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Onshore Wind Farm Suitability Analysis Using GIS-based Analytic Hierarchy Process: A Case Study of Fukushima Prefecture, Japan

Ahmed Derdouri^{1*} and Yuji Murayama²

Abstract

Fukushima prefectural government adopted a vision to become 100% renewable energy self-sufficient by 2040. Wind stands firm as one of the important renewable energy sources in the prefecture as it has a huge onshore potential that has not been exploited yet. The purpose of this study was to identify and evaluate the suitable locations for the sitting of onshore wind facilities in Fukushima prefecture based on a suggested framework that combines Geographical Information Systems (GIS) and Multi-Criteria Decision Making (MCDM) approach namely Analytic Hierarchy Process (AHP). The framework consisted of three key steps: First, we excluded all areas where wind farms cannot be installed due to law or landscape constraints. Second, we identified nine criteria influencing the suitability of areas for wind energy. These criteria were classified into three categories (environmental, social, and economic) and their significance weights in site assessment process were calculated by applying AHP approach based on opinions of local wind energy experts and stakeholders. Consequently, we evaluated areas according to their suitability. The third and the last step was to eliminate all the excluded areas from the evaluated ones, which we mapped and classified into ten suitability classes ranging from low to high. The results revealed the availability of 11% (1,561 km²) of areas for wind energy mostly located in the prefecture eastern side, 92% of which were labelled as moderately suitable. Interestingly, we found out that "Soso" where the famous 2011's Fukushima Daiichi power plant is located, is the sub-region containing the largest share of suitable areas, which suggests an available alternative to the unsafe and unpopular nuclear power. The produced map coupled with detailed statistics provides a comprehensive reference and essential insights not only for private wind farm developers but also for regional planners and researchers in quest of achieving the aforementioned vision.

Keywords

Onshore wind farms; Suitability analysis; Multi-criteria decision making; AHP; GIS; Fukushima prefecture; Japan

Introduction

The earthquake of March 2011 revealed the inflexibility of Japan's energy mix. The country was relying heavily on CO_2 contributing

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fossil fuels coming from politically instable Middle East for a long time since the 1970s [1]. In fact, The Japanese government has been looking for alternatives to change this problematic situation. The solution was to diversify the energy mix as much as possible. As a result, the share of nuclear energy rose exponentially during the last decade. However, following the nuclear disaster of Fukushima, all nuclear reactors were ordered to shut down until further notice. As of September 2014, none of the 48 reactors of 17 plants was in operation and nine reactors were scheduled to be decommissioned [2]. Consequently, Japan faced a serious problem of electricity shortage especially in Tohoku and Kanto regions. Japan has realized the need to rely on safe and renewable energy resources. In this context, the government introduced the Feed-In Tariff (FIT) scheme in July 2012 in order to encourage the development of renewables in the country.

In recent years, renewable energy is getting more and more important, essentially due to the decreasing conventional energy resources, coupled with high oil prices as well as the on-going climate change by greenhouse emissions like Carbon Dioxide and water vapour. CO_2 free renewable energy can be generated by using many kinds of sources including wind. Balat [3] affirms that wind energy is the fastest growing energy resource worldwide, and the forecasts predict that this trend will continue for the next decade and beyond [4]. Moreover, the Global Wind Energy Council projected the possibility of a 17-fold increase in the electricity generated by wind energy systems globally by 2030 [5].

In Japan, onshore as well as offshore wind has far greater potential compared with other renewable energy sources [1,6], mainly in the north of the country. Tohoku region is one of the leading regions in terms of wind potential in Japan. It is composed of six prefectures: Akita, Aomori, Fukushima, Iwate, Miyagi and Yamagata. According to the Ministry of Economy, Trade and Industry [7], all these prefectures except Miyagi enjoy strong wind conditions. Fukushima, which is located in the region, was the most damaged prefecture because of the 9-magnitude earthquake [8]. Consequently, the local government has set an ambitious vision of becoming 100% renewable energy self-sufficient by 2040. However, at present there are only three onshore wind farms operating in the prefecture. Therefore, it seems fruitful to explore new optimal locations for new possible inland wind parks.

In general, relying on wind energy systems among others may contribute to reduce emitting CO₂ and other greenhouse gases, conserve water and fuel, reduce the country's dependence on imported fuel for generating electricity and eventually increase the island country's energy security. However, Akella, et al. [9] mentioned that wind energy projects have social, economic, and environmental related disadvantages. On the other hand, Tsoutsos, et al. [10] pointed out that hurting the environment while producing energy is inevitable as these energy projects are man-made and will affect the environment one way or another. In other terms, wind and other renewable energy systems may have negative impacts on the environment and other aspects but these effects are significantly acceptable comparing with those of fossil fuels. To make sure that these side effects are minimum, a careful analysis should be conducted to evaluate the suitability of areas for locating wind energy facilities. The proper siting of wind farms however remains inherently problematic essentially due to

^{*}Corresponding author: Ahmed Derdouri, Division of Spatial Information Science, Graduate School of Life and Environmental Sciences, University of Tsukuba, Ibaraki, Japan, Tel: +212650387429; E-mail: ahmed.derdouri@gmail.com

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the multiplicity of criteria to include. Determining which criteria to take into consideration during the site selection process has been the subject of public debate and considerable research. Despite that fact, all agree that accurate resource assessments and proper site evaluation can save money, time and resources [11].

Suitability analysis exercises necessitate a concurrent evaluation of various criteria. To that end, Multi-Criteria Decision Making (MCDM) can assist decision makers in choosing the adequate alternatives [12]. Correspondingly, the deployment of a GIS is particularly beneficial in integrating, analysing multiple spatial data sets, related to different factors used for site selection process and finally offers a graphic access to information about suitable locations of wind power facilities for politicians, private companies, researchers and the public.

