Clean Technologies and Environmental Policy (2021) 23:1179–1195
https://doi.org/10.1007/s10098-020-01978-w

ORIGINAL PAPER

Decision support tools for wind and solar farm site selection in Isfahan Province, Iran

Mojtaba Barzehkar[1] · Kevin E. Parnell[1,2] · Naghmeh Mobarghaee Dinan[3] · Graham Brodie[4]

Received: 25 July 2020 / Accepted: 27 October 2020 / Published online: 11 November 2020

Abstract

Optimizing the location of wind and photovoltaic solar power plants is a significant environmental management problem. The effectiveness of the site selection process for renewable energy systems (RES) could be strengthened by flexible spatial and environmental planning strategies using decision support systems (DSS) to critically identify the most productive, environmentally friendly and acceptable sites for the production of sustainable and reliable wind and solar energy. This study discusses hybrid DSS, using multi-criteria evaluation based on the analytical hierarchy process (AHP), a geographical information system (GIS), fuzzy logic, and a weighted linear combination (WLC) approach to determine optimal locations for renewable energy generation infrastructure. In the first stage, the most decisive factors for evaluating the site suitability were identified, based on experts' opinions. Next, raster layers of ecological and socioeconomic sub-criteria were prepared GIS software. After incorporating the raster maps of each parameter, fuzzy membership functions were applied to normalize each raster layer between 0 and 1. The relative weights of different indicators were calculated using super decision software. Prioritizing vital elements were performed using AHP. In the final stage, the WLC approach was utilized to amalgamate layers in the GIS environment, which afforded the final site suitability maps. In Isfahan Province, Iran, 26% of the land area was found to be highly suitable for solar farms with 18% being highly suitable for wind farms. The results illustrate that using and comparing the results from combinations of computer-based DSS are more likely to result in better decisions than using individual DSS tools for the determination of the most suitable sites for RES location.

✉ Mojtaba Barzehkar
mojtaba.barzehkar@taltech.ee

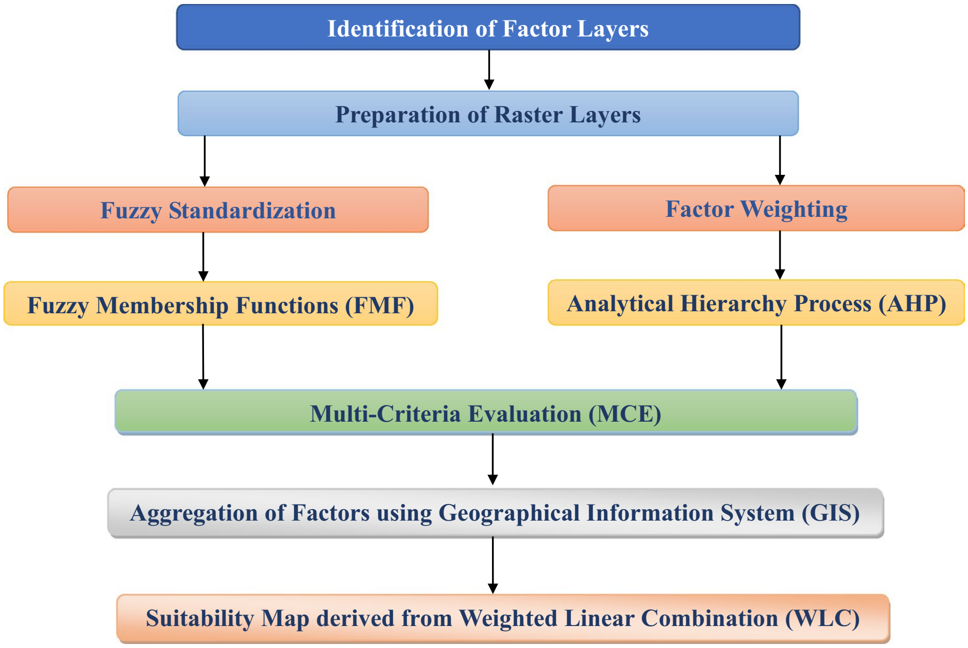
1 Department of Cybernetics, School of Science, Tallinn University of Technology, Tallinn, Estonia

2 College of Science and Engineering, James Cook University, Townsville, Australia

3 Environmental Sciences Research Institute, Shahid Beheshti University, Tehran, Iran

4 Faculty of Agricultural Sciences, Melbourne University, Melbourne, Australia

Graphic abstract



Keywords Solar energy · Wind energy · Renewable energy · Isfahan Province, Iran

Introduction

Human communities have been subjected to global warming effects caused primarily by the increasing usage of fossil fuels (Amjad and Ali Shah 2020). Conventional energy resources such as coal, oil, and gas are becoming less attractive because they release substantial amounts of greenhouse gases, especially CO_2, into the atmosphere (Pambudi and Nananukul 2019). Furthermore, they have been considered as the major contributing factor in disturbing the ecological values of important natural ecosystems, particularly through air pollution or reducing the quality of ecosystem services (Giamalaki and Tsoutsos 2019).

Existing electric power plants have been recognized as drivers in damaging habitats and degrading the soil through their construction and maintenance phases (Suuronen et al. 2017). Many countries are now choosing sustainable sources of energy, which could contribute to environmental sustainability and provide alternatives to meet the energy demands of a community (Solangi et al. 2019). The majority of countries, particularly wealthy nations, have embraced renewable energy power plants, which are considered to be sustainable and environmentally friendly, and are often more affordable than using traditional energy resources (Konstantinos et al. 2019). Renewable energy sources, such as wind and solar farms, have paved the way toward innovative, affordable, long-term investments and created much more profitable and economically viable solutions for the societies, as well as for the next generations, to satisfy energy needs and address climate change (Dhunny et al. 2019). In some instances, green jobs associated with renewable energy have been used to provide indigenous peoples with good employment opportunities and to tackle critical environmental challenges (Suuronen et al. 2017).

There has been a pressing obligation for environmental specialists and policy-makers to develop and apply new tools to help with these important energy priorities (Doorga et al. 2019), including developing strategies to find the most suitable locations for wind and solar energy infrastructure to both develop the energy potential and mitigate the consequences of climate change (Nait Mensour et al. 2019), in environmentally sustainable ways. A common and effective way to achieve these aims is to use decision support systems (DSS) to effectively and accurately identify the most suitable sites for the installation of wind and solar power plants, based on different indicator parameters (Villacreses et al. 2017).

Geographical information systems (GIS) have been commonly used as an efficient decision-support tool to store, analyze, and map the criteria regarding spatial planning for the renewable energy sector (Gasparovic and Gasparovic 2019). GIS is a tool that can help to minimize the time and cost of precise site planning while taking into consideration a database of information on the best possible sites. Another widely utilized method is multi-criteria decision-making

(MCDM), which is a powerful tool for specifying and prioritizing candidate locations in the site selection process for energy planning (Díaz-Cuevas 2018). The combination of GIS and MCDM provides a new possibility to devise an integrated approach to effectively investigate locations for the planning of wind and solar farms. This combined problem-solving model has high efficiency, flexibility, and inclusiveness in determining the environmental capacity of an area based on ecological, social, and economic factors to be applied to the site specifications (Baseer et al. 2017).

Since relying on only one kind of renewable energy cannot guarantee future generations' energy needs, it has become fundamentally important to consider both wind and solar farms to minimize intermittency problems. Based on the sustainable development goals for exploiting renewable energies, environmental sustainability and social welfare, indexes are incorporated into DSS for the identification of appropriate hybrid solar and wind generation sites (Aktas and Kabak 2019). It is feasible to develop both wind and solar farms at the same physical location (Ali et al. 2019).

There have been many studies regarding renewable energy plant site planning. Moradi et al. (2020) employed GIS and AHP as DSS for wind farm site selection in Alborz Province, Iran. Their research outcomes indicated that this method has high functionality to divide the spatial problem into smaller ones to achieve reliable results for site selection. Xu et al. (2020) undertook site selection for wind farms by considering stochastic VIKOR and interval analytical hierarchy processes (IAHP). They concluded that the integration of two methods could handle effectively the variability of weights given to the relative importance of parameters and the main calculations for selecting the candidate sites connected with diverse indicators. Koc et al. (2019) used GIS and AHP to identify desirable sites for solar and wind energy installations in Igdir Province, Turkey. They concluded that the best outcomes were obtained by comparing the results of the two methods. Dhunny et al. (2019) undertook wind and solar farm site selection by including fuzzy logic into the decision-making process. Their results showed that fuzzy logic assisted in the aggregation of qualitative and quantitative results for finding optimal locations.

