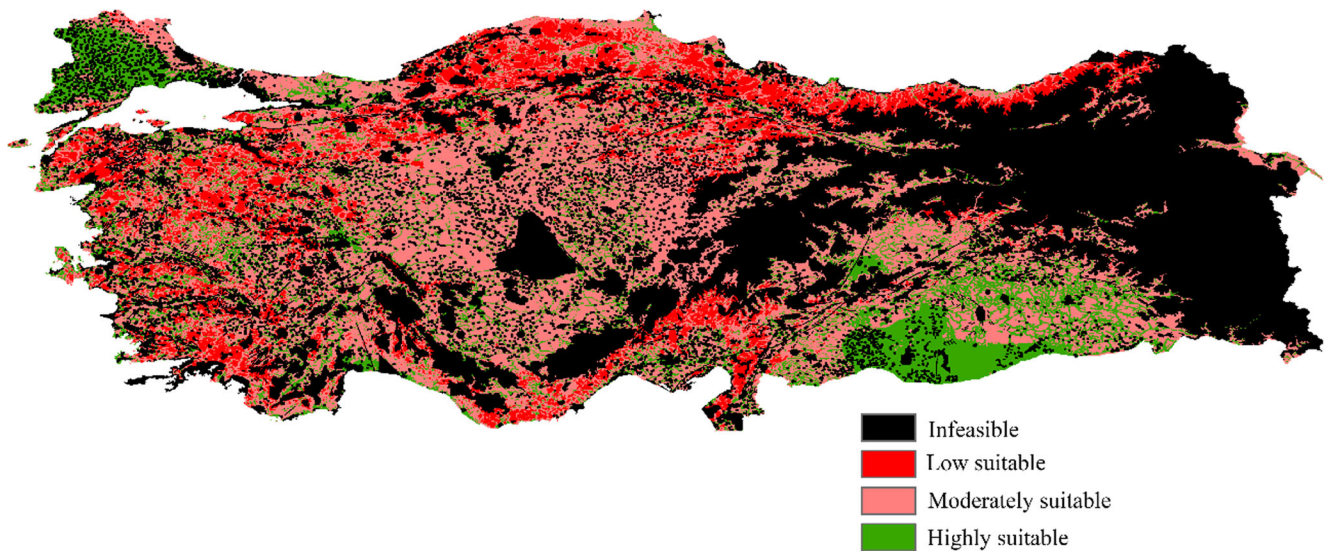
Fig. 6 Overall suitability index with the old airport regulation (2012) in four classes

preferentially exploited thus far and vice-versa for the low suitability areas, but this does not appear to be the case. The inconsistency between the calculated and the realized highly suitable areas could be attributed to the lumping of all regions with elevations between 0 and 1500 m in one class in our analysis and shows a preference of low-lying areas for wind farm development. On the other hand, the over-representation of exploited low suitability areas may be explained by an over-estimation of their wind potential to begin with.

Due to its modular nature, our methodology provides a flexible and adjustable framework to suit changing legislation as demonstrated by the case of changing airport regulations. It is a tool that can be used by developers and regulators alike since it can provide outputs for different scenarios and accommodate different expert groups.