Articles in the published literature that address the assessment of wind farms using MCDM methods are increasing in the present decade compared with the last. In many reviewed studies, various spatial MCDM methods have been applied successfully to resolve wind farm suitability analysis exercises including Analytic Hierarchy Process (AHP) (e.g. [13-23]), Weighted Linear Combination (WLC) (e.g. [24]), and ELECTRE-TRI (e.g. [25]) to name a few. In the following, we present an overview of the most notable studies sorted according to their publication year. Baban and Parry [13] identified the criteria influencing the sitting of wind farms in the UK by conducting a survey asking the opinions of administration bodies and wind companies. Then, these criteria were given equal scores initially to extract a suitability map. Moreover, the authors assigned weights to criteria as a result of a pairwise comparison. The results of the two methods show that the second scheme seems more efficient. Rodman and Meentemeyer [26] investigated the suitable locations for wind turbines in the Greater San Francisco Bay Area. To that end, they developed a rule-based GIS model to evaluate different scenarios. All layers representing criteria were given equal weights. Bennui, et al. [14] combined GIS and AHP method in order to develop a suitability model for large wind turbines in Thailand. Two types of parameters were defined: evaluation and exclusion. Although, the study successfully identified the most optimal locations, the method followed to determine the weights of different evaluation factors was not clear. In addition, any procedure to validate the obtained results was not applied. Tegou, et al. [16] extracted two areas that represent excluded and rated areas for wind power projects. The latter was derived by developing a spatial AHP model. Without consulting wind power experts or stakeholders and only based on their own judgements, the authors calculated the weights of the selected criteria. Al-Yahyai, et al. [17] applied a GIS-based AHP-OWA model to derive wind farm suitability index in Oman. Eight evaluation criteria were considered to perform the analysis and were categorized into two groups: Technical and combined social, economic and environmental. However, assigning weights to criteria was ambiguous and unclear as the authors could determine the values without asking experts. Gorsevski, et al. [24] developed a Spatial Decision Support System (SDSS) to evaluate the suitability of wind farms in Northwest Ohio using weighted linear combination (WLC). The proposed SDSS uses a framework that incorporate environmental and economic criteria in addition to restrictions parameters. The authors asked 30 students to assign weights to the different selected evaluation criteria. As a result, three alternative suitability maps were extracted. Three weak points of this study were identified: Firstly, wind farm suitability from a social perspective was neglected in the study; proximity to urban areas was selected as a restriction parameter and not as an evaluation criterion. Secondly, no pairwise comparison was performed to evaluate the criteria. Thirdly, the fact of asking students instead of experts and stakeholders to evaluate criteria remains ambiguous. Miller and Li [19] conducted a suitability analysis in the American state of Nebraska. In addition to exclusion factors, seven evaluation criteria were adopted to evaluate the final decision. According to the authors, weights were assigned based on the literature. However, the results remain invalidated especially that authors did not propose a way to verify their outcome. Latinopoulos and Kechagia [20] evaluated the suitability in Kozani of Greece by implementing a spatial AHP model that incorporates evaluation criteria in addition to restriction parameters. Three different scenarios were outlined: The first scenario considered equal weights option in which all the criteria receive a similar importance value. The second scenario emphasized environmental and social aspects. The last one concentrated on economic and technical feasibility. Consequently, three maps of the most suitable areas were extracted. However, it should be noted that the weight assignment was done based solely on authors' knowledge without considering opinions of experts. Sánchez-Lozano, et al. [25] carried out a suitability analysis of onshore wind parks in the Spanish region of Murcia by combining GIS, ELECTRI-TRI and lexicographic order method. The authors consulted an expert in order to assign weights to the evaluation criteria. The result of the study was a map of different alternatives for potential locations for wind parks. However, relying only on one judgement to perform the analysis remains questionable. Al-Shabeeb, et al. [22] combined GIS and WLC method in order to predict optimal sites for wind farms. Five evaluation criteria were identified, representing only environmental aspects. Weights were assigned as a result of criteria pairwise comparison performed by five local experts in renewable energy and GIS. However, authors did not consider restriction factors at all, which is a shortcoming of this study. Furthermore, social and economic aspects have not been taken into account. Among all the reviewed studies, Höfer, et al. [23] conducted the most complete study, which has been a useful reference for the present research. The research area is Städteregion Aachen of Germany. The authors combined AHP and GIS. Evaluation criteria (environmental, social and economic) and restriction factors were identified based on the literature and national legislations. Moreover, experts were consulted in order to pairewise-compare different criteria. The obtained outcome is a map of suitable areas classified into 10 classes that shows a detailed degree of suitability. The authors validated the results by comparing them with the locations of existing wind farms and by conducting a sensitivity analysis. In conclusion, the reviewed literature showed the usefulness of combining GIS and MCDM methods to evaluate the locations of onshore wind parks. Most of researchers opted for AHP as the preferred MCDM method, which may be attributed to the fact that it is a simple yet powerful and mature mathematical method to analyse complex problems of decision making by calculating the weights of criteria influencing the final decision. It is worth noting that there are many flaws in the previous mentioned literature: (1) Oversight of taking into consideration certain aspects while selecting evaluation criteria or restriction parameters (2) Assigning weights to evaluation criteria is done only based on authors' opinions without integrating experts and stakeholders' judgements, and (3) Validation of the results is neglected by many authors.

The present study aims at identifying and evaluating the most appropriate sites for wind development projects in Fukushima prefecture by following a methodological framework that combines GIS techniques and AHP approach. We address the following objectives: (1) to identify exclusion parameters based on a thorough

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literature review (2) to decide which evaluation criteria to consider and how much priority to assign to each criterion, and (3) to produce a suitability map of onshore wind farms.

Materials and Methods

Study area

The study area is Fukushima prefecture as shown in Figure 1. It is located in Tohoku region of Japan. The prefecture is divided into 3 regions: Aizu, Nakadori, and Hamadoori, 7 sub-regions, and 59 municipalities. According to Ministry of Internal Affairs and Communications, there are about 1,914,000 inhabitants overall with a total density of 140 per km² [27]. The total area according to the same source is approximately 13,784 km², an area that ranks the prefecture third in Japan. The prefecture was selected as a study area for this research mainly because the available wind power potential is estimated to be approximately ranging from 7,960 MW to 26,110 MW when considering a wind speed above 6 m/s [7]. However, less than 2% of this potential has been exploited through three wind farms and four single turbines with an aggregated capacity of 143.72 MW (as of 2013). As already mentioned, the prefecture is looking to produce all its energy needs from renewables by 2040. It is worth noting nevertheless that the study area presents a challenging environment for wind farms as the region is known for its mountainous landscape essentially in its western side, in addition to the dispersal of multiple natural parks that account for 13% of the total area as of April 1st, 2014 [28] [Figure 1].

