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Green Energy for a Green City—A Multi-Perspective Model Approach

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Abstract: The basis for implementing demands for a green city is the use of, among other things, innovative "clean" technologies. However, it is mostly and directly connected to the increased use of electric energy. Green transport is an appropriate example of this. By contrast, conventional sources of energy (e.g., based on coal) have a very negative impact on people and the environment. Therefore, this article mentions an attempt to solve a complex problem of employing renewable energy sources (RES) as an element of the "green city" system. The research was carried out on the basis of a feasibility study (decision game) for the location of a wind farm in the vicinity of the city of Szczecin, Poland. When constructing the decision models, multiple-criteria decision analysis (MCDA) methods were applied, especially analytic hierarchy process (AHP) and preference ranking organization method for enrichment evaluation (PROMETHEE).

Keywords: renewable energy sources; RES; multiple-criteria decision analysis; MCDA

1. Introduction

Green cities are defined as cities characterized as having clean air and water, running a low risk of major infectious disease outbreaks, being resilient to natural disasters, encouraging green behavior, and having a relatively small ecological impact [1]. Therefore, green cities are related to, among other things, renewable energy sources (RES), the use of which is environmentally friendly, minimizes ecological influence and increases the quality of air in the city. The relationship between green cities and renewable energy sources can be found in a report prepared by the European Green City Index, in which 30 European capitals were evaluated in terms of their current environmental performance [2]. The ranking takes the following factors into consideration: air cleanliness, CO_2 emission, a strategy of CO_2 reduction or the percentage of renewable energy in the total energy production [3]. Similarly, Albino and Dangelico [4] noticed that the RES use is closely related to the philosophy of green cities and is an essential practical aspect.

Another element of green cities is environmentally friendly transport [3,5]. It is about, among other things, supporting bicycle mobility, as is being done by municipal authorities of Polish cities, such as in the city of Szczecin, by building bicycle paths and urban bicycle stations. Nevertheless, a larger ecological potential for cities is the application of solutions used by a higher number of citizens rather than the expansion of bicycle infrastructure. It is obvious that far more city dwellers use their own cars and public means of transport. Consequently, better results in terms of reducing pollution emissions can be obtained by solutions such as electric or hybrid cars [6] as well as public transport powered by electricity, i.e., trams and electric buses [7]. However, it should be noted that the use of electric vehicles in the city causes increased demand for electric energy related to the necessity of charging vehicle batteries. As a result, such a demand brings about the increase in energy production from conventional sources, mostly from coal, even in cities where the power industry is to a great extent based on RES [8]. Therefore, air pollution reduction resulting from the use of electric vehicles is lower than is assumed [9]. The problem is even bigger, since almost all energy for the city is produced by coal power plants. It may turn out that air pollution emission generated by a coal power plant (resulting from the necessity of energy production for charging electric vehicles) is larger than the air pollution emission when conventional vehicles are used instead of electrically powered vehicles [10]. Therefore, one cannot talk about a green city as long as it mostly relies on coal energy. Instead, energy production technologies based on RES should be introduced more frequently.

The use of RES as pro-environmental action is one of the main aims of the energy policy [11]. Renewable energy sources are the basic element of a low-carbon economy [12], and their percentage in the total energy production is continuously increasing and will continue to increase in both the European Union [13] and Poland [14,15]. On the other hand, the highest portion of energy production in Europe [13] and Poland is supplied by wind turbines [15–17]. The Polish wind potential is comparable to that of the "world wind giant" Germany and other countries in which a significant share of energy is obtained from wind, such as Denmark or Sweden [18]. An inland wind turbine is distinguished by lower capital spending and maintenance costs among RES, as seen in Table 1.

Table 1. Capital spending and maintenance costs of renewable energy sources (RES) [19].

Energy Source	Capital Investment (€2005/kW)	Operational Costs (€2005/kW)
On-shore Wind	1140	35
Off-shore Wind	2000	80
Landfill Gas	1530	200
Biogas plant	3140	245
Hydropower—large scale	1350, 1800, 2510	40, 55, 75
Hydropower—small scale	2900, 4500	85, 130
Photovoltaics	4700	80
Concentrating Solar Power	5000	115
Biomass combustion steam cycle—large scale	2450	135
Biomass combustion steam cycle—small scale	3800	260

The data show that wind is the most optimal renewable energy source. What is more, the highest economic and market potential for wind energy in Poland (by 2020) is in West Pomeranian Province, as depicted in Table 2. The economic potential was determined by considering arable lands in a given province with appropriate wind conditions on which wind farms can be constructed. From the potential investment areas, all areas subject to protection were excluded. These areas are national parks, landscape parks, nature reserves, the Natura 2000 protected areas, areas of protected landscapes and protected area buffer zones. The market potential (part of the economic potential that can be used within a definite period of time) was calculated by means of a Modular Energy System Analysis and Planning Environment (MESAP) model, as part of an Energy [R]evolution project, on the basis of current market and political factors [20].

The city of Szczecin plays an important role in the West Pomeranian region. The analysis of the present energy policy of the city confirms that it is primarily based on a conventional source of energy; that is, coal [21]. There are two coal power plants, "Pomorzany" and "Szczecin", located in the city. They significantly support the electric power grid during rush hours and therefore generate harmful emissions in the city. The situation with regard to potential wind conditions and ecological limitations seems to be unfavorable and is reflected in the Regional Innovation Strategy which emphasizes the need for a continuous increase of the RES share in energy production, as presented by Urząd Marszałkowski Województwa Zachodniopomorskiego [22]. An analysis of other economic and social factors of the city also conveys substantial RES investment possibilities such as the use of technological and social potentials of the city and the region as well as the availability of investment grounds; for instance, neighboring districts that have low economic value but are also "good" locations for wind farms, e.g., an area between the town of Goleniów and the northwest part of DąbieLake [23].

Table 2. Economic and market potential of wind energy in Poland [20].

Province (Voivodeship)	Economic Potential (MW)	Market Potential (MW)
West Pomeranian	~14,100	~3100
Pomeranian	~10,400	~1900
Lower Silesia	~9800	~300
Warmian-Masurian	~7100	~300
Subcarpatian	~6700	~300
Kuyavian-Pomeranian	~5200	~1500
Greater Poland	~4100	~1400
Podlaskie	~4000	~800
Lesser Poland	~1800	~50
Opole	~1600	~50
Silesian	~1400	~50
Lublin	~1000	~50
Lubuskie	~500	~50
Świętokrzyskie	~200	~100
Łódz	~100	~100
Masovian	~50	~50

The complex analysis of an RES investment location also requires a detailed analysis of the technological potential of the city and the region. In Szczecin, and in the vicinity of the city, there are many production companies related to wind energy. In Goleniów, LM Wind Power is manufacturing rotor blades for wind turbines. In total, about PLN (Polish złoty) 600 million will be invested, which is going to generate about 1400 jobs (currently 600) [24]. LM Wind Power also has a service center in Szczecin, where approximately 140 workers are employed [25]. There is also KK Wind Solutions, located in Szczecin, which produces wind turbine control systems. The company employs about 570 workers in the area of Szczecin [26,27]. As for the ability of investment to diversify an economically unstable shipbuilding sector within the city, Bilfinger MARS Offshore serves as a prime example. This company manufactures foundations for offshore wind farms, and over PLN 500 million were invested to build the factory, which will employ about 500 workers [28].