Ali et al. (2019) applied GIS and MCDA, such as AHP, to determine areas that have the suitability for wind and solar installations in Thailand, advocating an integrated approach. Díaz-Cuevas et al. (2019) utilized an approach employing AHP and WLC in a GIS environment. They found this method useful for more sensibly prioritizing wind, solar, and biomass farm locations in Southern Spain. Uyan (2017) used GIS and AHP to optimize suitable locations for solar power plants in Karaman, Turkey. He found that the GIS-based MCE approach was a useful technique to determines feasible sites for solar farms from a range of alternatives.

Anwarzai and Nagasaka (2017) used MCDA and GIS to assess wind and solar energy farm locations in Afghanistan. They showed that the incorporation of MCDA applications in the ArcGIS environment could make a significant difference in determining better sites for energy development. Jahangiri et al. (2016) utilized Boolean logic to identify appropriate sites for the establishment of solar and wind power plants in the Middle-East. Their results indicated that this method was a more definitive approach to locate areas that have potential for energy exploitation. Watson and Hudson (2015) employed a GIS-based multi-criteria evaluation using Boolean logic and AHP to analyze the suitability of areas for large-scale wind and solar farm site assessments in England. They found that this method has the ability to make a significant contribution to the site selection process for renewable energy facilities in coastal regions. In a similar study, Janke (2010) used a GIS-based model using multi-criteria approaches to examine the potential areas for wind and solar farms in Colorado State, USA. The research results demonstrated that wind energy is more beneficial for large-scale farms, while solar power plants are more suited to small-scale farms.

As demonstrated above, the use of a decision support tool (or tools) to assist in site determination for renewable energy systems (RES) is now common. The main contribution and novelty of this study is the comparison and investigation of the diverse strategic, computer-based DSS available, and their use in combinations that can be implemented by experts and environmental authorities to help determine the best sites for RES location.

This research focuses on three objectives, and uses the case of Isfahan Province, Iran as a case study. Firstly, we identify areas that are environmentally preferred for the location of wind and solar farms. Secondly, we consider land use, where a balance between renewable energy expansion and environmental conservation must be considered and achieved, and where there must be a high-degree of community acceptance. Thirdly, we identify for the study area the optimal sites for wind and solar energy facility development. To achieve these goals, the most flexible and inclusive DSS for wind and solar power plant site selection are considered.

Site selection criteria

Site selection for wind and solar farms needs to incorporate a wide range of criteria to optimize electricity production and the protection of natural environments. As the goals of energy efficiency and environmental conservation are inextricably intertwined (Díaz-Cuevas et al. 2019), it is imperative to integrate both environmental and socioeconomic factors into decision-making to enable the generation of the required energy as well as respecting the natural ecosystems (Jahangiri et al. 2016).

Renewable energy farms should be at locations distant from protected areas. Areas which are prone to floods and soil erosion, and where there are steep slopes or nearby active faults should be excluded. Optimal sites should be in close proximity to power transmission lines and transport networks to avoid excess costs and maximize efficacy (Solangi et al. 2019). Obviously and most importantly, solar radiation and wind speed are key drivers for solar and wind renewable energy farm site selection. Potential sites for wind and solar energy farms are selected by considering several environmental specifications (Table 1) including wind speed, potential solar radiation, slope, probability of flooding, distance from faults, soil texture, geological formations, and distance from rivers. Protected areas, with high biodiversity values, are removed from consideration as possible sites. Socioeconomic factors (Table 1) such as distance from power transmission lines, distance from population centers, land use/cover, and distance from roads are incorporated in the analysis (Anwarzai and Nagasaka 2017). The importance of various parameters for site selection was determined through consultation with professional environmental and energy experts and scrutinizing reputable international publications on the identification of wind and solar farm sites. It has been universally recognized that the environmental and socioeconomic factors have different priorities (Dhunny et al. 2019) but with many commonalities, which may vary depending on local conditions. Data sources used for the parameters in this study are indicated: (1) Digital Elevation Model (DEM) derived from Isfahan Province Management and Planning Organization (2018); (2) Iran Energy Efficiency Organization (2018); (3) The World Bank (2017); (4) (5) (6) (7) (8) (9) (10) (11) (12) (13) Isfahan Province Management and Planning Organization (2018).

Materials and methods

The study area

The study area, Isfahan Province, is in the center of Iran. It covers an area of 107,017 square kilometers. The climate is generally described as arid and semi-arid, although there are a variety of physiographic regions. Due to densely populated cities and many industrial centers, satisfying the energy demands of the inhabitants of Isfahan is important (Zoghi et al. 2017). There are valuable wetlands and protected areas with high ecological values, in particular Ghomishloo National Park, Gavkhouni Wetland, Mouteh Wildlife Refuge, and Kolah Ghazi National Park, which must be considered and protected when renewable energy power plant site selection is undertaken. It is generally believed that solar radiation and wind speed are sufficiently high for renewable energy to provide for the sustainable development goals of the province (Noorollahi et al. 2016). Figure 1 shows the location of Isfahan Province in Iran, and Fig. 2 is a land-use map of the study area.

Methodology

Fuzzy logic

The first stage of the research was to identify the most effective criteria and sub-criteria concerning wind and solar farms site evaluation through a comprehensive literature review. This was supplemented using the international standards and regulations required for renewable energy spatial planning (Yushchenko et al. 2018). After identifying the ecological and socioeconomic parameters for renewable energy site evaluation, each sub-criteria or spatial factor was quantified into obtain raster layers. This was implemented with the pixel size of 10×10 m using the raster analysis operator of ArcGIS 10.7 software (Asakereh et al. 2017) in the coordinate system WGS 1984/UTM Zone 39.

For solar energy, the long-term yearly average of diffuse horizontal irradiance (DHI) based on kilowatt-hours per square meter (KWh/m^2), covering the period of 1999–2015 was sourced from The World Bank (2017), who used satellite digital images and atmospheric datasets. Solar energy of at least 1500 kWh/m^2/year is suitable. Wind energy was monitored by field measurements at large-scale (country level). Wind data were collected at 161 locations over the entire country (Iran) including 10 locations in Isfahan Province, and normalized to average annual wind speed 80 m above the ground (hub height). An inverse distance weighting (IDW) method was used to generate a wind raster map (Iran Energy Efficiency Organization 2018). Data for other parameters were obtained from Isfahan Province Management and Planning Organization (2018). Then, the raster layers of each parameter were standardized by applying a fuzzy membership function normalizing raster factors between the scales of 0 and 1, which relies heavily on fuzzy function types, whether it is increasing or decreasing (see below), for site suitability preferences (Wu et al. 2018). Table 2 shows the indicator parameters for wind and solar energy power plant site selection that were used.

In the fuzzy standardization method, the “membership” of a pixel in the raster map is evaluated from zero (lack of full membership) to one, (full membership). On

Table 1 The environmental, social, and economic criteria and sub-criteria for wind and solar farm site selection (Ali et al. 2019; Dhunny et al. 2019; Díaz-Cuevas et al. 2019; Nait Mensour et al. 2019; Solangi et al. 2019; Zoghi et al. 2017)