Usage of output

To decide in an organized way, three steps (exclusion of infeasible sites, criteria evaluation, and environmental impacts evaluation) were performed. However, it should be noted that although exclusion of infeasible sites and criteria evaluation were combined to remove unpermitted sites, and to rank the remaining sites with respect to their preferabilities, environmental impacts evaluation were not linked with suitability map. Therefore, the decision makers should initially select the three or four best places according to their preferences based on pairwise comparison results. The next stage is to evaluate these sites in terms of environmental aspects. The environmental criteria are either not a subject of a regulation or they are being overcome by special permissions if the developer applies to the related agency/ministry. Most of the time, the issue is resolved with an economical
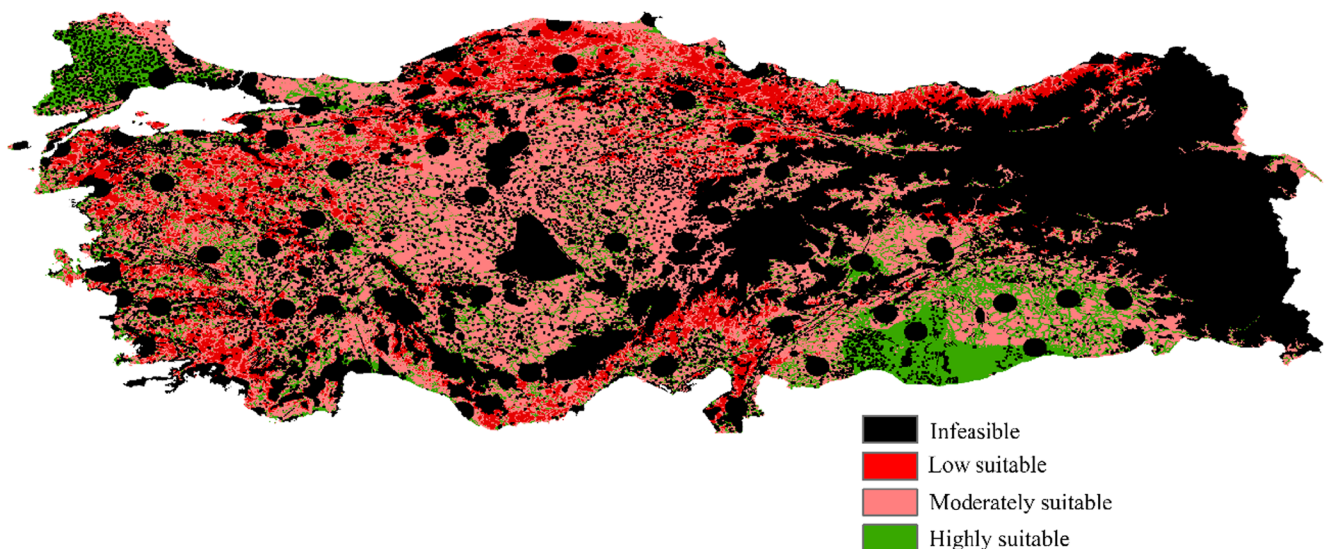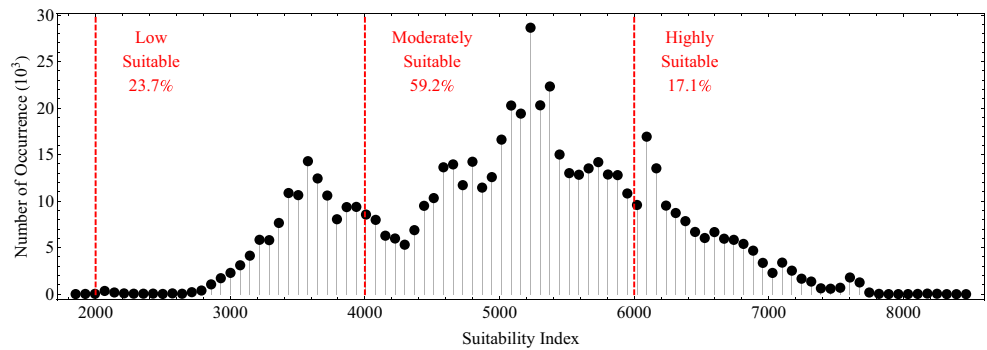

Fig. 7 Overall suitability index with the updated airport regulation (2016) in four classes

Fig. 8 Distribution of suitability index values and percentages (black) of existing wind farms within selected suitability zones (red)

agreement unless the location is not an environmentally protected historic or habitat area. Such procedure, which also changes frequently, creates uncertainties related to budget and decision-making steps. Therefore, the decision maker's approaches to this issue are quite decisive. The rationale behind this choice is that all decision makers are not necessarily faced with the same issues/pressures or do not prioritize environmental concerns in a similar way. For example, while some may be more concerned with visual impacts and establish wind farms away from residential places to minimize impact, others may evaluate visual impact as an unnecessary constraint for site selection and focus on habitat fragmentation instead.