Apart from manufacturers of wind farm elements, an important part of a potential investment process is planning and the realization of wind farm projects. Here, EPA-Wind, a Szczecin-based company, should be mentioned. This company, which employs over 40 workers [29], deals with data analysis, measurements, preparation and realization of wind energy projects. A Polish division of the RP Global concern also has its registered office in Szczecin. RP Global Poland deals with the design, implementation and maintenance of wind farms [30]. There are many business entities that act as subcontractors and are responsible for constructing wind turbines. The detailed analysis of a broader social context of investment makes us consider the social potential of the city. Wind energy investment in the vicinity of Szczecin would also positively increase the number of workplaces related to wind energy when investment preparation is concerned, as well as the management, maintenance and repair of wind turbines. Estimates concerning the number of positions created by the wind energy sector are presented in Table 3.

Table 3. Number of jobs created by the wind energy sector [31].

Kind of Job	No of Jobs for 1 MW of Wind Farm Power Installed in a Given Year	No of Jobs for 1 MW of Cumulated Wind Farm Power Installed in a Given Year
Production of wind farm elements—direct workplace	7.5	-
Production of wind farm elements—indirect workplace	5	-
Wind turbine installation	1.2	-
Management and maintenance of wind farms	-	0.33
Other indirect workplaces	1.3	0.07
Total employment potential in the sector	15	0.4

Furthermore, according to research for the European Commission, people employed in the RES sector often come from other sectors where they had lost their jobs, such as the shipbuilding or steel industries [32]. This observation is of utmost importance in the context of Szczecin, where the most significant social problem has been the bankruptcy of one of the biggest employers, i.e., Szczecin Shipyard, in 2002 [33].

On the basis of the arguments presented above, one can state that the construction of wind farms in the vicinity of Szczecin is very important, both for perceiving the city as a "green city" and for social and economic reasons. Therefore, the aim of this paper is to identify conditions that should take place so that a potential investor would chose the Szczecin region as a construction area of wind farms. The aim is achieved by means of a kind of a decision game, which assumes that the investor, who has several good locations for constructing wind farms, makes a decision with the use of a multiple-criteria decision analysis (MCDA) method. Methodologically, the article presents an attempt to build guidelines for using MCDA methods as a tool for identifying and constructing the decision-maker's preference model by maximizing the utility of a given decision variant. Such an approach is a complement to possible plains of application of MCDA methodology in areas different than classical problems of choice, ranking and sorting.

2. State of the Art

Decisions related to RES ought to be seen as multiple criteria decision making problems with correlating criteria and alternatives [34]. As far as RES decision problems are concerned, many criteria, which are usually mutually conflicting, should be considered [35]. Often, a decision made in this field is related to the necessity of taking into account different and contradictory interest groups [36,37]. This is because of complex relationships between technological, economic, environmental, ecological, social and political conditions and aspects of the application of RES. Therefore, a natural tool for supporting such decisions are MCDA methods [38]. This stems from the fact that MCDA methods can provide a technical–scientific decision-making support tool that is able to justify choices clearly and consistently, especially in the renewable energy sector [39,40].

In the literature, one can find many examples of MCDA applications in the field of RES. These methods are employed in order to: choose an energy production technology, analyze different scenarios of RES development, optimize energy production, and evaluate RES-based power plants on the environment or to select location for this kind of power plants. RES-related problems and MCDA methods applied to solve the problems have been variously reviewed [34,36,41]. Research also deals with the application of MCDA methods to wind energy; for example, Kaya and Kahraman [42] first selected an energy production technology (wind energy received the highest mark), and then faced the problem of finding a location for an on-shore wind farm working in the chosen technology. Lee, Chen and Kang [43] presented the problem of location selection of an on-shore power plant and Wątróbski, Ziemba and Wolski [44] for an off-shore power plant. Moreover, Latinopoulos and Kechagia [45] as well as Al-Yahyai et al. [46] based frameworks for location evaluation of on-shore wind farms on GIS (Geographical Information System); Aydin, Kentel and Duzgun [47] presented a similar framework for location evaluation of hybrid power plants, which use wind energy and solar-PV energy. Yeh and

Huang [48] determined criteria and their weights for the problematic of selection of a wind farm location. Aras, Erdogmus and Koc solved another problem concerning the location selection of a wind observation station [49]. Chang [50] considered a more complex problem presented in the selection of specific energy production technologies and their locations. As for other decision problems, Cavallaro and Ciraolo [40] carried out an evaluation of wind power plants designs. The designs were different in quantity and power of wind turbines and were evaluated in terms of their suitability to one specific location. Lozano-Minguez, Kolios and Brennan [51] evaluated foundations (truss) for off-shore wind installations. Individual articles, along with their criteria and MCDA method are presented in Table 4. Here, the criteria were divided into seven categories:

- technical aspects of the wind farm and its devices;
- spatial location of the farm with reference to surrounding area;
- economic issues especially ones related to the planned investment costs;
- social factors related to building and operating the wind farm;
- issues concerned with ecological aspects of the investment;
- environmental factors of the vicinity in which the farm is to operate; and
- legal articles and aspects related to the internal policy in terms of constructing wind farms.

In Table 4, one can find out that the location evaluation of wind farms is often influenced by spatial criteria, such as a distance from the road network and the power grid. Another frequent technical criterion is the amount of generated energy. In the context of generated energy, the environmental aspect is essential; i.e., wind speed, as it directly influences the amount of generated energy. Among the economic criteria, the most crucial ones seem to be investment, operation and maintenance costs. Social factors are also of importance; above all, the social acceptance of constructing a wind farm and of changes to the surroundings. A basic ecological factor that is often mentioned among the criteria is an estimated emission intensity reduction related to withdrawals from fossil fuels. The volume level of wind turbines, the influence on protected area and distance from such areas are often listed among the ecological factors.

Lately, a dynamic development of MCDA methods has been observed. Both new methods are created and well-known techniques are further developed. They are widely used in decision problems related to, for instance, sustainable development, ecology or wind energy. In this area, both European and American school decision-making methods are applied [52]. When analyzing the literature, one can notice in order to solve decision problems related to wind energy, the analytic hierarchy process (AHP) method is most often used. A generalization of the AHP method, in the form of analytic network process (ANP), is also employed. The reasons for this are relatively simple: computational algorithms for these methods and the possibility of hierarchical structurization of a decision problem [43]. However, AHP/ANP methods are based on qualitative evaluations, therefore, they do not make it possible to precisely present quantitative data. In decision problems related to wind power engineering, other methods of the American decision-making school are also applied, such as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Vlsekriterijumska Optimizacija I KOmpromisno Resenje (VIKOR), simple additive weighting (SAW) or ordered weighted averaging aggregator (OWA) and their developments using fuzzy number arithmetic [42]. As far as the European decision-making school methods are concerned, ELimination Et Choix Traduisant la REalité (ELECTRE) methods as well as the preference ranking organization method for enrichment evaluation (PROMETHEE) method are often used [44]. These methods are especially used when a quantitative data approach is applied. Independently, e.g., Latinopoulos and Kechagia [45], Al-Yahyai et al. [46] as well as Yeh and Huang [48] attempted, successfully, to combine several methodological approaches. The AHP (or also ANP) method is frequently used to determine a priority vector, whereas other techniques (e.g., Decision Making Trial and Evaluation Laboratory (DEMATEL), OWA, and SAW) are often employed in the aggregation process of final decision variants.