Criterion	Sub-criteria	Description	Data source
Environmental	Slope[1]	One of the natural factors with a significant impact on the selection of the optimum location of wind and solar power plants is the land slope. This is because the land potential for wind and solar energy usage, as well as wind and solar energy input, changes depending on the slope. Areas with slopes of 3–5% are the most appropriate sites for wind and solar power plants (Ali et al. 2019; Zoghi et al. 2017)	Digital elevation model (DEM) derived from Isfahan Province Management and Planning Organization (2018)
	Wind speed[2]	Wind speed is the first and the most fundamental variable with respect to wind energy potential and its assessment. Annual wind speed average, wind power density, and percentage of windy days are very important features for choosing a site for wind power plants. A wind speed map plays an important role in the selection of the optimal sites for the wind farms and this is the most influential factor supporting the financial evaluations of the installations. The range of 6–> 7 m/s for wind energy is suitable for site selection because it has been identified as achieving the best performance for wind turbines. This means that a minimum threshold of 6 m/s for wind energy measured 80 m above the land surface is required, with speeds at or above 7 m/s being optimal (Ali et al. 2019)	Iran Energy Efficiency Organization (2018)
	Solar radiation[3]	Solar radiation is measured as the yearly amount of solar energy intake at one point on the earth's surface which depends on various factors including latitude, longitude, sunshine hours, humidity, evaporation, air temperature, angle of the sun, and other factors. The minimum required diffuse horizontal irradiance (DHI) is 1500 kWh/m^2/year, with DHI at or above 1500 kWh/m^2/year desirable to optimize power generation (Solangi et al. 2019)	The World Bank (2017)
	Distance from rivers[4]	Since land near rivers may be subject to the risk of flooding, remoteness from the river will increase the safety of the construction project. A minimum distance of 500 m from rivers is considered appropriate (Nait Mensour et al. 2019)	Isfahan Province Management and Planning Organization (2018)
	Flooding[5]	Floods are among the most frequent natural phenomena that can jeopardize the safety of construction projects in riverine locations. To identify the flooding potential for the site, it is vital to know the topographic features of the region. In selecting sites, areas located on flood plains are generally unsuitable (Díaz-Cuevas et al. 2019)	Isfahan Province Management and Planning Organization (2018)
	Distance from fault lines[6]	Wind and solar power plants like other construction projects should be remote from fault lines. Faults that may be active must be at least 500 m from a site for both wind or solar energy systems (Zoghi et al. 2017; Noorollahi et al. 2016)	Isfahan Province Management and Planning Organization (2018)

Table 1 (continued)

Criterion	Sub-criteria	Description	Data source
	Soil texture[7]	The selection of suitable sites with the best soil texture is an important engineering decision in construction projects. Clayey textures, for example, are often more stable than sandy textures because they have a more suitable structure. Soil maps are a useful tool for helping decision-makers to determine the best location for renewable energies projects (Dhunny et al. 2019)	Isfahan Province Management and Planning Organization (2018)
	Geological formations[8]	Local geology must be considered with respect to providing the best foundations for the building of wind and solar energy farms (Dhunny et al. 2019)	Isfahan Province Management and Planning Organization (2018)
	Distance from wetland and protected areas[9]	Wetlands and protected areas, including protective buffers, are entirely unsuitable for the construction of wind and solar power plants. Sites at least 500 m distant may be considered in the analysis (Nait Mensour et al. 2019)	Isfahan Province Management and Planning Organization (2018)
Social	Distance from population centers[10]	Since cities are one of the main consumers of power, proximity to residential areas is an important factor in selecting the optimum locations of solar power plants. Electric power distribution costs and energy dissipation can be reduced by proximity to cities. Locating renewable energy facilities near residential areas can, however, cause adverse environmental impacts on the human communities. For this reason, areas at the distance of at least 500 m from residential areas are considered suitable (Díaz-Cuevas et al. 2019; Zoghi et al. 2017; Uyan 2017)	Isfahan Province Management and Planning Organization (2018)
Economic	Distance from roads[11]	Transport is one of the most important criteria for locating industries. The proximity to roads will reduce transportation costs of power plant equipment, personnel transport, and plant support. A distance of less than 500 m from roads is regarded as appropriate for wind and solar energy installations (Nait Mensour et al. 2019)	Isfahan Province Management and Planning Organization (2018)
	Distance from power transmission lines[12]	Solar and wind power plants require access to the transmission grid, and the grid connection is typically at high voltage. The high cost associated with constructing power transmission lines means that proximity to existing transmission lines avoids additional capital cost and power losses. However, due to environmental and efficiency considerations, wind or solar farms should be located at a minimum distance of 500 m from power transmission lines so that an efficient function affecting transmission lines will increase the safety of the energy facilities or protect the environment. A minimum threshold of 500 m would be required to avoid energy loss and to increase the productivity of power generation (Zoghi et al. 2017; Noorollahi et al. 2016)	Isfahan Province Management and Planning Organization (2018)

Table 1 (continued)

Criterion	Sub-criteria	Description	Data source
	Land use/cover[13]	In terms of ecological value and potential, as well as their role in environmental quality and agricultural/industrial production, the land use of regions is considered (Díaz-Cuevas et al. 2019)	Isfahan Province Management and Planning Organization (2018)

this scale, larger numbers are more desirable. There are diverse approaches for fuzzy standardization of data layers using minimum and maximum values. The logical way is using a linear scale, which has been applied to this study. The fuzzy membership approach using this method functions differently for any particular variable based on decreasing or increasing functions (Barzehkar et al. 2016). Some parameters such as slope, and distance from population centers, power transmission lines and roads, are of a decreasing type. This means that between a minimum threshold (a) and a maximum threshold (b) which is acceptable, the number assigned decreases. An increasing type is the opposite. Distance from rivers, fault lines and protected areas are of increasing type, which indicates that the anything above the maximum threshold is also suitable. Formulas (1) and (2) show how to calculate the fuzzy standardized degree. For example, for distance from fault lines, "a" is 500 m, which means less than 500 m from the fault lines is not acceptable and gives zero number. The number "b" is 1000 m and is assigned the value 1, and distances greater than 1000 m are also suitable and assigned the value 1. The fuzzy standardization of other parameters based on Table 2 was also calculated using Eqs. (1) and (2), where X_i is the value assigned to the fuzzy standardized layer, R_i is raw score of each pixel of the map, $R_{\min}$ is the minimum threshold and $R_{\max}$ is the maximum threshold, and whether the parameter is of increasing or decreasing type is shown in Table 2.

$$X_i = \frac{R_i - R_{\min}}{R_{\max} - R_{\min}} \tag{1}$$

$$X_i = \frac{R_{\max} - R_i}{R_{\max} - R_{\min}} \tag{2}$$

AHP approach

Because the significance of different factors varies based on experts' knowledge, it was crucially important to assign weights to each sub-criterion using the AHP before employing the WLC method. One of the most popular decision-making tools, an analytical tool based on super decision software (SDS) for prioritizing and weighting various factors, was used (Uyan 2017). The SDS was utilized to obtain the final weights of each parameter by applying a pairwise comparison matrix of distinct elements. Before implementing this vital step, the comments of highly qualified environmental and energy experts were sought using questionnaires regarding the relative importance of different parameters (values from 1 to 9). As can be seen from Table 3, twenty experts from the Iran Energy Efficiency Organization and