Methodology

The methodological framework applied in this study is illustrated in Figure 2. It is similar to the one followed in studies carried out by Tegou, et al. [16], Watson, et al. [21] and Höfer, et al. [23] among others. The suggested approach consisted essentially of three key steps: First, the extraction of excluded areas, which refer to areas that are restricted for construction of new wind power plants due to constraints imposed by law or based on factual considerations. In the second step, we extracted the evaluated areas, which denote classified areas according to their degrees of suitability for wind farms. This classification is based on the selected evaluation criteria. Each criterion is given an important weight, determined by the application of AHP [29] by asking local wind experts and different stakeholders. Exclusion parameters and evaluation criteria were identified based on a comprehensive literature review of eleven similar studies through which we counted the number of occurrences of these parameters. The final critical step of the proposed methodology is to derive suitable areas by combining previously extracted areas. To validate the results, we followed two approaches: First, we compared the locations of the existing wind farms in the prefecture with newly found suitable locations. Second, we conducted a sensitivity analysis based on equal criteria weights approach as proposed by several studies (e.g. [16,20-24]) [Figure 2].

Identification of exclusion parameters

The first critical step of the proposed approach is the exclusion of areas where wind development projects cannot be constructed due to factual considerations or regulations-based constraints. It should be noted that there is no general agreement among researchers about the restriction criteria as they depend heavily on the landscape configurations, national regulations and social aspects of the selected study area. Consequently, we conducted a review of eleven peerreviewed studies to identify the most considered exclusion parameters. Overall, 25 restriction parameters were found in the literature. Urban





areas were excluded in about half (6 times) of the studies. Five studies considered wind speed and slope as exclusion parameters; however, thresholds of these parameters above/below which an area is judged to be excluded vary from study to another. In this research, we excluded areas where slopes are above 30% because of inaccessibility issues and negative effects of strong turbulence on wind turbines' production. As per wind speed, 6 m/s was assumed as a threshold as speeds below are considered to be unfeasible economically for energy production [23]. In addition to the above-mentioned parameters, 4 out of 11 studies included airports, archaeological/historical monuments, protected landscapes, natural environment/sensitive areas, and wetlands. Other criteria that occurred in the reviewed literature at least three or two times include land use/land cover (LULC), water bodies, tourism attractions, infrastructure (e.g. roads, railways, electricity grid). Subsequently, in this study we selected all the aforementioned exclusion criteria as presented in Table 1 except for LULC and tourism attractions. This is attributed to the fact that we excluded already the relevant and unsuitable land uses and land covers including built-up areas, water bodies, protected natural environment. Moreover, agricultural fields and forests may always be suitable for wind projects as the case of Koriyama city wind farm, which is located within an agricultural field [30].

Identification of evaluation criteria

The next key step of the methodology consisted of defining the most important criteria that affect the siting of wind farms. It should be mentioned that no agreement in the literature about the evaluation factors to consider when assessing the suitability of a location for siting a wind farm as these factors are highly dependent on geographical location, social aspects and national regulations of the selected study area. Nonetheless, we conducted a similar approach to the previous step to identify the most used evaluation factors. Overall, thirty criteria were identified, 21 of them occurred only once or twice. The criteria adopted more than twice in the reviewed studies found to be: slope (9 times), wind speed (8 times), distance to roads (8 times), LULC (7 times), distance to urban areas (6 times), distance to electricity grid (5 times), distance to natural environment (3 times), electricity demand (3 times), and distance to place of interests (4 times). Consequently, we retained these relevant criteria except for LULC, which was substituted by land price. The main reason is that land in Japan is a scarce and costly resource and wind farms requires vast lands to be constructed. In summary, nine criteria were selected as the optimal number of criteria for AHP approach is seven plus or minus two [31,32]. Figure 3 summarizes the factors adopted to evaluate the suitability of areas, classified into three categories: environmental, social and economic.

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In this study, three classes of suitability were considered (low, medium and high). These classes were defined according to the value of a suitability degree index ranging from 1 to 10: Low (1-4), Medium (5-7) and High (8-10). For each evaluation factor and based on similar studies, we classified the values of each evaluation factor into 10 ranges to which we assigned their corresponding suitability degree indexes (1-10). Furthermore, areas where evaluation criteria values are below/above the set threshold, received a suitability index of zero. The results of this scoring scheme are presented in Table 2.

Wind speed: Wind speed corresponds to the annual average wind speed at a certain height. The majority of reviewed scientific publications took into account this criterion and considered it as a key factor (e.g. [16,20,23]). Typically, a wind turbine starts to produce electricity at around 3 or 4 m/s [33]. However, from an economic perspective, wind speed below 6 m/s is deemed to be no longer feasible [23]. Consequently, we excluded areas where wind speed is less than 6 m/s whereas areas with speeds equal or greater than 7 m/s were considered highly suitable.

Terrain slope: Fukushima prefecture is characterized by its mountainous landscape mainly in its western side. Steep terrain slopes pose many problems to projects related to wind farms in terms of site accessibility mainly for huge trucks carrying the blades of long turbines, which requires high costs of construction and future maintenance. Although wind turbines are more productive if sited at the top of a hill or on a slope, steep slopes ranging between 10% and 20% can create turbulence that affects negatively the turbine production [34]. In the literature, most of reviewed studies considered slope as either an evaluation factor, exclusion factor or both. However, there is a divergence in terms of the threshold to consider. For example, based on a survey conducted among experts of UK wind companies, Baban and Parry [13] found that slope must be less than 10%. In this study, taking into account site accessibility and issues related to turbulence effects, we chose 30% as the limit value of the slope. In other terms, areas where slope is greater than 30% were excluded.

Proximity to wildlife and natural environment: According to the Japanese Ministry of Environment, 13% of the total area of Fukushima prefecture is designated as national parks [28].

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Table 1: Exclusion features and conditions.							
Layer	Exclusion condition	Buffer zone					
Wind speed	<6 m/s	-					
Slope	>30 %	-					
City areas	All area	-					
Lakes	All area	50 m					
Forest Reserve	All area	-					
Nature Conservation Areas	All area	-					
Special Protection Zones	All area	-					
National Parks	All area	-					
Wildlife Management Areas	All area	-					
Airports	All area	200 m					
Railways	All area	100 m					
Highways	All area	20 m					
Transmission Lines	All area	100 m					

 Table 2: Evaluation criteria classified according to their suitability degree index.