Table 4. Application of multiple-criteria decision analysis (MCDA) methods in the field of wind Energy.

Decision Problem	C	Main Criteria							NC	MCDA Method	Reference
		Te	**Ec**	**So**	**El**	**En**	**Sp**	**Po**			
Selection of location for on-shore wind farm	SLo	TE	IC, OC	SA, VI	AN, IE				7	Fuzzy AHP + Fuzzy VIKOR	[42]
Selection of location for on-shore wind farm	SLo	TE, TS	IC, OC	SC		WS, GS		RS, OS	25	AHP	[43]
Selection of location for off-shore wind farm	SLo	EP	IC, PT	SC	PA	GS	DE		10	PROMETHEE II	[44]
Geographical Information System (wind)	SLo					SL, WS	DR, DP		6	AHP + SAW	[45]
Geographical Information System (wind and solar-PV)	SLo				AN	SL, WS	DE, DR, DP		10—wind; 9—solar	OWA	[47]
Geographical Information System (wind)	SLo					WS	DR		7	AHP + OWA	[46]
Key factors of location for wind farms	SLo	TS		LB, VI	CR	WS	DR	RS, OS	15	Fuzzy DEMATEL + ANP	[48]
Selection of location for a wind observation station	SLo		IC, OC	IA		TB	DE		13	AHP	[49]
Adjustment of energy production technology for their best locations	SLo	EP	IC, OC	LB, SA	CR				7	MCGP	[50]
Selection of foundations for off-shore wind installations	TSl	TE, TS	NV		CR	TB			9	TOPSIS	[51]

Abbreviations: AHP—analytic hierarchy process, AN—acoustic noise, ANP—analytic network process, C—category, CR—carbon reduction, DE—distance from the national energy connection, DEMATEL—decision making trial and evaluation laboratory, DP—distance from protected areas, DR—distance from road network, El—Ecological, Ec—Economic, En—Environmental, EP—energy production, GS—geology suitability, IA—infrastructure accommodation, IC—investment cost, IE—impact on ecosystems, LB—local benefits, MCGA—multi-choice goal programming, NC—number of criteria, NV—net present value, OC—operational cost, OS—other support, OWA—ordered weighted averaging aggregator, PA—influence on the protected areas, Po—Political, PROMETHEE—preference ranking organization method for enrichment evaluation, PT—payback time, RS—regulation for energy safety, SA—social acceptability, SAW—simple additive weighting, SC—social conflicts, SLo—site location, SL—Slope, So—Social, Sp—Spatial, TB—topography-natural barrier, Te—Technical, TE—technical efficiency, TOPSIS—technique for order of preference by similarity to deal solution, TS—technical safety, TSl—technology selection, VI—visual impact, VIKOR—vlsekriterijumska optimizacija i kompromisno resenje; WS—wind speed.

3. Methodological Background

3.1. General Assumptions

The adopted research procedure is based on Roy's [52] four-stage model of a decision process. The model consists of the following stages:

1. determining the object of the decision and defining the set of potential decision alternatives A;
2. analyzing consequences and developing the consistent set of criteria C;
3. modeling comprehensive preferences and operationally aggregating performances; and
4. the investigation and development of the recommendation, based on the results of Stage 3.

Roy stresses that the stages do not go serially, but, for example, some elements of Stage 1 can require performing elements of Stage 2. Similarly, a decision process cannot be simplified by eliminating individual elements of Stage 2. In Stage 3, there are three possible operational approaches for the decision-maker in respect of the scope of aggregating performance of alternatives:

1. use of a single synthesizing criterion;
2. synthesis by outranking relation; and
3. interactive local judgments with trial-and-error iterations.

It should be noted that among methods selected to solve the decision problem, there is both a method using a single synthesized criterion (AHP) and a method carrying out a synthesis with the use of an outranking relation (PROMETHEE). Both of these methods are described, Sections 3.2 and 3.3, respectively.

In Stage 1, the object of a decision is determined. The considered decision problem concerns the selection of the best location, among those suggested, for a wind farm. The problem is considered from an investor's point of view, as it is the investor who wants to build a wind farm in a location with suitable spatial, environmental, social and ecological characteristics and at the same time he or she wants the investment to by economically rational. The decision problem is a background for presenting a decision game, in which one alternative location is in the vicinity of Szczecin. Other alternatives were situated in potentially the most attractive locations in other regions of the country. Assuming a certain decision model, the decision game is to point out the conditions that the Szczecin location would have to meet to be the best alternative. In order to accurately present all alternative locations, it is necessary to define criteria according to which the alternative locations are to be evaluated.

In Stage 2 of the research procedure, a set of criteria relating to individual alternatives were assessed are prepared. The basic technical aspect depending indirectly on a location is the amount of generated energy. It is mainly influenced by the number and power of wind turbines installed in the wind farm. The number of wind turbines is limited by the area of the available location. It is assumed that turbines should be at a distance of at least four times greater than the rotor diameter (usually about 80–90 m $\times$ 4 m) [53]. Furthermore, the amount of generated energy is to a great extent dependent on wind speed in a given region [54]. Therefore, among the considered criteria, the environmental conditions, such as wind speed at the height of 100 m, were taken into account.

Among spatial criteria, the following were taken into consideration: distance from a power grid connection, voltage of the power grid at the connection and its vicinity, and distance from the road network. The distance from a power grid connection influences the ease of connecting the wind farm to the grid, whereas the voltage of the transmission grid to which the wind farm is going to be connected is related to the voltage sweep, which consequently leads to power grid failures. Connecting high electric power (from several dozen megawatts) wind farms to grids with too low voltage (i.e., 110 kV) may cause damages to transmission lines or transformers [55]. The distance from the road network is closely related to, among other things, the construction of the wind farm, since the shorter the distance from roads, the easier it is to deliver elements on the construction site and the less expensive it is to connect the area to the road network. It is a significant factor, for in Poland the road infrastructure in areas characterized by good wind conditions is usually insufficiently developed [54].

As far as ecological criteria are concerned, it is important to know if a location belongs to Natura 2000 nature protected areas. In these areas, it is forbidden to take any action that would negatively influence the protection aims of the Natura 2000 area. However, in the case of an important public interest, business activity permits can be issued even if this activity might have a significant negative impact on the aims of protecting the Natura 2000 area [56]. Nevertheless, it is necessary to take efforts, incur financial costs and devote much time to obtain such permits. Furthermore, wind farms, like other buildings and technical facilities, cannot be located in national parks, landscape parks or nature reserves [56].

The most essential social factor conditioning the construction of a wind farm is social acceptance of such an investment. This social acceptance also contains other social factors influencing the level of acceptance, such as changes to the surrounding area, generated noise or benefits for the local community. It is worth noting that, according to research, a high level of acceptance for a wind farm is declared by about 12% of Poles, 85% of Poles accepts wind energy at a medium level, and 3% at a low level [57].