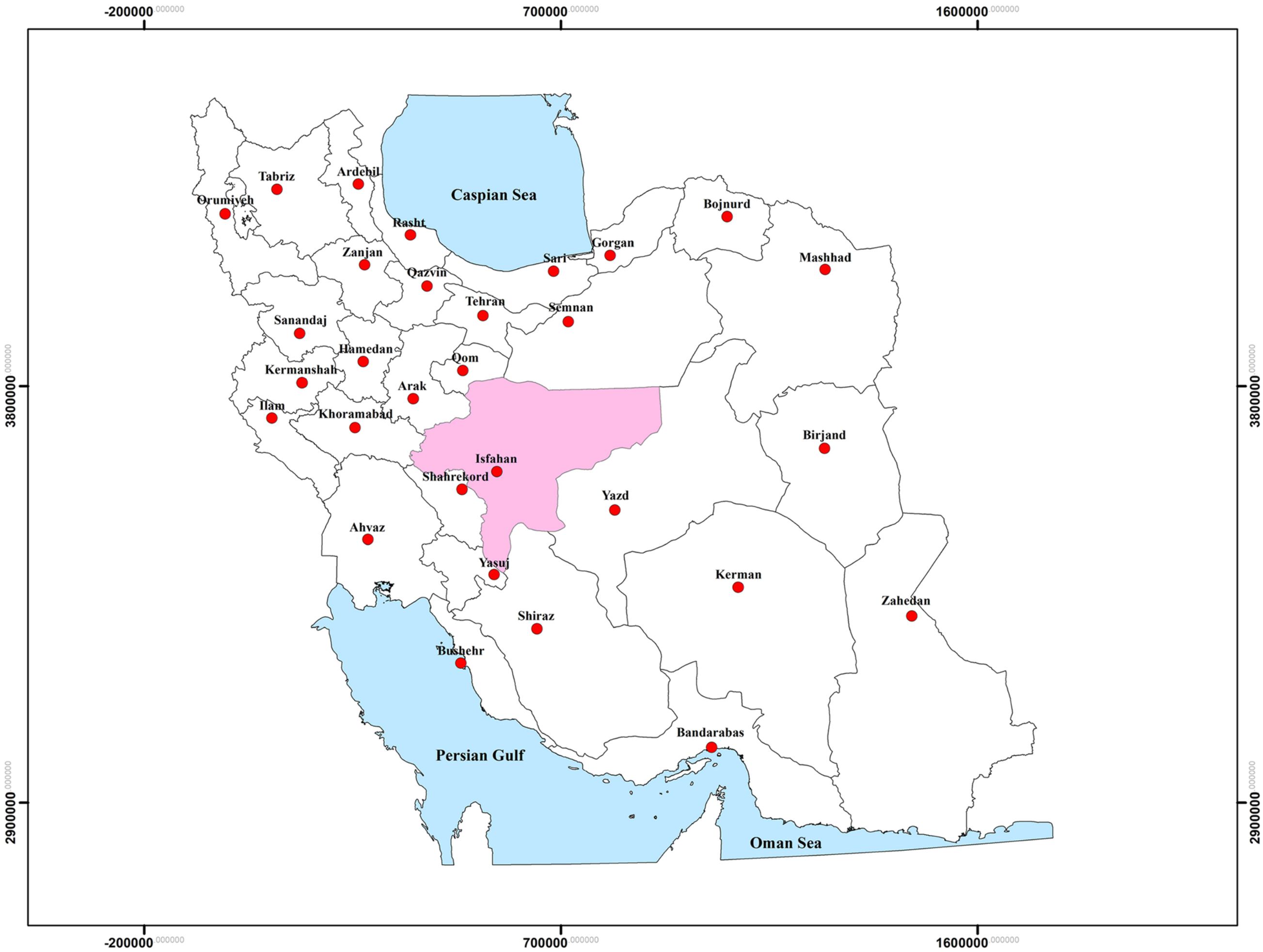


Fig. 1 Location of Isfahan Province (in pink), Iran (Isfahan Province Management and Planning Organization (2018))

Iran's Department of Environment, plus five others from academic institutions chosen based on their expertise were asked to prioritize factors. A matrix was developed based on the geometric mean values of the expert opinions, which reflects the importance of each factor compared to other factors. As shown in Table 4, for example, the distance from a protected area is 2 times more important than land use when assessing the sites of wind farms. The geometric mean of the responses to the questionnaires was utilized as an input to the super decisions software to attain the final weights of ecological and socioeconomic sub-criteria (Davtalab and Alesheikh 2018). Inconsistency between expert judgments was determined by obtaining an inconsistency ratio (IR) among a variety of factors. IR is determined by energy experts and environmental specialists using a prioritization process of parameters in SDS (Aydin et al. 2013). An IR > 0.1 represents a low evaluation of the criteria and the outcomes should not be accepted, while IR ≤ 0.1 indicates a consistency between specialists' judgments and the results are acceptable.

Table 5 represents the priorities of decision-makers for ranking of site selection factors concerning the importance of each parameter to others based on the scale 1–9.

WLC approach

One of the most widely used methods for the combination of different raster layers in ArcGIS is to employ the WLC approach (Barzehkar et al. 2016). In the following stage, the determination of the final site suitability map for either wind or solar farms was carried out by multiplying each fuzzy standardized factor and its weight, and aggregation of all factors using the raster analysis function based on WLC method in ArcGIS (Tavana et al. 2017). The multi-criteria evaluation (MCE), which was used in this research, used Eq. (3) (Ali et al. 2019) below, where S is the site suitability of the region, W_i is the relative weight of the sub-criteria, X_i is the fuzzy standardized layer, and n is the number of sub-criteria (Ali et al. 2019). Figure 3 shows the steps for wind and solar farms

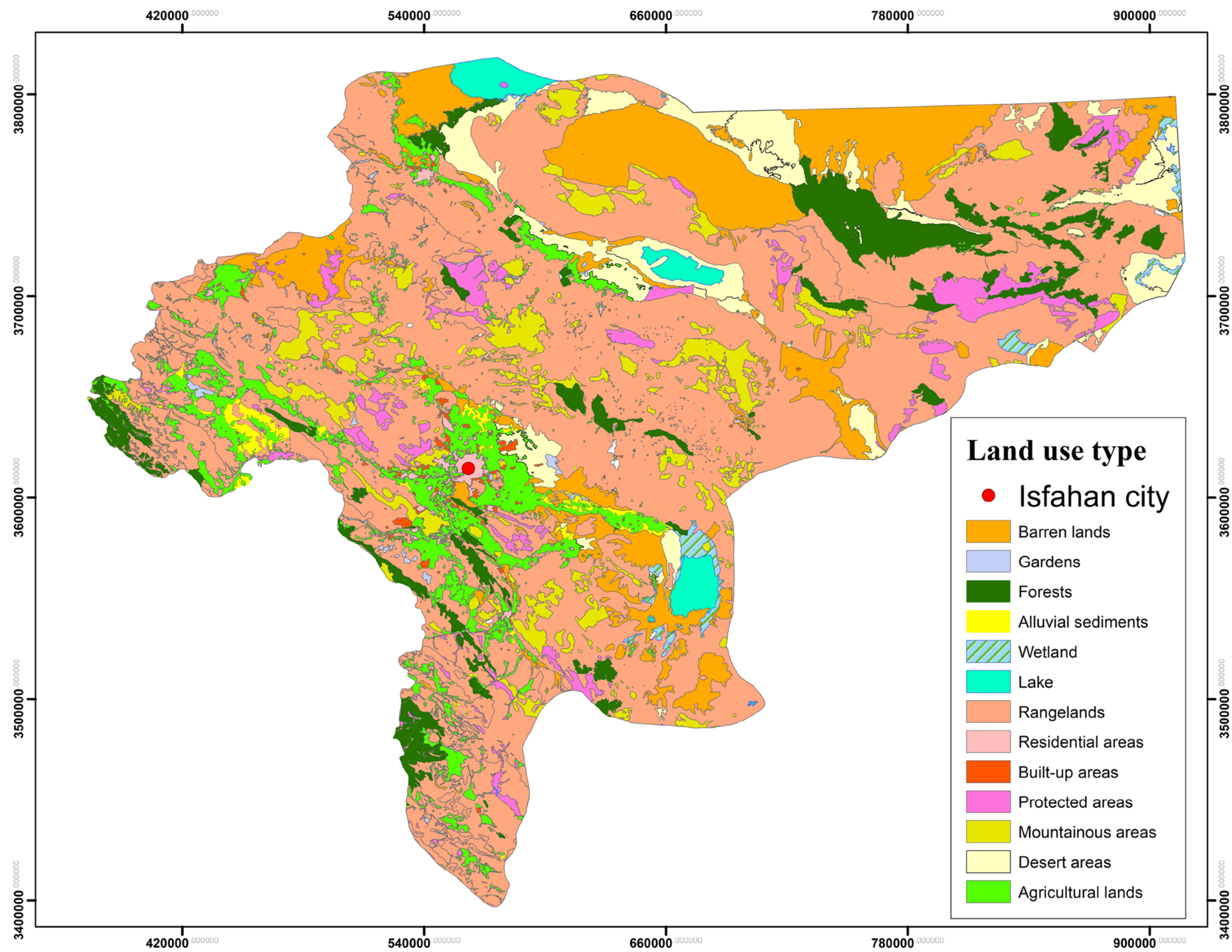


Fig. 2 Land-use map of Isfahan Province, Iran (Isfahan Province Management and Planning Organization (2018))

site selection using the fuzzy logic and WLC method in Isfahan Province.

$$S = \sum_{i=1}^{n} X_i W_i \tag{3}$$

Results and discussion

In this study, integration of GIS, multi-criteria evaluation based on AHP, fuzzy membership functions and the WLC approach has been employed to investigate and identify which sites have the feasibility to become wind and solar power plant locations. Since either wind or solar energy alone might not be able to address the energy shortages in a society and owing to the unpredictability of climate conditions in each region of Isfahan, both are considered.