Thus, if three locations have been chosen from a suitability map, and one of them lies in forested terrain, a choice will have to be made among the two remaining locations. Or if all three were in forested terrain, then one should compare the extents of the forested areas.

Several factors that are known to create complications for wind farm sites, such as military districts and radars, bird migration routes, bat habitats, protected forests, world heritage sites, and natural sites, are missing from the site suitability analysis due to security regulations or inaccessibility of the relevant data. The inclusion of these factors will certainly be a requirement for wind

farm siting and EIA that could alter considerably the feasible and suitable areas, at least at the local level.

Another limitation of the study is that the buffer zone around river/lakes is not clear in any regulation. Aydin et al. (2010) and Van Haaren and Fthenakis (2011) have taken the distance from water bodies as 400 m with reference to the study of Baban and Parry (2001). Baban and Parry (2001) collected guidelines from 60 local authorities in the UK by means of a survey and determined a representative distance of 400 m to water bodies. However, it has not yet been confirmed in the literature. On the other hand, Bennui et al. (2007) and Phuangpornpitak and Tia (2011) excluded a zone of 200 m from water bodies and main rivers arbitrarily without any reasoning. Turkish legislation of wetland protection also causes some conflicts, since wind power plants investments are allowed by permission. Due to the uncertainties regarding lakes, this study has not taken this matter into consideration as a parameter.

Conclusion

The wind energy sector needs a planning tool to shorten the planning process, and a visualized suitability map for wind
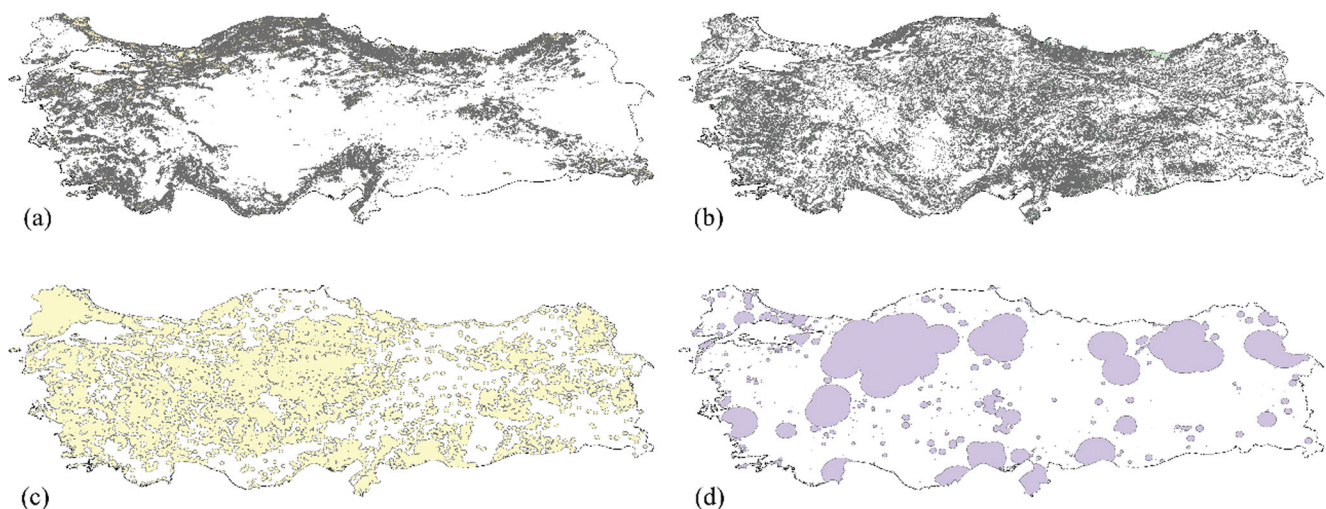