With reference to economic rationality, the basic criterion should be the investment cost, which mainly consists of: the costs of purchase and assembly of the wind farm (turbine and tower), power grid connection, foundations and design preparation. It is estimated that an average cost of constructing wind farms per 1 MW of installed power amounted to PLN 6.6 million/1 MW and the price is similar to the price of constructing an equivalent coal power station. Only gas energy requires lower investment costs [31]. In addition, operational costs, both fixed and variable costs, should be considered. Fixed costs include: operation and overhaul, maintenance, land lease, management, insurance, energy consumption of the wind farm, taxes and payment to the local community. Variable costs include variable maintenance and balance costs. In total, it is assumed that operational costs of a wind farm in 2011 amounted to PLN 83/MWh [31]. The profit is the price for generated energy that is sold to consumers. The average price of electric energy on the competitive market in the third quarter of 2015 came to about PLN 173/MWh [58]. However, new regulation in the form of a so-called RES auction influences the estimated profits. The regulation reads that RES-based power stations can participate in energy sales auctions. The bidder offering the lowest energy price will have a guaranteed purchase price of their energy for a period of 15 years at their offered price indexed by an inflation level [59]. The reference price for an RES auction in 2016 for on-shore wind energy of the total power greater than 1 MW amounts to PLN 385/MWh [60].

The selection of criteria used for considering location alternatives results from the fact that the problem of location selection was considered from an investor's point of view. Based on the above considerations, a set of criteria is presented in Table 5.

Table 5. Criteria adopted for evaluation of wind farm locations.

	Criterion	Unit	Preference Direction
C1	yearly amount of energy generated	(MWh)	Max
C2	average wind speed at the height of 100 m	(m/s)	Max
C3	distance from power grid connection	(km)	Min
C4	power grid voltage on the site of connection and its vicinity	(kV)	Max
C5	distance from the road network	(km)	Min
C6	location in Natura 2000 protected area	[0;1]	Min
C7	social acceptance	(%)	Max
C8	investment cost	(PLN)	Min
C9	operational costs per year	(PLN)	Min
C10	profits from generated energy per year	(PLN)	Max

Locations of individual decision alternatives are presented on maps in Figure 1, against the background of wind conditions (Figure 1a), the road network (Figure 1b), the power grid (Figure 1c), and Natura 2000 protected areas (Figure 1d).

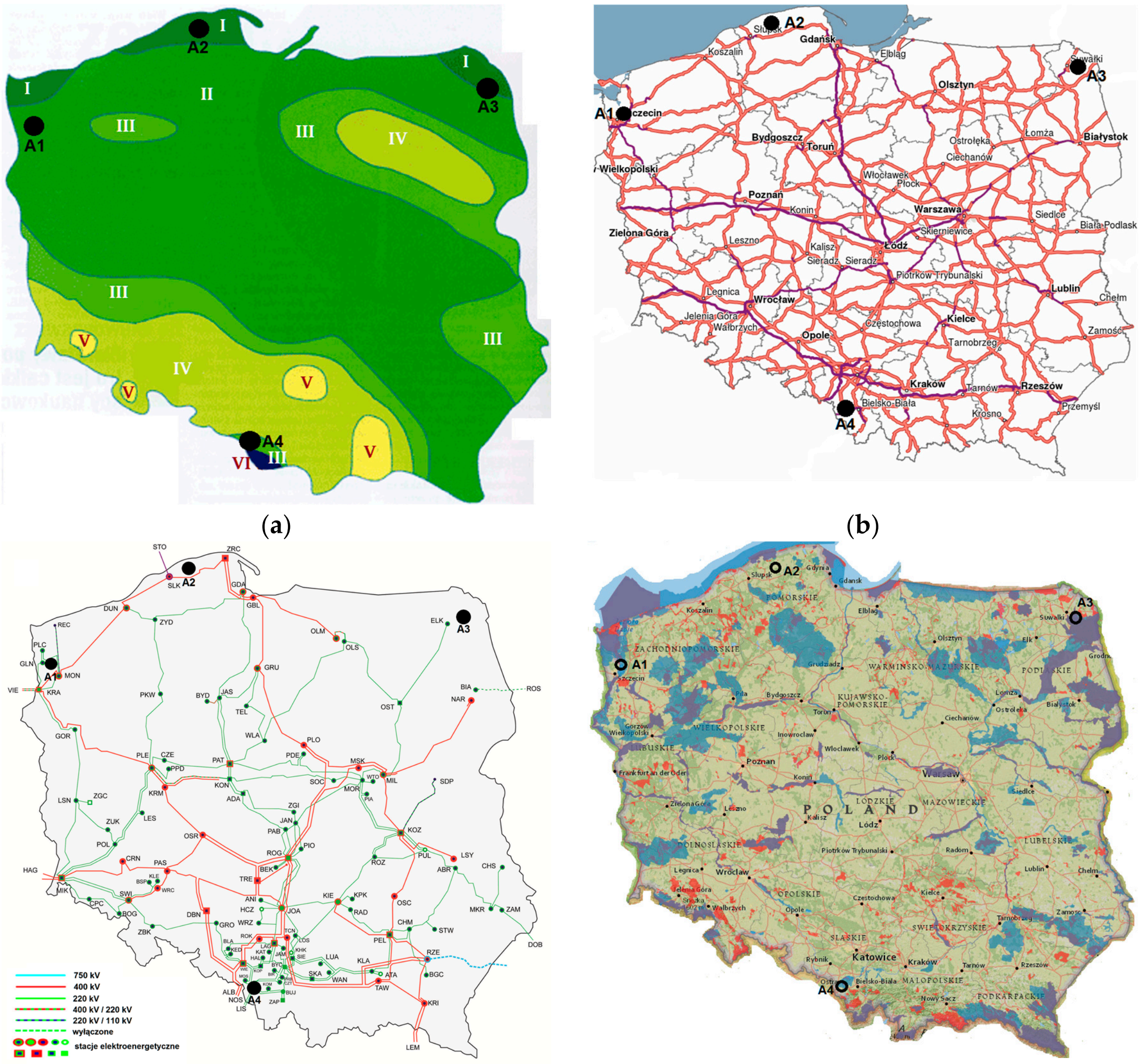

Figure 1. (**a**) Alternative locations on the map of wind conditions [61]; (**b**) Alternative locations on the map of Poland's road network [62]; (**c**) Alternative locations on the map of the power grid [63]; and (**d**) Alternative locations on the map of Natura 2000 protected areas [64].

Criteria values of individual alternatives in the spatial scope (among other things, distance from the road network) were obtained from Google Maps. Mean wind speed was received on the basis of analyses conducted by the authors of Global Atlas of Renewable Energy [65]. As far as the kind of wind turbines is concerned, research indicated that Vestas V90 3 MW (Vestas Wind Systems A/S, Aarhus, Denmark) turbines would be installed in the wind farms [66]. The amount of generated energy was calculated by means of the power output of the turbine and mean wind speed. Costs and profits were calculated on the basis of the data presented in this paper concerning approximate wind investment costs and estimated energy prices. Moreover, an average value of social acceptance was assumed for the alternatives. The exception here is alternative A2, because recently Pomeranian Province residents have expressed opposition to constructing more wind farms [67,68]. Criteria values of individual alternatives are presented in Table 6.

Table 6. Criteria values for individual alternatives.