An integrated site selection process is the best strategic decision-making system to equally prioritize both environmental protection goals and demands for socioeconomic development. An efficient site selection strategy could strengthen coordination in environmental conservation measures especially among energy efficiency organizations and other governmental corporations. Consequently, the land-use conflicts between renewable energy development

Table 2 Threshold values and fuzzy membership function to standardize different layers in fuzzy logic for (a) solar farm (Nait Mensour et al. 2019; Doorga et al. 2019; Solangi et al. 2019; Ali et al. 2019; Tavana et al. 2017) and (b) wind farm (Konstantinos et al. 2019; Díaz-Cuevas et al. 2019; Ali et al. 2019; Rezaian and Jozi 2016; Azizi et al. 2014), site selection

Row	Environmental and socioeconomic layers	Suitability	Threshold value		Type of the fuzzy membership function
			Minimum threshold a	Maximum threshold b	
1	Slope	3–5%	3%	5%	Decreasing
2a	Solar radiation	1500–2000 kWh/m^2/year	1500 kWh/m^2/year	2000 kWh/m^2/year	Increasing
2b	Wind speed	6–7 m/s	6 m/s	7 m/s	Increasing
3	Distance from rivers	500–1000 m	500 m	1000 m	Increasing
4	Flooding	Areas outside the flood plain	–	–	User-defined
5	Distance from fault lines	500–1000 m	500 m	1000 m	Increasing
6	Soil texture	Clay and silt clay textures	–	–	User-defined
7	Geological formations	Igneous, metamorphic, and sedimentary rocks	–	–	User-defined
8	Distance from wetland and protected areas	500–1000 m	500 m	1000 m	Increasing
9	Distance from population centers	500–2000 m	500 m	2000 m	Increasing
10	Distance from roads	500–2000 m	500 m	2000 m	Decreasing
11	Distance from transmission lines	500–1000 m	500 m	1000 m	Decreasing
12	Land use	Barren lands and areas with very low plant density	–	–	User-defined

Table 3 Demographics of the experts used for prioritizing the relative importance of parameters

	Governmental departments	University
Male/female (number)	13/7	3/2
Age range (years)	30–57	38–60
Education (degree)	Bachelors, Masters, PhD	PhD
Field of expertise	Energy management Energy engineering Environmental planning and management Environmental protection and education Environmental impact assessment	Land-use planning Environmental impact assessment

and environmental preservation would be substantially reduced.

Experts' perspectives, together with international regulations, were used for determining the parameters for wind and solar energy power plant site selection. Not surprisingly, experts and decision-makers assigned the highest weights to wind speed and solar radiation. Distance from power transmission lines and distance from population centers were of secondary importance. Soil texture and geological formations had the lowest priorities, based on the specialists' perceptions.

Figure 4 shows the final weights and priorities assigned to the environmental and socioeconomic factors for wind farm site selection, and Fig. 5 presents the final weights and priorities assigned to the environmental and socioeconomic factors for solar farm site selection.

Figure 6 shows results from the fuzzy logic and WLC approach for wind farm site selection (range 0.015–0.9), and Fig. 7 shows the results for solar farm site selection (range 0.068–0.88). In this research, the IR was calculated to be 0.09 in the super decision software environment for the ecological and socioeconomic parameters of wind and solar power plants site evaluation. The consistency between experts' perspectives is acceptable. The final suitability map for either wind or solar farms was classified into five categories shown in Tables 6 and 7. For wind energy, 18% of the province has high suitability, and for solar energy 26% has high suitability.

In this research, fuzzy logic and WLC approach are employed to standardize the environmental and socioeconomic raster layers and the aggregation of them,

Table 4 Pairwise comparison matrix of parameters for wind and solar farm site selection

Parameters for wind and solar farm site selection	Pairwise comparison matrix												
	Slope	Wind speed	Solar radiation	Distance from river	Flooding	Distance from fault lines	Soil texture	Geological formations	Distance from wetland and protected areas	Distance from population centers	Land use	Distance from transmission lines	Distance from roads
Slope	1	1/6	1/8	1	1/3	2	3	3	1/6	1/6	1/5	1/6	1/5
Wind speed	6	1	1	6	4	7	8	8	4	4	5	4	5
Solar radiation	8	1	1	7	5	7	9	9	5	5	6	5	6
Distance from river	1	1/6	1/7	1	1/4	4	6	6	1/6	1/6	1/5	1/6	1/5
Flooding	3	1/4	1/5	4	1	5	7	7	1/5	1/5	1/4	1/6	1/3
Distance from fault lines	1/2	1/7	1/7	1/4	1/5	1	3	3	1/7	1/7	1/5	1/7	1/5
Soil texture	1/3	1/8	1/9	1/6	1/7	1/3	1	1	1/8	1/8	1/7	1/8	1/7
Geological formations	1/3	1/8	1/9	1/6	1/7	1/3	1	1	1/8	1/8	1/7	1/8	1/7
Distance from wetland and protected areas	6	1/4	1/5	6	5	7	8	8	1	1	2	1	2
Distance from population centers	6	1/4	1/5	6	5	7	8	8	1	1	3	1	2
Land use	5	1/5	1/6	5	4	5	7	7	1/2	1/3	1	1/3	1
Distance from transmission lines	6	1/4	1/5	6	6	7	8	8	1	1	3	1	3
Distance from roads	5	1/5	1/6	5	3	5	**7**	7	1/2	1/2	1	1/3	1

Table 5 The priorities of decision-makers for pairwise comparison of parameters (Saaty 1980)

Priorities of decision-makers	Numerical value
Extremely prioritized	9
Less important than the above priority	8
Very strongly prioritized	7
Less important than the above priority	6
Strongly prioritized	5
Less important than the above priority	4
Moderately prioritized	3
Less important than the above priority	2
Equally prioritized	1
Less important than the above priority	1/2
Moderately unprioritized	1/3
Less important than the above priority	1/4
Strongly unprioritized	1/5
Less important than the above priority	1/6
Very Strongly unprioritized	1/7
Less important between the above priority	1/8
Extremely unprioritized	1/9

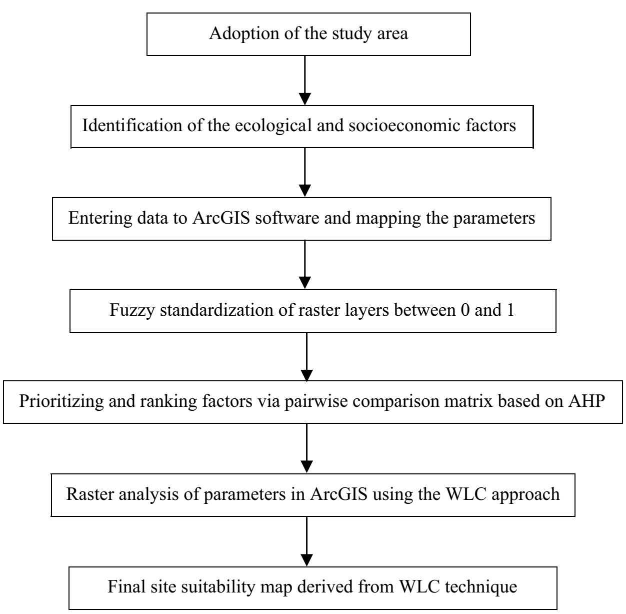


Fig. 3 Steps for wind and solar farms site selection using fuzzy logic and WLC method

respectively, leading to an estimate of the degree of site suitability on a continuous scale. The high class of land suitability is located in the areas where the probability of flooding is low, with low permeable soils such as clay, and which are far from the wetland and protected areas, fault lines and rivers. The potential locations are also located in the areas with proximity to cities, roads, and transmission lines, which is logical to guarantee the socioeconomic benefits of energy generation for the community. The suitable sites for wind farms are influenced by the wind speed of 6–7 m/s, and the appropriate sites for solar farm are influenced by a DHI of 1500–2000 kWh/m^2/year.

The previous studies implemented by Díaz-Cuevas et al. (2019) and Anwarzai and Nagasaka (2017) suggested that the combination of WLC, AHP, and GIS would be useful for ranking the potential sites of wind and solar farm. In this research, the application of fuzzy logic is also used to standardize the raster maps on a wider scale (from 0 to 1). This gives the decision-makers more choice with better information when considering wind and solar farm site selection. The fuzzy membership functions are also effective in reducing the uncertainty of site selection, by standardization of pixels in each raster layer. Therefore, the integration of fuzzy logic with AHP, WLC, and GIS is a flexible approach to the analysis of land suitability for either wind or solar energy.