Suitability class	Excluded	Low	Low				Medium			High		
Suitability degree index	0	1	2	3	4	5	6	7	8	9	10	
Wind speed [m/s]	< 6	-	6.00 6.25	-	6.25 6.50	-	6.50 6.75	-	6.75 7.00	-	> 7	
Slope [%]	> 30	27 30	24 27	21 24	18 21	15 18	12 15	9 12	6 9	3 6	0 3	
Proximity to wildlife and natural environment [m]	0 - 300	300 400	400 500	500 600	600 700	700 800	800 900	900 1,000	1,000 1,100	1,100 1,200	1200	
Proximity to city areas [m]	0 - 550	550 600	600 700	700 800	800 900	900 1,000	1,000 1,100	1,100 1,200	1,200 1,300	1,300 1,400	> 1,400	
Proximity to tourist attractions [m]	-	0 600	600 700	700 800	800 900	900 1,000	1,000 1,100	1,100 1,200	1,200 1,300	1,300 1,400	> 1,400	
Proximity to road network [m]	-	> 500	450 500	400 450	350 400	300 350	250 300	200 250	150 200	100 150	0 100	
Proximity to electricity grid [m]	0 - 100	> 9,000	9,000 8,000	8,000 7,000	7,000 6,000	6,000 5,000	5,000 4,000	4,000 3,000	3,000 2,000	2,000 1,000	1,000	
Land price [¥/m²]	80,000 46,000	46,000 34,000	34,000 25,000	25,000 18,000	18,000 14,000	14,000 11,000	11,000 9,000	9,000 8,000	8,000 6,000	6,000 4,000	4,000 1,000	
Electricity demand [MWh]	-	1 2,000	2,000 5,500	5,500 10,000	10,000 15,000	15,000 20,000	20,000 26,000	26,000 34,000	34,000 47,000	47,000 71,000	71,000 100,600	

Additionally, other protected areas are found in the prefecture including forest reserves and wildlife management areas. These areas are habitats of different species including birds and bats among other flying species. Wind turbine blades pose major threat of collision to these animals if wind farms are located close to their habitat or on their migratory paths. To minimize these risks, buffer zones of 0.3 km were applied around these areas and further were excluded. Based on a study that analysed the effects of wind turbines on birds in Germany, Höfer, et al. [23] recommended a distance of 1.2 km separating wind farms and wildlife and natural environment.

Proximity to city areas: In Japan, according to National Land Numerical Information [35,36], city areas refer to: "Regions that need comprehensive development, maintenance and preservation as one city unit, and designations as City Planning Areas under the City Planning Act, Article 5 are for corresponding regions. These areas include (1) Urbanization Promotion Areas under City Planning Act Article 7 (paragraph 1), (2) Urbanization Control Areas under City Planning Act Article 7 (paragraph 1) (3) Designated land use zone under City Planning Act Article 8, (paragraph 1)." These areas encompass cities and areas reserved for other purposes for instance housing, commerce or industry. Wind farms are restricted to be built near population centres to prevent noise disturbance and visual

impacts. Most of previous studies considered distance to urban areas as an evaluation and exclusion factor (e.g. [13,16,20,23]). However, the difference resides in the minimum distance that should separate settlements and wind parks. Based on many studies, this distance varies from 0.5 km to 2.5 km depending on population density and size of the built-up areas (i.e. big city, small town). As per this research, we set a threshold value of 0.55 km similar to Höfer, et al. [23] considering the fact that the maximum sound pressure level allowed at night is 40 dB in residential areas and 45 dB in mixed-use areas, which correspond to 0.4 km and 0.55 km, respectively.

Proximity to tourist attractions: Tourism attractions refer to tourism resources and culturally significant properties such as temples, museums and cultural heritage sites, etc. From a social perspective, attractions located closer to wind farms are likely to receive fewer tourists because of the impacts of wind farms mainly noise and visual pollutions. In the literature, this aspect was included as a an evaluation factor by many researchers including Baban and Parry [13], Bennui et al. [14] and Tegou et al. [16] among others.

Proximity to road network: Distance to road network is an important factor to evaluate the suitability of wind farms, according to several reviewed papers (e.g. [13,15,16,24]). Wind turbines should be located closely to roads in order to minimize costs related to

transportation, construction and maintenance. Among the reviewed literature, there is no agreement on the maximal distance from wind parks that should be set. Gorsevski et al. [24] for instance chose 10 km whereas Höfer, et al. [23] set it to 0.5 km because the road network density is relatively high in their study area. For the same reason, we selected 0.5 km in this study.

Proximity to electricity network: Power transmission over long distances results in electricity losses in addition to high cabling costs. Thus, from an economic point of view, the maximum distance between a wind energy facility and electricity towers should be minimal. The reviewed literature, however, shows a strong divergence in terms of the optimal maximal distance that should separate wind facilities and electricity grid. It ranges from 2 km [16] to 20 km [24] depending mainly on the density of the transmission lines in a giving study area. In this study, we considered a threshold of 9 km. In other words, areas distant of 9 km or greater from electricity network receive low suitability degree index of 1. On the other hand, a high suitability index of 10 is assigned to regions within a range of 0.1 km-1 km.

Land price: This criterion refers to the economic value of a land. In Japan, land prices are very high due to limited flat terrains coupled with high population density. Additionally, wind farms require vast areas to be constructed. Tegou, et al. [16] considered a similar criterion called "land value" calculated using a formula of four pairwised compared factors including land use, distance to roads, distance to shoreline and certain municipal district coefficient defined by national Greek legislation. In this study, we estimated land prices all over the study area using regression kriging. According to the results, prices are within a range from 1,000 $\frac{1}{2}$ /m² to 80,000 $\frac{1}{2}$ /m².

Electricity demand: Electricity consumption corresponds to the amount of electricity consumed by a population in a given year. Wind turbines should be located as closely as possible to areas where electricity demand is high in order to minimize electricity losses over long transmission distances. This criterion considered by many scholars including [16] for instance.

GIS data collection and pre-processing

Data used in this study includes free of charge datasets downloaded mainly from Japanese governmental websites including National Land Numerical Information and New Energy and Industrial Technology Development Organization (NEDO). Furthermore, the data also comprises AHP survey results that will be described fully in the next section. Table 3 summarizes the data used in the analysis, in addition to their formats, resolution and sources.