	Basic Data	A1 (Szczecin)	A2	A3	A4
	No of turbines V90-3 MW (pieces)	23	17	21	14
	Installed power (MW)	69	51	63	42
	Criterion				
C1	yearly amount of energy generated (MWh)	106,780	86,370	104,850	46,600
C2	average wind speed at the height of 100 m (m/s)	6.75	7.12	6.95	6.04
C3	distance from power grid connection (km)	2	3	60	1
C4	power grid voltage on the site of connection and its vicinity (kV)	220	400	220	220
C5	distance from the road network (km)	6	10	7	3
C6	location in Natura 2000 protected area [0;1]	1	0	1	0
C7	social acceptance (%)	52	20	60	50
C8	investment cost (million PLN)	455.5	336.5	416	277
C9	operational costs per year (million PLN)	8.9	7.2	8.7	3.9
C10	profits from generated energy per year (million PLN)	36.8	29.8	36.2	16

Having a defined set of criteria and alternative values, Stages 3 and 4 of the decision process were carried out; that is, preference modeling and aggregating performances as well as issuing a recommendation. The stages were conducted separately for methods AHP and PROMETHEE.

3.2. The Analytic Hierarchy Process (AHP) Method

The AHP is a MCDA method stemming from the expected utility hypothesis. One can distinguish four steps:

1. defining a decision problem and the kind of knowledge one is looking for;
2. preparing a hierarchical structure containing the main goal, intermediate goals (criteria) and alternatives;
3. a pairwise comparison of alternatives in relation to each of the criteria and a pairwise comparison of importance of individual criteria; and
4. using vectors of priorities obtained in comparisons to receive a solution to the decision problem [69].

A decision problem and the construction of hierarchical structure are closely related to each other. The decision problem, while constructing the hierarchical structure, is decomposed into subgoals (criteria), which are placed on subsequent structure levels. Decision alternatives play the role of leaves in the structure. One should individually define the goals of the decision, its subgoals, evaluation criteria and potential subcriteria as well as hierarchical connections between them, decision alternatives and actors [70]. An example of a hierarchical structure is illustrated in Figure 2.

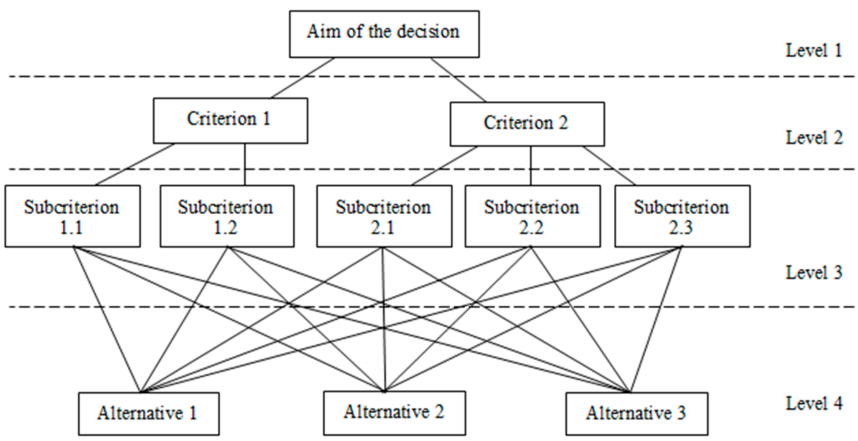

Figure 2. Hierarchical structure in the analytic hierarch process (AHP) method.

Comparison of criteria and their alternatives comparisons are conducted with the use of a pairwise comparison matrix. Each matrix should be reciprocal and positive. The proportion means that every matrix element fulfills the characteristics defined by Equation (1):

$$a_{ji} = 1/a_{ij} \tag{1}$$

The interpretation of Equation (1) is as follows: if an element a_{ij} contains a value a, then the element a_{ji} should contain an opposite value, i.e., 1/a. Moreover, elements on the main diagonal a_{ii} should include unitary values [71]. When specifying the positivity of matrices, one needs to point out that it should contain the Saaty's ratio scale, i.e., from the range of 1 to 9 and their opposite values, where 1 indicates equality of compared alternatives or criteria and 9 indicates an extreme advantage of an alternative or criterion i over j [69]. Therefore, each matrix is completed with one of 17 values: 1/9, 1/8, . . . , 1/2, 1, 2, . . . , 8, 9 [72]. The meanings of individual values of the Saaty's ratio scale are presented in Table 7.

Table 7. Numerical and verbal values of the scale for the AHP method [73].

Numerical Evaluation	Verbal Evaluation
1	Compared objects (decision alternatives or criteria) are equivalent
2	The decision-maker hesitates between an equivalent and weak advantage of one object compared to over the other
3	A weak advantage of one object over the other
4	The decision-maker hesitates between a weak advantage and a considerable advantage of one object compared to the other
5	A considerable advantage of one object over the other
6	The decision-maker hesitates between a considerable advantage and a significantly bigger advantage of one object compared to the other one
7	A significantly bigger advantage of one object over the other
8	The decision-maker hesitates between a significantly bigger advantage and a huge advantage of one object compared to the the other
9	A huge advantage of one object over the other

For every pairwise comparison matrix, a preference vector $w = [w_1, w_2, \ldots, w_n]^T$ is defined, which demonstrates the force of alternatives or criteria compared in matrices. Components of the vector are included in the pairwise comparison matrix, which is presented in Equation (2) [70]:

$$\begin{array}{c|c} & \begin{array}{cccc} A_1 & A_2 & \cdots & A_n \end{array} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_n \end{array} & \begin{pmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{pmatrix} \end{array} \tag{2}$$

In the AHP method, one calls for determining a preference vector W by determining a right eigenvector of a matrix [74]. It is calculated by solving Equation (3):

$$A\,w = \lambda_{max}\,w \tag{3}$$

If a pairwise comparison matrix is consistent, then there is only one non-zero eigenvalue λ_{max} of a matrix and it is equal to the size of the matrix. A vector w is a preference vector related to the value λ_{max} [61]. When there are relatively insignificant inconsistencies in the matrix, the preference vector is one related to the highest eigenvalue (other λs have values close to 0). In other words, when the matrix is consistent, the preference vector w corresponds to a true preference vector v. Consistency of the matrix takes place if: $a_{ij} \times a_{jk} = a_{ik}$ for each i, j, k [75], when elements of the preference vector are their own multiples (e.g., $[1\ 3\ 6]^T$ or $[4\ 2\ 1\ 8]^T$). Therefore, preference consistency is identical to transitivity of evaluations, for instance, if in the decision-maker's opinion that an alternative ai is two times better than an alternative aj and four times better than a_k, then the alternative a_j should be two times better than the alternative a_k. However, the true preference vector v mostly does not contain single and exclusive values, which are their mutual multiples; therefore, the vector w is only its approximation [76]. The phenomenon brings about the occurrence of minor inconsistencies in the pairwise comparison matrix, which results from rounding of true preferences to the values from a set {1/9, 1/8, . . . , 1, . . . , 8, 9}. More significant inconsistencies in the pairwise comparison matrix are most often caused by the decision-maker's mistakes which lie in the omission of the rule of full transitivity of evaluations between compared alternatives [77].