As seen in Fig. 6, areas in the north and east of the province have generally higher suitability for wind farms than the areas located in south and west. The most suitable locations are generally areas that are sparsely populated with little vegetation, are distant from protected areas, and have generally higher wind speeds and a higher number of windy days. With respect to solar wind farm location, Fig. 7 shows that the north and east are even more favored than the south and west, with solar energy levels being higher than in other regions due to fewer cloudy and rainy days. For both wind and solar farm location, the north and east were also more favored by decision-makers than the south and west.

Using these methods, environmental authorities and planners have better tools to understand the energy generation capability of this diverse province, and increased ability to incorporate both environmental and socioeconomic capacity for renewable energy utilization into planning frameworks. Fuzzy logic, which has been utilized

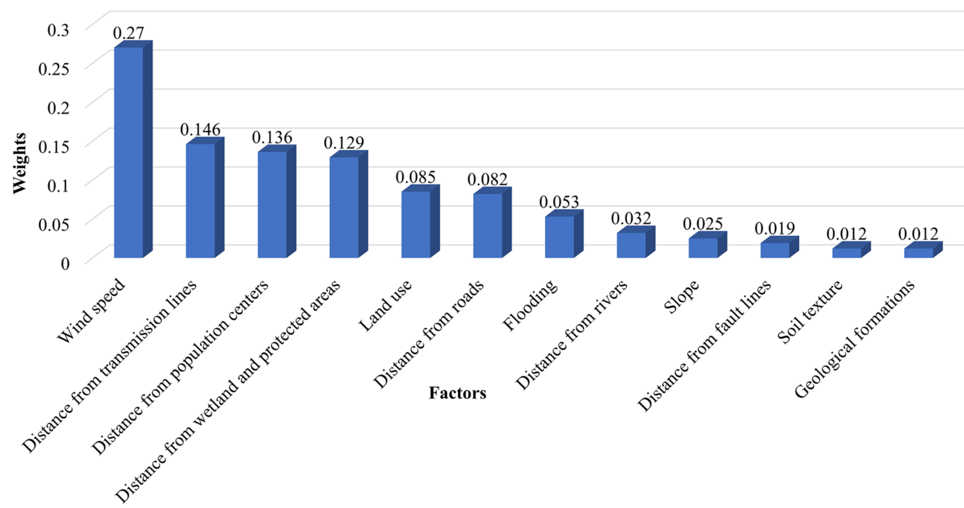


Fig. 4 Final weights and priorities assigned to the environmental and socioeconomic factors for wind farm site selection

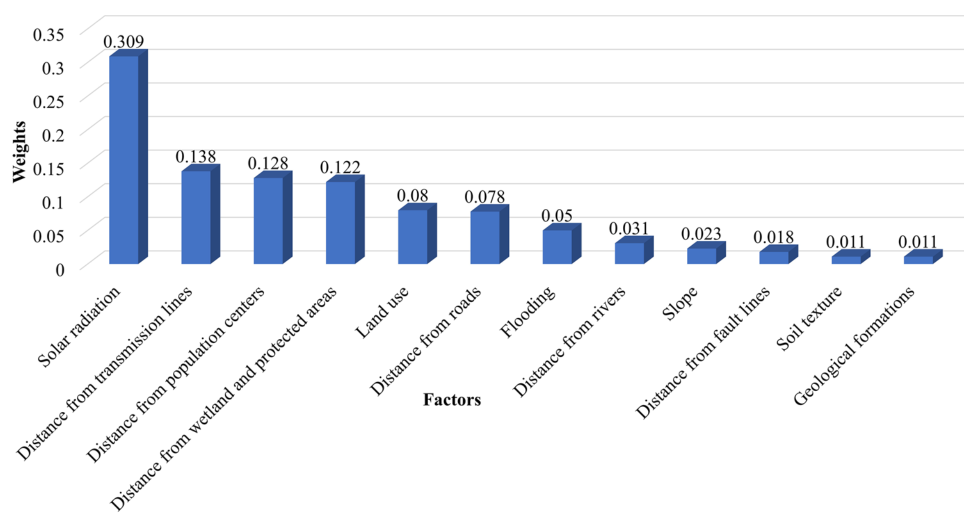


Fig. 5 Final weights and priorities assigned to the environmental and socioeconomic factors for solar farm site selection

in this study, is highly effective as a logical research framework for comparative assessment of possible sites of wind and solar power projects with great ability to handle the uncertainty of large-scale suitability analysis through the normalization of relevant factors. The appropriate prioritization of wind and solar farm sites is of importance with respect to land use for environmental protection and energy development. The proposed fuzzy approach, coupled with AHP, WLC, and GIS, is useful in ranking the suitability of different candidate sites. It has also been determined that the outcomes of an integrated approach, through the combination of diverse decision-making tools, may provide better information than using single tools.

Conclusions

This study highlights a combination of desirable decision support tools that encompass MCE based on AHP, fuzzy logic, the WLC method, and GIS models to formulate a meaningful research framework that incorporates environmental and socioeconomic data associated with site selection for wind and solar farm installations. The application of MCE enabled us to define a set of important parameters, which represent the site suitability for renewable energy power plants in the Isfahan Province, Iran. It may be possible to incorporate a wider variety of parameters including further ecological, social, and economic indicators to improve site selection even further.

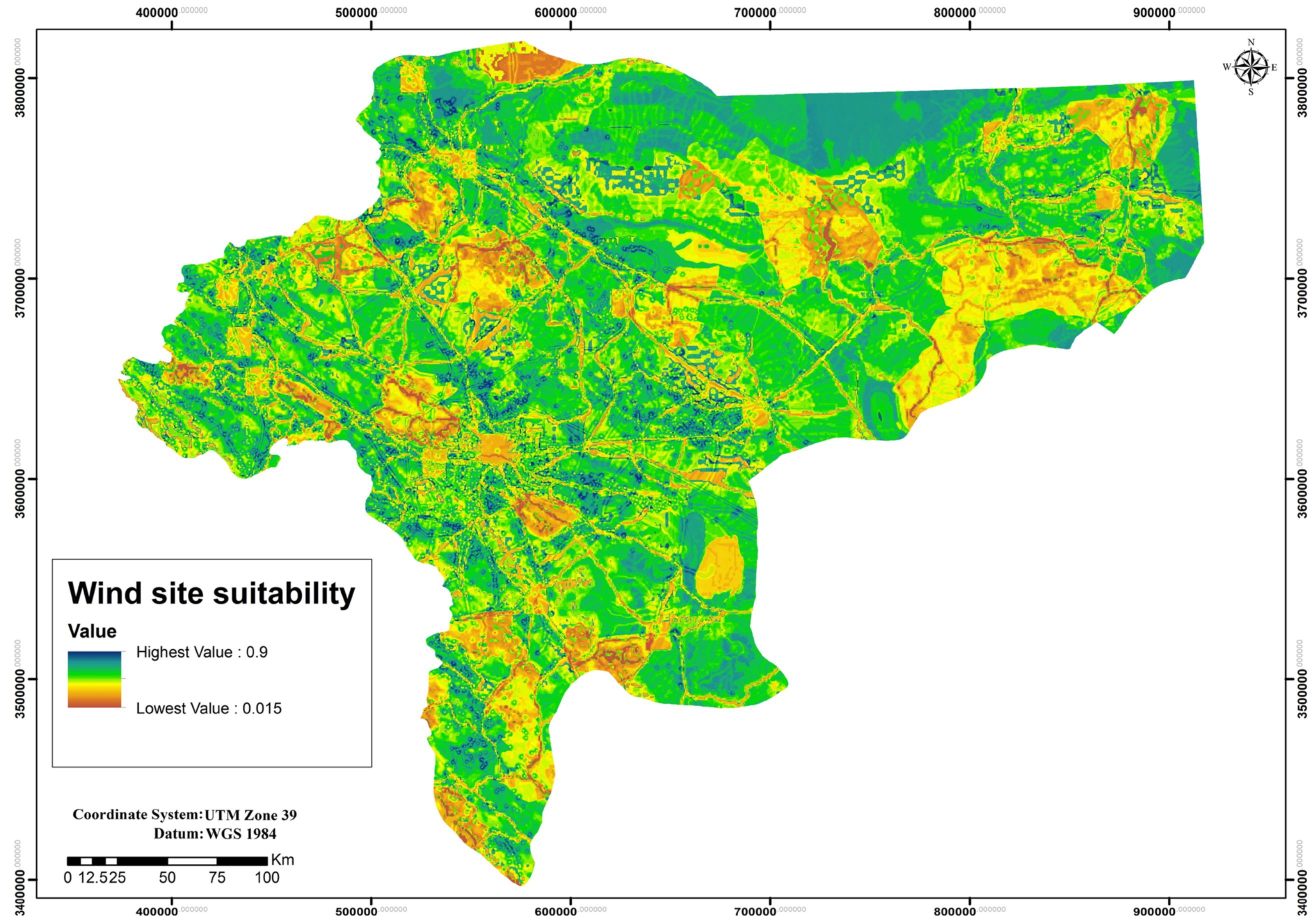


Fig. 6 Wind farm site suitability

The use of the high suitability sites selected may help rationalize the provision of energy to people in the community with protection of the environment for the next generations. Not only is this an intelligent problem-solving approach for decision-makers to tackle environmental issues of renewable energy system site selection, but it could also provide impetus for further development of wind and solar energy in a region.