Wind speed data was downloaded as DAT files. Each file contains a header showing the extent of the covered area represented by geographic coordinates (longitude and latitude) and the number of rows and columns of the mesh (100 \times 100). The next lines contain IDs of the rows and columns followed by elevation and wind speed values at heights of 30, 50, and 70 m. We first created a fishnet for each DAT file. Then, using Microsoft Excel we opened the DBF file associated with each fishnet and added the wind speed data columns. This process was repeated 11 times because the study area is covered by 11 meshes of 100×100 . These meshes were merged together and the grid result was clipped based on administrative boundaries layer.

The slope layer was extracted from 1 arc-second SRTM data offered by the U.S. Geological Survey. The spatial resolution of the raster is approximately 30 m. In this study, we calculated the slope gradient using percent rise measurement.

Electricity demand values were calculated for every minor municipality district using population census data of 2015. The electricity consumption map was extracted by multiplying the number of residents in every district and electricity consumption per capita, taking into consideration that every year one person in Japan consumes 7.86 MWh of electricity according to 2015 statistics report of the International Energy Agency.

Land price map was derived using regression kriging approach following the methodology applied by Tsutsumi et al. [37] to derive land price map of the Tokyo metropolitan area. The electricity transmission lines layer was downloaded as a KMZ file and converted to ESRI layer using ArcMap function "KML To Layer" and then was exported to a shapefile. Consequently, we extracted the suitability map for criterion "proximity to electricity grid" using "Euclidian distance" function of ArcMap with respect to the values of the different suitability indexes and their assigned ranges as shown in Table 2. The same procedure was applied to derive the maps of suitability of other criteria namely: "Proximity to wildlife and natural environment", "Proximity to city areas", "Proximity to tourist attractions" and "Proximity to road network".

		Table 3: Descri	ptive list of the data used in this study.
Data	Format	Resolution	Source
Wind speed at 70 m	DAT files	500 m Mesh	New Energy and Industrial Technology Development Organization (NEDO)
DEM	GeoTiff	30 m	Shuttle Radar Topography Mission (SRTM)
Roads and railways	Shapefile	NA	Geospatial Information Authority of Japan (GSI)
Transmission Grid	KMZ file	NA	Fukushima power generation Co., Ltd.
Population	Shapefile	NA	Statistics Bureau of Japan
Existing wind farms	Shapefile	NA	
City areas	Shapefile	NA	
Natural park areas	Shapefile	NA	
Nature conservation areas	Shapefile	NA	
Forest areas	Shapefile	NA	
Wildlife management areas	Shapefile	NA	National Land Numerical Information
World natural heritage	Shapefile	NA	
World cultural heritage	Shapefile	NA	
Administrative zones	Shapefile	NA	
Airports	Shapefile	NA	
Cultural property designated by the prefecture	Shapefile	NA	

AHP survey

The nine evaluation criteria selected for this study were categorized into three groups: environmental, social, and economic. They were retrieved from previous studies with respect to the regional sittings of the selected study area. However, assigned weights representing their relative importance in the site selection process vary strongly in the literature. For this reason, the most accurate way to assign weights is to conduct a survey by asking local wind power experts and wind projects stakeholders to pairwise-compare the selected nine criteria based on their experiences.

Table 4 lists the organizations which the 16 survey participants who accepted to participate in the survey are affiliated to. They are classified into 5 groups: (1) Social welfare related bodies, (2) Environment protection related bodies, (3) Energy related bodies, (4) Wind technologies, engineering and structures experts, and (5) Regional wind farms owners, operating and developers' companies. This composition was selected with the aim to make the final judgement results balanced and unbiased. It has to be noted that the weights of all groups are equal to a value of 1 except for the last group that we judged their opinions are two times more important than the other groups', thus, we assigned a weight of 2. Moreover, the opinions expressed by individuals are strictly based on personal work experiences and do not match necessarily the opinions of their organizations.

Upon the completion of collecting answers from the participants. The consensus index [38] was calculated, which was equal to 43.2%, a very low percentage that indicates a significant divergence of experts' opinions. The next step consisted of checking the inconsistency of each pairwise judgement matrix and adjusting it accordingly if its consistency ratio (CR) is greater than 0.1. Consequently, the priority vectors were calculated. The aggregation of individual priorities was done by applying the Aggregation of Individual Judgments (AIJ) method using an Excel template tool developed by Goepel [38]. Figure 4 illustrates the final aggregated weights of evaluation criteria.

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The results show that "wind speed" (17.5%), "proximity to electricity network" (15.9%), and "proximity to wildlife and natural environments" (14.4%) were considered by the experts as the most important factors influencing the wind farms siting. This result relatively coincides with the results of previous studies (e.g. [14,16,23]). Criterion "proximity to city areas" (11.8%) is also considered as one of the most important factors, this can be attributed to the fact that Japanese population are sensitive to the negative effects of energy power facilities including noise distribution and visual impacts. In addition, three criteria found to be relatively of equal importance that range from 7% to 10% namely "land price" (9.9%), "proximity to road network" (9.5%) and "electricity demand" (7.7%). Finally, "Terrain slope" (6.8%) was rated as the less important factor along with "proximity to tourist attractions" (6.7%).

Results

Map of allowed areas

As already described above, the extraction of the suitability map is the result of consolidating exclusion and evaluation maps. The exclusion map defines the areas where wind development projects are prohibited either for legal or factual reasons. For each exclusion parameter, map showing the areas excluded are presented in Figure 5. Table 5 shows a summary of exclusion conditions and statistics of the excluded areas out of the total area of the prefecture. More than half of the prefecture area (61.33%) is excluded because the wind speed is below 6 m/s which is not economically feasible [23]. Furthermore, about 39% of the total area is excluded because the slope is greater than 30%.

Figure 6 shows the map result of the restricted areas. Only 11% of the total areas is considered as allowed for wind power facilities which corresponds to 1,561 km² (c.f. Table 6). These areas are concentrated mainly in the eastern and middle parts of the prefecture. All the three existing farms in Fukushima prefecture were found to be within or close to the allowed areas, which indicates a reliable result from a real-world point of view.