Inconsistencies of a pairwise comparison matrix can be calculated by, among other things, determining a consistency index (CI), and then by determining a consistency ratio (CR) in accordance with Equations (4) and (5) [70]:

$$CI = (\lambda_{max} - n)/(n - 1) \tag{4}$$

$$CR = CI/R \tag{5}$$

Here, R is a constant whose value depends on the size of a pairwise comparison matrix. The values of R, dependent on the size of a matrix, are presented in Table 8.

Table 8. Values of a consistency factor R depending on the size of a matrix [78].

n	1	2	3	4	5	6	7	8	9	10
R	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Solving the decision problem is obtained by a synthesis of weights of criteria and alternative preference with relation to every criterion. This synthesis is in the form of a weighted mean in which every alternative product of weights of criteria and evaluations of a given alternative with relation to these criteria are added up. As a result, a generalized utility measure of this alternative is obtained. It is presented in Equation (6) [70]:

$$U_i = \sum_{k=1}^{n} w_k * u_{ik} \tag{6}$$

where U_i is the total utility of the i-th alternative, w_k is the weight of the k-th criterion, and u_{ik} is the value of the i-th alternative with regard to the k-th criterion.

3.3. The PROMETHEE Method

The PROMETHEE method uses an outranking relation in order to choose the best decision alternative [79]. The method employs positive and negative preference flows determining how much a given alternative outranks other ones and how much it is outranked by other alternatives [80]. The procedure PROMETHEE I consists of four steps and PROMETHEE II consists of five steps:

1. pairwise comparison decision alternatives with regard to subsequent decision criteria;
2. applying a preference function selected for each criterion;
3. determining an alternative preference index according to accepted weights of criteria;

4. determining positive and negative preference flows for alternatives; and
5. determining net preference flow [81].

In the PROMETHEE method, the decision-maker may choose from six preference functions using a usual criterion, a quasi-criterion with an indifference threshold, a criterion with linear preference and a preference threshold, a level-criterion with indifference and preference thresholds, a criterion with linear preference and an indifference area, or, finally, a Gaussian criterion, described by [82]. Preference functions of the PROMETHEE method are graphically presented in Figure 3.

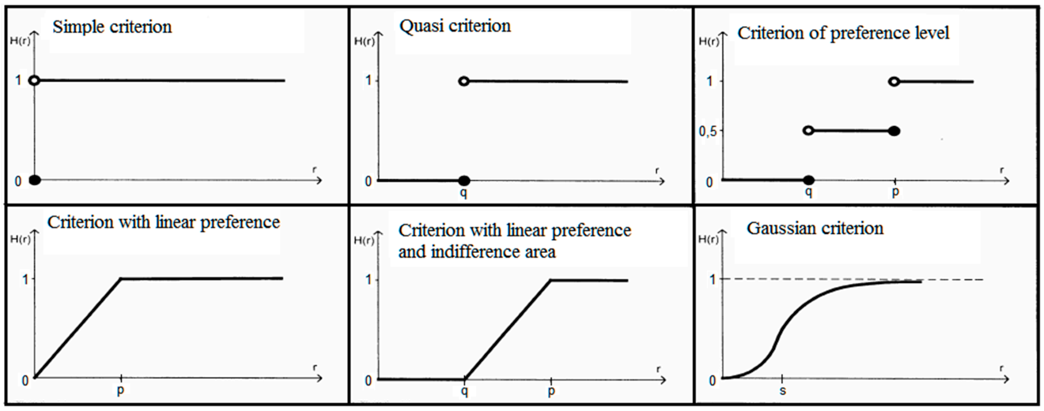

Figure 3. Preference functions used in the preference ranking organization method for enrichment evaluation (PROMETHEE) method [83].

A preference index of alternatives calculated according to Equation (7):

$$\pi(a_i, b_j) = \frac{\sum\limits_{k=1}^{n} w_k * f_k(a_i, b_j)}{\sum\limits_{k=1}^{n} w_k} \tag{7}$$

where ϕ_k means a concordance factor for a pair of alternatives compared with regard to a criterion k in accordance with the assumed preference function. Positive and negative preference flows are calculated with the use of Equations (8) and (9).

$$\phi^+(a_i) = \sum_{j=1}^{n} \pi(a_i, b_j) \tag{8}$$

$$\phi^-(a_i) = \sum_{j=1}^{n} \pi(b_j, a_i) \tag{9}$$

Up to this point, operations in the PROMETHEE I and II methods are the same. While solving the task, the decision-maker can create a partial (PROMETHEE I) or total (PROMETHEE II) ranking of alternatives. The partial ranking employed in the method PROMETHEE I is based on isolated positive and negative preference flows. In the ranking, one can distinguish indifference, preference and incomparability relations:

- an alternative a_i is preferred over b_j (a_i P b_j) when $\phi^+(a_i) \geqslant \phi^+(b_j)$ and $\phi^-(a_i) \leqslant \phi^-(b_j)$, but at least one of the inequalities should be strong (> or <);
- an alternative a_i is indifferent to an alternative b_j (a_i I b_j) when $\phi^+(a_i) = \phi^+(b_j)$ and $\phi^-(a_i) = \phi^-(b_j)$; and
- in other cases, alternatives are incomparable (a_i R b_j).

According to the PROMETHEE II method, in order to construct a total order of alternatives, a net preference flow described by Equation (10) should be calculated:

$$\phi(a_i) = \phi^{+}(a_i) - \phi^{-}(a_i) \tag{10}$$

In this method, indifference and preference relations can be distinguished:

- an alternative a_i is preferred over b_j (a_i P b_j), when $\phi(a_i) > \phi(b_j)$; and
- an alternative a_i is indifferent to an alternative b_j (a_i I b_j), when $\phi(a_i) > \phi(b_j)$ [84].

4. Research Results

Preference modeling in the PROMETHEE method consists of defining a preference direction for each criterion (max, min), indicating preference functions used for individual criteria (usual criterion, quasi-criterion, criterion with linear preference, level-criterion, a criterion with linear preference and indifference area or Gaussian criterion) and determining potential thresholds and providing their weights of criteria. These preferences are depicted in Table 9.

Table 9. Preference model for the PROMETHEE method.

Criterion		Weight of Criterion	Preference Direction	Preference Function [1]	Indifference Threshold (q)	Preference Threshold (p)
C1	yearly amount of energy generated (MWh)	12	max	(5)	2000	20,000
C2	average wind speed at the height of 100 m (m/s)	8	max	(3)	-	1
C3	distance from power grid connection (km)	6	min	(3)	-	15
C4	power grid voltage on the site of connection and its vicinity (kV)	6	max	(4)	0	2
C5	a distance from the road network (km)	2	min	(3)	-	15
C6	location in Natura 2000 protected area [0;1]	6	min	(1)	-	-
C7	social acceptance (%)	10	max	(3)	-	20
C8	investment cost (million PLN)	10	min	(5)	1	40
C9	operational costs per year (million PLN)	20	min	(5)	0.1	2
C10	profits from generated energy per year (million PLN)	20	max	(5)	0.5	10

[1] (1)—usual criterion; (2)—quasi-criterion; (3)—criterion with linear preference; (4)—level-criterion; (5)—criterion with linear preference and indifference area; and (6)—Gaussian criterion.