Fig. 9 Areas of concern **a** forests, **b** agricultural lands, **c** 5-km buffer zone around urban areas to avoid visual impact, and **d** important bird areas
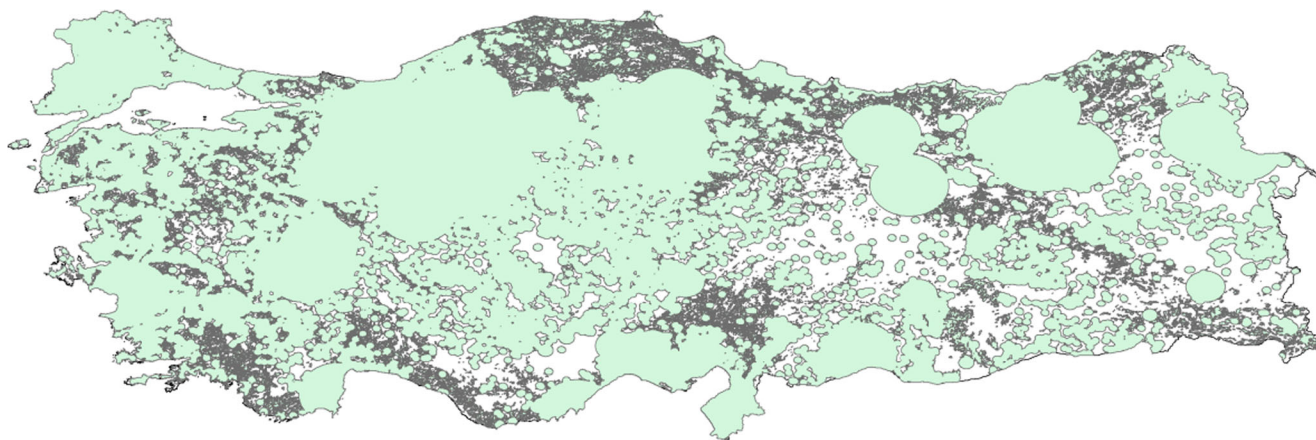
Fig. 10 Areas that should be subject to a full environmental impact analysis

energy installation based on the current regulations and scientific studies. Despite the limitations discussed above, this study succeeded in developing a combination of GIS and MCDM analysis tools by using AHP for site selection modeling in Turkey, as continuous attempt to build a more complete basis for research and development. The GIS model provides to create a dataset for the analysis and demonstration of the suitability of areas for wind farms, whereas the AHP method was applied for assessment of the pairwise importance of criteria on determining suitability of wind farm location.

Based on the results of this study, several recommendations can be made:

– Final spatial analysis of the environmental impact areas shows that the most suitable areas left to install wind farms are mostly at high altitude regions. That means, if the developers would like to stay away from environmental impact issues, they would move on developing wind farms at high altitude regions in the next decade.
– Another possibility to expand wind power capacity and lower the impact on the environment is to re-build already available wind farms with higher capacity wind turbines. Results show that the most of the active wind farms are already using high-capacity locations according to site suitability indexes.
– Although the forested and urban areas are excluded in this study to find the locations with lowest environmental impact, that does not mean that some wind farms would not be erected near or in forested areas or near urban areas. In such cases, the wind turbines will be affected from the high turbulence generated by the forests or urban areas. Therefore, forest and complex terrain modeling for site assessment should be studied and improved by the Turkish developers in order to make more efficient and with lower environmental effect final micro siting.

– With respect to environmental aspects, it should not be forgotten that the number of wind farms has been increasing dramatically to meet the set targets, hence wind farms will occupy more space on top of the 2063 ha which is the current size of the wind farm areas. To minimize the impacts, it is vital that the government and wind energy sector should work together in partnership to provide a single web-based resource to inform future research and project development.

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