Orga	anization	Weight	Number					
I. So	I. Social welfare related organizations							
1	National Institute for Environmental Studies (NIES) - Planning Department	1	1					
2	Iwaki city - Urban Planning Department	1	1					
II. Er	nvironment related organizations							
3	Aizuwakamatsu city - Department of Environmental Affairs	1	1					
4	Iwaki city - Environment Planning Department	1	1					
5	Koriyama city – Environment Planning Department	1	1					
6	University of Tsukuba - World Heritage Studies and Nature Conservation	1	2					
7	NIES - Centre for Social and Environmental Systems Research	1	1					
III. Energy related organizations								
8	Institute of Energy Economics (IEEJ) - New and Renewable Energy & International Cooperation Unit	1	1					
9	Fukushima Prefecture – Planning and Coordination Unit Energy Division	1	1					
IV. W	/ind technologies, engineering and structures related organizations							
10	University of Tokyo - Department of civil engineering (Wind Engineering and structures)	1	1					
11	Fukushima Renewable Energy Institute – Advanced Industrial Science and Technology (AIST)	1	1					
V. W	ind farms developers, owners and operating companies							
12	DNV GL Japan	2	2					
13	Eurus Energy - Engineering Department	2	1					
14	EcoPower Co., Ltd	2	1					
		Total	16					

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Map of AHP-based evaluated areas

In order to extract the AHP evaluation map, we first created the classified suitability maps for each of the nine selected criteria according to the intervals and suitability indexes illustrated in Table 2. Figure 7 presents the map results.

By multiplying each criterion map by its AHP weight and then overlying the nine maps using "Raster Calculator" of ArcMap, we derived the final suitability map of wind farms in the Fukushima prefecture (see Figure 8). The map result shows that highly suitable areas are concentrated mainly in the eastern and middle parts of the study area. This is due to the fact that these areas are enjoying good wind conditions and a dense electricity grid. On the other hand, urban areas and their surroundings are considered as the less suitable zones because they were downvoted by experts taking into consideration that Japanese people are sensitive to noise and visual pollutions generated by such facilities. Regarding the three existing wind farms in the prefecture, most of the turbines are located within areas where suitability is rated as high (8-10) or medium (5-7).

Suitability map of wind farms

By overlying the two map results previously described, we have been able to extract the suitability map of wind farms in Fukushima prefecture. Figure 9 shows the final map. Most of the suitable areas are located in the sub-regions of Soso and Iwaki. For the sake of validating the obtained results, we compared the location of the three existing farms with the obtained results and it appeared that all farms are within or close to areas characterized by medium or high suitability which affirms the reliability of the results of the proposed framework.

In summary, we found that only 11% of the prefecture total area is considered as available for wind power facilities projects. About 92% of these areas are rated as medium suitable whereas approximately 5% are considered as highly suitable (Table 7).

Sensitivity analysis

In order to validate the results, we investigated the suitability of the locations where the existing wind parks were built. In addition to this approach, as found in the previous studies, sensitivity analysis is





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rame of Excluded area statistics for each parameter.								
	Freely size a sendition	D //	Excluded areas (out of total area)					
Layer	Exclusion condition	Butter zone	%	km²				
Wind speed	<6 m/s	NA	61.33	8,453.73				
Slope	>30%	NA	38.59	5,319.25				
City areas	All area	NA	24.61	3,392.24				
Forest reserve	All area	NA	20.25	2,791.26				
Natural parks	All area	NA	13.16	1,813.97				
Wildlife management areas	All area	NA	10.63	1,465.24				
Transmission lines	All area	100 m	2.38	328.06				
Special protection zones	All area	NA	1.23	169.54				
Railways	All area	100 m	1.22	168.16				
Lakes	All area	50 m	1.22	168.16				
Highways	All area	20 m	0.68	93.73				
Nature conservation areas	All area	NA	0.32	44.11				
Airports	All area	200 m	0.03	4.14				





Table 6: Statistics of restricted areas for wind farms by sub-regions.

Sub-regions Aizu Iwaki Kenchu Kenpoku Minamiaizu Soso	Total area	Not excluded area							
Sub-regions	[km ²]	[km²]	[%] of sub-region total area	[%] of prefecture total area					
Aizu	3,076.37	172.28	5.6	1.25					
Iwaki	1,231.06	275.29	22.36	2					
Kenchu	2,404.52	311.38	12.95	2.26					
Kennan	1,232.19	59.41	4.82	0.43					
Kenpoku	1,752.03	110.31	6.3	0.8					
Minamiaizu	2,341.47	143.49	6.13	1.04					
Soso	1,737.34	489.10	28.15	3.55					
Total area	13,774.99	1,561.27		11.33					

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another method to evaluate the results. In this study, we conducted a sensitivity analysis by assigning an equal weight of 11.1% to all criteria. Figure 10 illustrates the results of the sensitivity analysis compared with the results of the AHP method.

The results show that there is a quasi-similar distribution of suitable areas of the two approaches considered: AHP and equal weights sensitivity analysis especially for the medium classes (5-7). However, as a result of applying equal criteria weights' approach, significant shifts particularly from classes of medium suitability to classes of high suitability and vice versa were observed. This result indicates the suggested framework is sensitive to the alteration of criteria weights.

Discussion

The aim of this paper was to conduct a suitability analysis to locate and evaluate the most appropriate sites for wind development projects in Fukushima prefecture by following a methodological framework that combines GIS and AHP. The suggested framework consisted of three key steps: The first step was to extract the map of excluded areas where wind farms cannot be located either based on legal or factual reasons for instance inland water bodies, city areas, national parks and low wind speed regions. Additionally, depending on the nature of the exclusion parameter, we applied a buffer zone to incorporate legal or factual aspects for instance wind turbines should