Next, performance aggregation of alternatives based on the PROMETHEE procedure was conducted. The obtained positive, negative and net values of preference flows are presented in Table 10.

Table 10. The values of ϕ^{net} and positions in the ranking of individual alternatives.

Alternative	Œ$^{+}$	Œ$^{-}$	Œ^{net}	Rank
A1 (Szczecin)	0.2925	0.2979	−0.0054	3
A2	0.3711	0.3535	0.0176	1
A3	0.3209	0.3168	0.0041	2
A4	0.4036	0.4199	−0.0163	4

The analysis of the obtained ranking (Table 10) indicates that the location of Szczecin is not an alternative that should be selected. Therefore, which actions should be taken in the active decision model so that alternative A1 would win the first place in the ranking should be considered. There are two kinds of action that can be taken:

1. persuading the investor to change their criteria preferences and support Szczecin as better than Alternatives A2 and A3; or
2. taking action in order to increase the values of alternative A1 to improve the criteria that currently the location of Szczecin is considered worse than alternatives A2 and A3.

The research, conducted with the use of a sensitivity analysis into an investor's criteria preference changes was carried out in such a way it could influence the improvement of the Szczecin location. Location A1 outperforms the best alternatives with regard to criteria C1, C3, C5 and C10. Therefore, it can be in first place in the case of increasing weights of only these criteria. The sensitivity analysis for the weights of the above-mentioned criteria is presented in Figure 4.

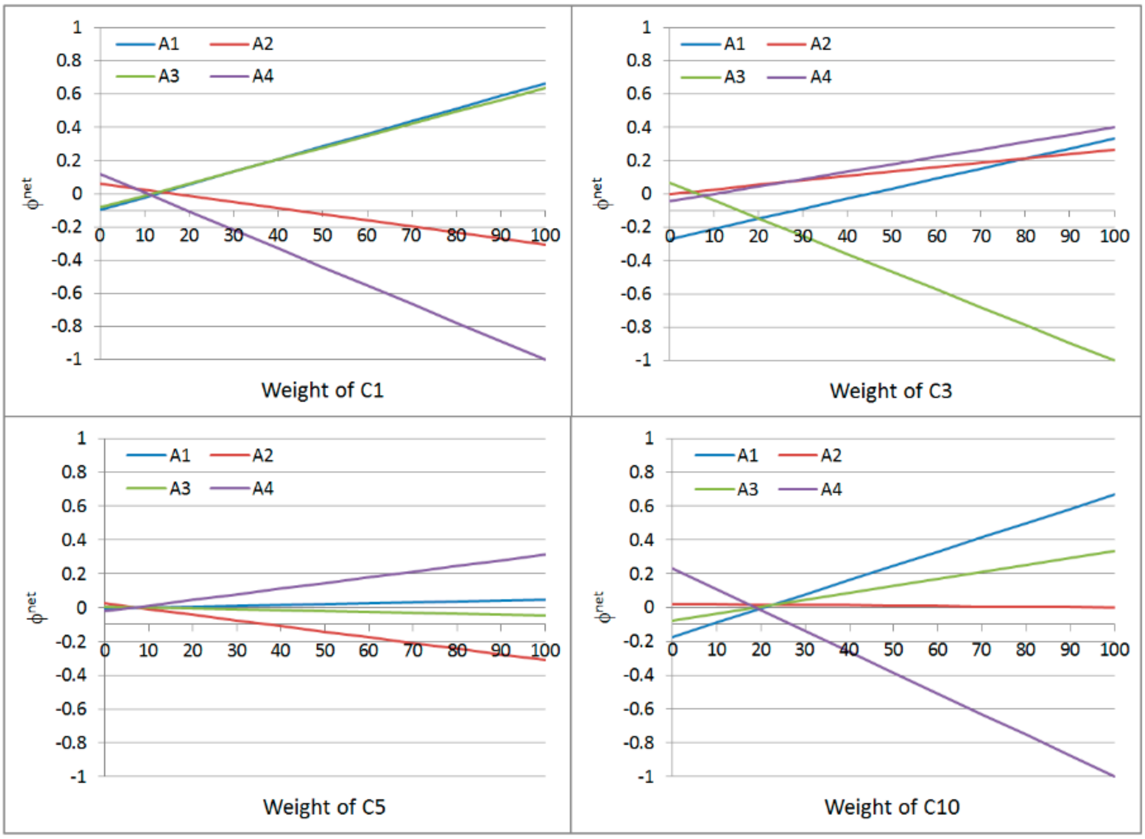

Figure 4. Sensitivity analysis (criteria C1, C3, C5 and C10).

The sensitivity analysis points out that for any increase in the weights of the criteria C3 and C5, alternative A1 will never be first in the ranking. The effect can be achieved only by increasing the weights of the criteria C1 and C10 and proportionally decreasing the other criteria. For C1, the limit weight when alternative A1 is first in the ranking is 35%. With reference to the initial weight of 12%, it would be a considerable change in the decision-maker's preference. However, for criterion C10 it is 23%, which is only 3% higher than the initial weight of this criterion. The values of ϕ^{net} and rankings obtained for the indicated weights of the criteria C1 and C10 are depicted in Table 11.

Table 11. The values ϕ^{net} and positions in the ranking of alternatives for given weights of the criteria C1 and C10.

Alternative	Criterion C1—Weight: 35%		Criterion C10—Weight: 23%	
	ϕ^{net}	Rank	ϕ^{net}	Rank
A1 (Szczecin)	0.1703	1	0.0198	1
A2	−0.0668	3	0.0169	2
A3	0.1699	2	0.0164	3
A4	−0.2734	4	−0.0532	4

It is doubtful that the decision-maker changes their criteria preferences, so one needs to consider how alternative A1 could become more attractive than A2 and A3. Considering criteria, one should eliminate those which would be difficult to influence. These include mean wind speed, the amount of generated energy, the distance from the road network and being situated in the Natura 2000 protected area. Similarly, one cannot significantly influence the estimated investment costs and profits because they are based on approximate data. One can take into account the connection of the potential wind farm to a 400 kV power grid, which would improve the evaluations of alternative A1 with reference to the "power grid voltage" criterion. However, such action results in a significant increase in the distance to the connection and moves the location of Szczecin into the second position in the ranking, just behind alternative A2. Justified action would be to increase acceptance for the potential investment in the local community (social acceptance). Indeed, an analysis of the value of this criterion for alternative A1 without introducing any modifications to other criteria indicates that when social acceptance for locating a wind farm in the vicinity of Szczecin is at the level of 59%, alternative A1 is ranked first. The analysis is presented in Figure 5.