It is concluded that the optimal energy systems are likely to be achieved by a mix of two or more renewable energy technologies to provide sustainable electricity in terms of satisfying the energy demands of people in the society and overcoming intermittency of supply, as well as providing a cost-effective way for energy expansion. Blended decision support tools lead to more satisfactory and flexible environmental planning decisions. In this study, three main criteria and 12 sub-criteria for wind or solar farms were applied to the decision-making process, with the north and east of the province being found to be generally more suitable for both solar and wind farm location than the south and west, but with considerable local variability within the regions. The number of parameters considered can be increased in future research to enhance the performance of the site evaluations.

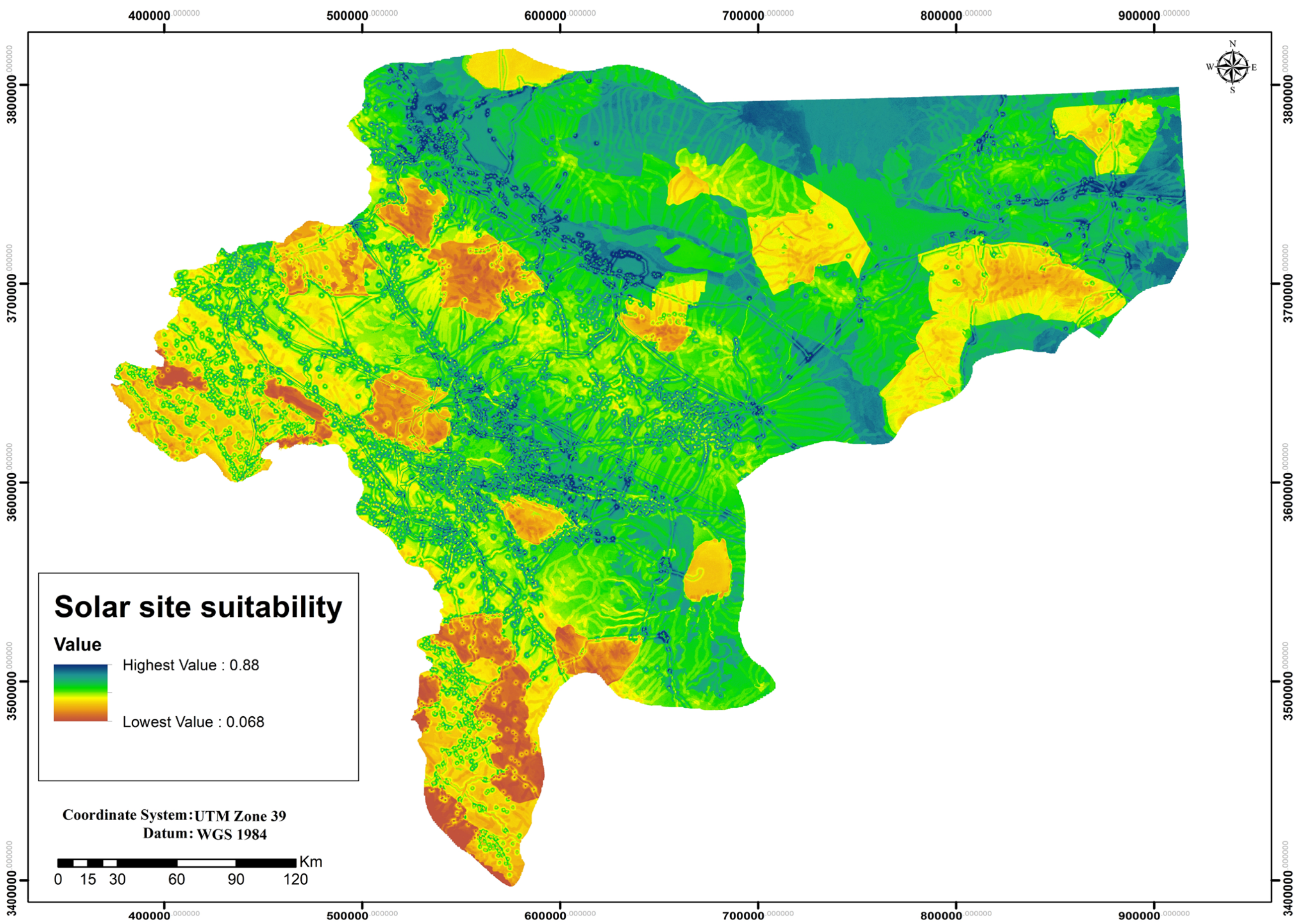


Fig. 7 Solar farm site suitability

Table 6 Land suitability as a percentage of the area of Isfahan Province for wind farm site selection using the fuzzy logic and WLC approach

Class of suitability	Area (km^2)	Percentage of area (%)
Very Low	15,771	15
Low	31,494	29
Moderate	40,959	38
High	18,793	18
Sum of Suitability	107,017	100

Table 7 Land suitability as a percentage of the area of Isfahan Province for solar farm site selection using the fuzzy logic and WLC approach

Class of suitability	Area (km^2)	Percentage of area (%)
Very low	7656	7
Low	26,813	25
Moderate	44,929	42
High	27,619	26
Sum of suitability	107,017	100

Acknowledgments We would like to express our thanks from Dr. Reza Samadi of the Energy Efficiency Organization of Iran for assisting us with this project. Analysis and preparation of the final paper were supported by the European Regional Development Fund program Mobilitas Plus, reg.nr 2014-2020.4.01.16-0024 and Estonian Research Council Grant IUT33-3.

Data availability Data can be made available upon request.

Code availability Not applicable.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there are no conflicts of interest for this project.

Ethical approval All those that answered the questionnaire were acting in their professional capacity and agreed to participate. Data gathered were anonymized, and no participants can be individually recognized.

Consent for publication The corresponding author states that the manuscript has not already been submitted to another Journal and it is a new work regarding decision support tools for wind and solar farm site selection. All the authors have approved the submission of the manuscript to Clean Technologies and Environmental Policy.

References

Aktas A, Kabak M (2019) A goal programming model for grid-connected hybrid energy system operations. SN Appl Sci 2:71. https://doi.org/10.1007/s42452-019-1878-1

Ali S, Taweekun J, Techato K, Waewsak J, Gyawali S (2019) GIS based site suitability assessment for wind and solar farms in Songkhla, Thailand. Renew Energy 132:1360–1372. https://doi.org/10.1016/j.renene.2018.09.035

Amjad F, Ali Shah L (2020) Identification and assessment of sites for solar farms development using GIS and density based clustering technique—a case of Pakistan. Renew Energy 20:304. https://doi.org/10.1016/j.renene.2020.03.083

Anwarzai MA, Nagasaka K (2017) Utility-scale implementable potential of wind and solar energies for Afghanistan using GIS multi-criteria decision analysis. Renew Sustain Energy Rev 71:150–160. https://doi.org/10.1016/j.rser.2016.12.048

Asakereh A, Soleymani M, Sheikhdavoodi MJ (2017) A GIS-based Fuzzy-AHP method for the evaluation of solar farms locations: case study in Khuzestan province, Iran. J Sol Energ 155:342–353. https://doi.org/10.1016/j.solener.2017.05.075

Aydin NY, Kentel E, Sebnem Duzgun H (2013) GIS-based site selection methodology for hybrid renewable energy systems: a case study from western Turkey. Energy Convers Manag 70:90–106. https://doi.org/10.1016/j.enconman.2013.02.004