Table 7: Statistics of suitable areas for wind farms per each sub-region	Table 7: Statistics	of suitable areas	s for wind farms	per each sub-region.
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	Total area of sub-region [km ²] ([%] out of prefecture total area)	Suitable areas [km²] ([%] out of prefecture total area)	Percentage of suitable areas out of sub-region total area [%]										
Sub-regions			Low				Medium			High			
			1	2	3	4	5	6	7	8	9	10	
Aizu	3,076.37 (22.33%)	172.29 (1.25%)	0	0	0	0.3	1.6	2.4	1.2	0.0	0	0	
lwaki	1,231.05 (8.94%)	275.23 (2%)	0	0	0.1	0.7	2.5	10.7	7.8	0.6	0	0	
Kenchu	2,404.51 (17.46%)	311.54 (2.26%)	0	0	0	0.5	1.7	5.1	5.1	0.5	0	0	
Kennan	1,232.19 (8.95%)	59.40 (0.43%)	0	0	0	0.1	0.9	2.2	1.5	0.1	0	0	
Kenpoku	1,752.04 (12.72%)	110.27 (0.8%)	0	0	0	0.2	1.5	2.3	1.9	0.4	0	0	
Minamiaizu	2,341.47 (17%)	143.38 (1.04%)	0	0	0	0.4	1.9	2.4	1.2	0.1	0	0	
Soso	1,737.36 (12.61%)	489.18 (3.55%)	0	0	0.1	0.4	2.5	9.0	13.6	2.4	0	0	
Total	13,774.98 (100%)	1,561.29 (11.33%)											

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be located at least 200 m away from airports to avoid radar interference. In total, we selected 13 exclusion parameters based on a thorough review of previously published literature. For every parameter, we downloaded corresponding freely available GIS layers and thereby overlaid all the layers to extract the final map of restricted areas for wind parks. We found out that most of the turbines of the three existing wind farms in the prefecture are located within or adjacent to areas designated as unrestricted, which validates the produced map. Höfer, et al. [23] used a similar scheme to confirm the validity of the results from a real world perspective. The results of the exclusion showed that approximately 11% of the prefecture lands are available for wind farms projects, which corresponds to 1,561 km². Unfeasible wind speed (below 6 m/s) and steep slopes (> 30%) were the parameters responsible for restricting most of the areas across the prefecture excluding respectively 61% and 39% of the total area. Regarding the LULC of the excluded areas, all city areas (25%) situated mainly in the eastern side of the prefecture were judged restricted for installing new wind farms. Legal restrictions were the reason behind excluding areas designated as protected natural environment scattered across the western side of the prefecture and incorporates mainly forest reserve (20%), natural parks (13%) and wildlife management areas (11%). Overall, restricted areas were found to be concentrated mainly in the eastern side of the prefecture alongside the borders separating sub-regions Soso-Kenchu, Soso-Kenpoku and Soso-Iwaki. This is attributed essentially to the fact that these regions are enjoying good wind conditions above 6 m/s, characterized by relatively flat landscape, away from city areas and protected environmental areas. The second critical step is the core of the proposed methodology and it consisted of extracting the map of AHP-based evaluated areas for wind energy projects. First, we identified the most relevant factors affecting the sitting of wind power facilities through a comprehensive literature review of 11 notable similar studies done in different parts of the world. It is worth noting that there is no consensus among researchers about the criteria to

take into account as they greatly depend on the geographical location of the study area, its landscape configurations, social acceptance aspects in addition to national legislations of the concerned country. Nevertheless, we counted the number of criteria occurrences in the selected articles. The results showed that the most considered evaluation criteria among 30 identified factors were: slope (9 times), wind speed (8 times), distance to roads (8 times), LULC (7 times), distance to urban areas (6 times), distance to electricity grid (5 times), distance to natural environment (3 times), electricity demand (3 times), and distance to place of interests (4 times). Consequently, we retained only nine relevant criteria because the most optimal number of criteria for AHP approach is seven plus or minus two [31,32]. These nine evaluation criteria were classified into three categories: Environmental (wind speed, terrain slope and proximity to wildlife and natural environment), social (proximity to city areas and proximity to tourist attractions), and economic (proximity to road network, proximity to electricity grid, land price and electricity demand). Despite more than half of the reviewed studies considered criterion LULC, it was not selected as an evaluation factor in the present study. This is because wind farms can be located within any type of LULC in the prefecture including agricultural fields as the case of Koriyama wind farm [30], except for city areas, national parks, water bodies and other built-up infrastructure, which were previously excluded in the first step. Instead of LULC, we considered land price as an alternative factor because lands in Japan are limited and expensive. The next step was to assign weights to these criteria following AHP method coined by Saaty [31]. Assigning weights to criteria is a complex task and the approach to apply varies. Recent studies tend to apply different MCDM methods for instance AHP [13-23], WLC [24] and ELECTRE-TRI [25]. AHP method was selected because of its simplicity and effectiveness. Other researchers in similar studies have previously applied it successfully. Indeed, 7 out of 11 reviewed studies opted for AHP, however, it should be noted that authors of the majority of these studies relied only on their own

knowledge to assign weights ignoring expertise of experts and opinions of different stakeholders. This study tried to cover this gap by inviting several experts and stakeholders to participate in a survey to pairwise-compare the nine criteria previously selected. To make the judgements unbiased as much as possible, we invited participants from different working and education backgrounds belonging to diverse bodies working on wind energy projects for instance wind farm developers, environment and social welfare related organizations. In total, 16 experts agreed to take part in the survey and were given the choice to fill their answers through a website designated specifically for this purpose or via traditional questionnaire document. Based on the completed forms, we calculated criteria weights for every expert and then we aggregated all the resulted weights. Results showed that experts evaluated wind speed (17.5%), proximity to electricity network (15.9%) and proximity to wildlife and natural environment (14.4%) as the most important factors influencing the sitting of wind farms. Results coincide partially with most of studies in terms of ranking wind speed as the most influencing factor [16, 23]. The reason behind the high weight of proximity to electricity network is probably attributed to the wideness of the study area where the density of electricity grid is quite low mainly in the eastern side. Experts assumed that wind farms should be built as close as possible to transmission cables to minimize the costs of cabling and to decrease electricity losses due to long transmission distances. On the other hand, the high ranking of criterion proximity to wildlife and natural environment may be explained by the fact that national parks without counting other natural reserves consist of 13% of the total area of Fukushima prefecture in addition to the strict protection laws governing such areas in Japan. The next important factor is proximity to city areas (11.8%). Other factors such as Land price, proximity to road network and Electricity demand received relatively equal weights ranging from 7.7% to 9.9%. Slope and proximity to tourist attractions were judged as the least important criteria receiving 6.8% and 6.7%, respectively. Following weights assignment, GIS layers of corresponding criteria were downloaded free of charge from authentic websites. Using ArcGIS's Raster Calculator, we then generated the map of AHP-based evaluated areas. The results showed that highly suitable areas are located in the west of the prefecture in addition to some scattered sites in the middle of the prefecture. This is due to the fact that these areas enjoy medium to high wind speed conditions in addition to a dense electricity grid and road network. Furthermore, they are farther away from protected natural environment and city areas. Following the previously detailed steps, the third and the final step consisted of consolidating the two maps of restricted and evaluated areas by excluding all the areas previously deemed restricted for wind projects from evaluated areas.

Overall, this study revealed that opportunities for new onshore wind development projects still exist in the prefecture, yet limited. Indeed, despite the constraints posed by either laws, landscape or factual reasons, approximately 11% of the prefecture area, which corresponds to around 1,561 km², was found to be deemed available for wind power facilities. The largest share of suitable areas are located in the western side of the prefecture alongside the borders separating Soso and its three neighbouring sub-regions namely Kenpoku, Kenchu and Iwaki. These results explain the existence of two wind farms in these areas out of three operating in the whole prefecture. In addition, there are additional suitable areas scattered in the middle and eastern sides of the prefecture. In terms of suitability classification, 92.66% of the suitable areas are of medium suitability whereas high and low suitability classes accounted only for 4.71% and 3.62%, respectively.

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Soso sub-region contains 3.55% (489.18 km²) of suitable areas in the prefecture followed by sub-regions Kenchu and Iwaki offering shares of 2.26% (311.54 km²) and 2% (275.23 km²), respectively. Based on these results and giving the fact that Soso sub-region was the primary target of the 2011's disastrous tsunami that caused serious damages to currently disabled Fukushima Daiichi nuclear power plant and its sister Fukushima Daini, this study suggests installing wind farms in the northwest of Soso sub-region, which may cover the energy produced by these unsafe plants. As mentioned before and similarly to the study done by Höfer, et al. [23], the locations of the three existing wind farms in the prefecture were used to validate the obtained results as we found out that most of the turbines of these farms fall within or close to areas of medium or high suitability. Moreover, as other studies suggested (e.g. [16,20,21,23,24]), we performed a sensitivity analysis using equal criteria weights approach through which we assigned a weight of 11% to all criteria to investigate the framework's sensitivity to changes. The outcomes confirmed the high sensitivity of the proposed framework to these changes as we detected considerable fluctuations of areas' shifts between different suitability classes.

This study might be a good contribution to the ongoing efforts to achieve the promising 2040's vision to become a totally renewable energy self-sufficient prefecture, which was adopted in recent years by the prefectural government. In the literature, only one study has been carried out in the study area with the aim to find areas with high wind potential among other renewable resources across the region [8]. However, to the extent of authors' knowledge, the present study is the first in the study area and among few studies in the literature to apply AHP approach based on a survey among local experts and stakeholders to compare documented aspects influencing wind farms and consequently to assess the suitability of such facilities. The produced maps coupled with detailed statistics provide a comprehensive reference and essential insights about the potential locations and sub-regions where to install prospective wind farms. This information might be helpful not only for private wind farm developers but also for regional planners and researchers. Furthermore, it is worth noting that the suggested framework might be applied elsewhere in Japan or beyond at a regional or national level, nonetheless certain adjustments are required essentially in terms of aspects influencing wind farms sitting which depend heavily on the legislations, social aspects and environmental configurations of the targeted study area.

Conclusion

Japan found itself in a dilemmatic situation concerning its energy mix following the Fukushima Daiichi disaster in 2011. The country started to rely heavily again on fossil fuels to generate its demand of electricity which means more CO₂ emissions, an embarrassing situation for one of the countries that ratified Paris climate agreement. With the increase of Japanese people awareness of the risks associated with nuclear energy generation, the country begun to diversify its energy resources mix focusing mainly on renewable resources including solar, wind, biomass, etc. Fukushima prefecture suffered the most damage because of the 2011's nuclear crisis. For that reason, its local government adopted an ambitious vision to become completely renewable energy self-sufficient by 2040. Wind seems to be one of the resources that will be used in this futuristic strategy as the prefecture has a huge unexploited wind potential given its location in the north of Japan known for its good wind conditions. However, for a wind facility to be built in a certain location, wind potential is not the only factor that should be considered, several factors

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representing different aspects need to be taken into account. To that end, site suitability assessment is a crucial task in wind farm planning and decision-making. Therefore, the aim of this study was to conduct a suitability analysis of onshore wind farms across the prefecture of Fukushima combining GIS techniques and AHP approach.

The study results show that Fukushima prefecture still has suitable locations for wind farms, yet limited and restricted to certain areas. Only 11% (1,561 km²) of the total area is deemed appropriate for such facilities. Approximately, 92% of these available areas are rated as moderately suitable whereas only around 5% are of high suitability. These locations are concentrated mainly in the eastern side of the prefecture alongside the borders between Soso and its neighbouring sub-regions namely Kenchu, Kenpoku and Iwaki. This explains the fact of the installation of two out of three wind farms operating in the prefecture in these regions. The main reason for such result is the favourable conditions of these areas in terms of medium to high wind speed conditions, dense electricity and road networks, long distance from city areas and less protected natural environment. Additionally, scattered suitable areas are also found in the middle part of the prefecture, mainly in the southwest and southeast of Koriyama city. Areas that are closer to city areas and steep mountainous areas received low suitability scores. Soso sub-region is found to have the largest share of suitable areas in the prefecture (3.55% which corresponds to 489.18 km²), interestingly enough it was the most damaged sub-region in the aftermath of 2011's Fukushima Daiichi nuclear power plant accident. This result affirms the availability of locations with alternative safe wind energy resources that might cover the energy produced by harmful and unpopular nuclear facilities.

This study may help Japanese decision makers and wind farms companies to have an idea about the opportunities that Fukushima prefecture still offers regarding onshore wind development projects. The produced map with ten levels of suitability ranging from low to high provides an essential information that might save time and money of authorities and investors. The suggested framework may be applied elsewhere either at national or prefectural level. Nevertheless, it should be mentioned that some adjustments might be required to achieve better and accurate results depending on the requirements of the wind farm developers or governmental bodies.

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Author Affiliations

¹Division of Spatial Information Science, Graduate School of Life and Environmental Sciences, University of Tsukuba, Tennodai, Tsukuba, Ibaraki, Japan

²Faculty of Life and Environmental Sciences, University of Tsukuba, Tennodai, Tsukuba, Ibaraki, Japan

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