Azizi A, Malekmohammadi B, Jafari HR, Nasiri H, Amini-Parsa V (2014) Land suitability assessment for wind power plant site selection using ANP-DEMATEL in a GIS environment: case study of Ardabil province, Iran. Environ Monit Assess 186:6695–6709. https://doi.org/10.1007/s10661-014-3883-6

Barzehkar M, Mobarghaee Dinan N, Salemi A (2016) Environmental capability evaluation for nuclear power plant site selection: a case study of Sahar Khiz Region in Gilan Province, Iran. J Environ Earth Sci 75:1016. https://doi.org/10.1007/s12665-016-5825-9

Baseer MA, Rehman S, Meyer JP, Mahbub Alam M (2017) GIS-based site suitability analysis for wind farm development in Saudi Arabia. J Energy 141:1166–1176. https://doi.org/10.1016/j.energy.2017.10.016

Davtalab M, Alesheikh AA (2018) Spatial optimization of biomass power plant site using fuzzy analytic network process. Clean Technol Environ Policy 20:1033–1046. https://doi.org/10.1007/s10098-018-1531-5

Dhunny AZ, Doorga JRS, Allam Z, Lollchund MR, Boojhawon R (2019) Identification of optimal wind, solar and hybrid wind-solar farming sites using fuzzy logic modelling. J Energy 188:116056. https://doi.org/10.1016/j.energy.2019.116056

Díaz-Cuevas P (2018) GIS-based methodology for evaluating the wind-energy potential of territories: a case study from Andalusia (Spain). Energies 11(10):2789. https://doi.org/10.3390/en11102789

Díaz-Cuevas P, Domínguez-Bravo J, Prieto-Campos A (2019) Integrating MCDM and GIS for renewable energy spatial models: assessing the individual and combined potential for wind, solar and biomass energy in Southern Spain. Clean Technol Environ Policy 21:1855–1869. https://doi.org/10.1007/s10098-019-01754-5

Doorga JRS, Rughooputh SDDV, Boojhawon R (2019) Multi-criteria GIS-based modelling technique for identifying potential solar farm sites: a case study in Mauritius. Renew Energy 133:1201–1219. https://doi.org/10.1016/j.renene.2018.08.105

Gasparovic I, Gasparovic M (2019) Determining optimal solar power plant locations based on remote sensing and GIS methods: a case study from Croatia. Remote Sens 11(12):1481. https://doi.org/10.3390/rs11121481

Giamalaki M, Tsoutsos T (2019) Sustainable siting of solar power installations in Mediterranean using a GIS/AHP approach. Renew Energy 141:64–75. https://doi.org/10.1016/j.renene.2019.03.100

Iran Energy Efficiency Organization (2018) Average annual wind energy speed at a height of 100 meters. In: Atlas of the country's renewable and clean energy sources, 1st edn. Tehran, pp 80–85

Isfahan Province Management and Planning Organization (2018). Land use planning. http://www.mpo-es.ir/index.aspx?sub=11

Jahangiri M, Ghaderi R, Haghani A, Nematollahi O (2016) Finding the best locations for establishment of solar-wind power stations in Middle-East using GIS: a review. Renew Sustain Energy Rev 66:38–52. https://doi.org/10.1016/j.rser.2016.07.069

Janke JR (2010) Multicriteria GIS modeling of wind and solar farms in Colorado. Renew Energy 35:2228–2234. https://doi.org/10.1016/j.renene.2010.03.014

Koc A, Turk S, Sahin G (2019) Multi-criteria of wind-solar site selection problem using a GIS-AHP-based approach with an application in Igdir Province/Turkey. Environ Sci Pollut Res 26:32298–32310. https://doi.org/10.1007/s11356-019-06260-1

Konstantinos I, Georgios T, Garyfalos A (2019) A decision support system methodology for selecting wind farm installation locations using AHP and TOPSIS: case study in Eastern Macedonia and Thrace region, Greece. Energy Policy 132:232–246. https://doi.org/10.1016/j.enpol.2019.05.020

Moradi S, Yousefi H, Noorollahi Y, Rosso D (2020) Multi-criteria decision support system for wind farm site selection and sensitivity analysis: case study of Alborz Province, Iran. Energy Strateg Rev 29:100478. https://doi.org/10.1016/j.esr.2020.100478

Nait Mensour O, El Ghazzani B, Hlimi B, Ihlal A (2019) A geographical information system-based multi-criteria method for the evaluation of solar farms locations: a case study in Souss-Massa area, southern Morocco. Energy 182:900–919. https://doi.org/10.1016/j.energy.2019.06.063

Noorollahi E, Fadai D, Akbarpour Shirazi M, Ghodsipour SH (2016) Land suitability analysis for solar farms exploitation using GIS and fuzzy analytic hierarchy process (FAHP)—a case study of Iran. Energies 9:643. https://doi.org/10.3390/en9080643

Pambudi G, Nananukul N (2019) A hierarchical fuzzy data envelopment analysis for wind turbine site selection in Indonesia. Energy Rep 5:1041–1047. https://doi.org/10.1016/j.egyr.2019.08.002

Rezaian S, Jozi SA (2016) Application of multi criteria decision-making technique in site selection of wind farm—a case study of Northwestern Iran. J Indian Soc Remote 44(5):803–809. https://doi.org/10.1007/s12524-015-0517-6

Saaty TL (1980) The analytical hierarchy process, planning, priority setting, resource allocation (decision making serious), 1st edn. McGraw-Hill, New York, pp 154–155

Solangi YA, Ali Shah SA, Zameer H, Ikram M, Saracoglu BO (2019) Assessing the solar PV power project site selection in Pakistan: based on AHP-fuzzy VIKOR approach. Environ Sci Pollut Res 26:30286–30302. https://doi.org/10.1007/s11356-019-06172-0

Suuronen A, Lensu A, Kuitunen M, Andrade-Alvear R, Guajardo Celis N, Miranda M, Perez M, Kukkonen JVK (2017) Optimization of photovoltaic solar power plant locations in northern Chile. J Environ Earth Sci 76:824. https://doi.org/10.1007/s12665-017-7170-z

Tavana M, Santos Arteaga FJ, Mohammadi S, Alimohammadi M (2017) A fuzzy multi-criteria spatial decision support system for solar farm location planning. Energy Strateg Rev 18:93–105. https://doi.org/10.1016/j.esr.2017.09.003

The World Bank (2017) Longterm yearly average of diffuse horizontal irradiation—Islamic Republic of Iran. Solargis 19115:2003/19139

Uyan M (2017) Optimal site selection for solar power plants using multi-criteria evaluation: a case study from the Ayranci region in Karaman, Turkey. Clean Technol Environ Policy 19:2231–2244. https://doi.org/10.1007/s10098-017-1405-2

Villacreses G, Gaona G, Martínez-Gómez J, Juan Jijón D (2017) Wind farms suitability location using geographical information system (GIS), based on multi-criteria decision making (MCDM) methods: the case of continental Ecuador. Renew Energy 109:275–286. https://doi.org/10.1016/j.renene.2017.03.041

Watson JJW, Hudson MD (2015) Regional Scale wind farm and solar farm suitability assessment using GIS-assisted multi-criteria evaluation. Landsc Urban Plan 138:20–31. https://doi.org/10.1016/j.landurbplan.2015.02.001

Wu B, Yip TL, Xie L, Wang Y (2018) A fuzzy-MADM based approach for site selection of offshore wind farm in busy waterways in China. Ocean Eng 168:121–132. https://doi.org/10.1016/j.oceaneng.2018.08.065

Xu Y, Li Y, Zheng L, Cui L, Li S, Li W, Cai Y (2020) Site selection of wind farms using GIS and multi-criteria decision making method in Wafangdian, China. Energy 207:118222. https://doi.org/10.1016/j.energy.2020.118222

Yushchenko A, de Bono A, Chatenoux B, Kumar Patel M, Ray N (2018) GIS-based assessment of photovoltaic (PV) and concentrated solar power (CSP) generation potential in West Africa. Renew Sustain Energy Rev 81:2088–2103. https://doi.org/10.1016/j.rser.2017.06.021

Zoghi M, Ehsani AH, Sadat M, Amiri MJ (2017) Optimization solar site selection by fuzzy logic model and weighted linear combination method in arid and semi-arid region: a case study Isfahan-IRAN. Renew Sustain Energy Rev 68:986–996. https://doi.org/10.1016/j.rser.2015.07.014