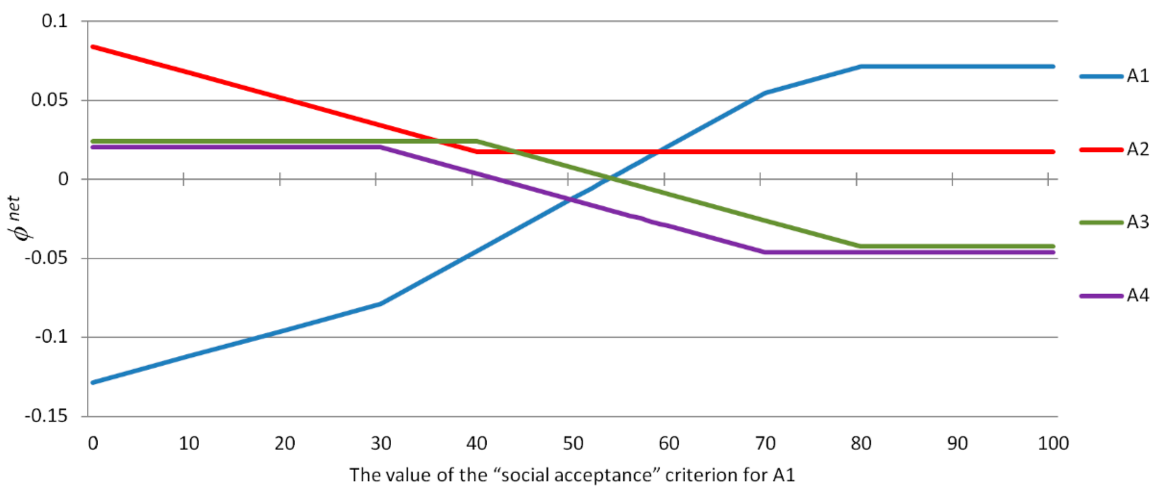

Figure 5. Analysis of the influence of the value of "social acceptance" criterion for alternative A1 on positions in the ranking of alternatives.

It should be noted that when the value of social acceptance for alternative A1 is at the level of ca. 40%, there is a change in the sequence of alternatives A2 and A3 in the ranking, although these alternatives have not been modified in any way. Nevertheless, such a phenomenon is possible in the case of methods based on an outranking relation, and PROMETHEE method belongs to this family.

In the case of the AHP method, preference modeling is carried out by pairwise comparisons of criteria. The weights of the criteria are very close to those used in the PROMETHEE method. A pairwise comparison matrix of the criteria is depicted in Table 12.

Table 12. Pairwise comparison matrix of criteria.

CR = 0.006	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	Vector of Weights
C1	1	2	2	2	6	2	1	1	1/2	1/2	0.1165
C2	1/2	1	1	1	4	1	1	1	1/2	1/2	0.0804
C3	1/2	1	1	1	3	1	1/2	1/2	1/3	1/3	0.0614
C4	1/2	1	1	1	3	1	1/2	1/2	1/3	1/3	0.0614
C5	1/6	1/4	1/3	1/3	1	1/3	1/5	1/5	1/9	1/9	0.0205
C6	1/2	1	1	1	3	1	1/2	1/2	1/3	1/3	0.0614
C7	1	1	2	2	5	2	1	1	1/2	1/2	0.1064
C8	1	1	2	2	5	2	1	1	1/2	1/2	0.1064
C9	2	2	3	3	9	3	2	2	1	1	0.1926
C10	2	2	3	3	9	3	2	2	1	1	0.1926

The performance aggregation of the alternatives was conducted by pairwise comparison of the alternatives with regard to subsequent criteria. Aggregated preference vectors for individual criteria as well as the final preference vector, synthesized to a single criterion, are presented in Table 13.

Table 13. Preference vectors for subsequent criteria.

	CR	A1 (Szczecin)	A2	A3	A4
C1	0.0302	0.4269	0.1067	0.4269	0.0394
C2	0.0227	0.1576	0.516	0.284	0.0423
C3	0	0.3214	0.3214	0.0357	0.3214
C4	0	0.1667	0.5	0.1667	0.1667
C5	0.0039	0.227	0.1223	0.227	0.4236
C6	0	0.0833	0.4167	0.0833	0.4167
C7	0.0092	0.2525	0.0405	0.4545	0.2525
C8	0.0116	0.0954	0.2772	0.1601	0.4673
C9	0.0011	0.0924	0.1922	0.0924	0.6229
C10	0.0302	0.4269	0.1067	0.4269	0.0394
Preference vector	-	0.2393	0.2239	0.2603	0.2765
Rank	-	3	4	2	1

When comparing Tables 10 and 13, it can be easily noticed that due to the application of the AHP method, alternatives A2 and A4 changed their positions in the ranking. The change is drastic, since the positions were not neighboring ones, but the first and the second positions in the ranking. Moreover, alternative A1, as in the PROMETHEE ranking, comes third.

In the case of the AHP ranking, an increase in weight of selected criteria cannot put alternative A1 first in the ranking. This statement results from the analysis of Table 12, where it can be noticed that there is no criterion with regard to which alternative A1 would outperform alternatives A3 and A4, which take the leading positions in the ranking. This is why, in this case, the sensitivity analysis was omitted.

In the next step of the research, when the preference vector of variants was calculated, similar to the ranking obtained by means of the PROMETHEE method, whether leveling evaluations of A1 and A4 with regard to criterion C7 (social acceptance) would allow alternative A1 to be the best in the ranking was tested. However, it turned out that it was unsuccessful, since after this, alternative A1 came second, just behind A4. Only a considerable increase in the value A1 for criterion C7 allowed it to move to the first position and become a preferred alternative. Pairwise comparison matrices and preference vectors for social acceptance and the final ranking of alternatives, obtained with a given pairwise comparison matrix, are presented in Tables 14–16.

Table 14. Pairwise comparison matrix for a criterion "social acceptance" and the final ranking of alternatives.

CR = 0.0092	A1	A2	A3	A4	Preference Vector C7	Final Preference Vector	Rank
A1	1	7	1/2	1	0.2525	0.2393	3
A2	1/7	1	1/9	1/7	0.0405	0.2239	4
A3	2	9	1	2	0.4545	0.2603	2
A4	1	7	1/2	1	0.2525	0.2765	1

Table 15. Modified pairwise comparison matrix for a criterion "social acceptance" and the final ranking of alternatives.

CR = 0.0092	A1	A2	A3	A4	Preference Vector C7	Final Preference Vector	Rank
A1	1	9	1	2	0.3756	0.2524	2
A2	1/9	1	1/9	1/7	0.0376	0.2236	4
A3	1	9	1	2	0.3756	0.2519	3
A4	1/2	7	1/2	1	0.2112	0.2721	1

Table 16. Pairwise comparison matrix for the criterion knows as "social acceptance" which allows alternative A1 to be the first in the ranking.

CR = 0.006	A1	A2	A3	A4	Preference Vector C7	Final Preference Vector	Rank
A1	1	9	2	5	0.5259	0.2684	1
A2	1/9	1	1/9	1/7	0.0354	0.2233	4
A3	1/2	9	1	2	0.2825	0.242	3
A4	1/5	7	1/2	1	0.1562	0.2663	2

5. Summary

Conditions and environmental, economic and social factors determine the complexity of issues related to green cities. They reflect a close relationship between green technology and transport as well as green RES. Local economic and social conditions can simultaneously be a way to redirect goals and priorities set in the given decision problem of a RES location.

The article makes a successful attempt to model the problem of evaluating the usefulness of a wind farm location for the needs of the green city of Szczecin. Therefore, the article has carried out a multiple-criteria evaluation of the potential of the wind farm location in the region of the city of Szczecin against the background of reference (regarding the best wind conditions) location alternatives in Poland. Consequently, the detailed analysis of the economic and social factors of the city resulted in including them in the prepared decision model. The research was conducted in the form of a decision game with the use of carefully-selected MCDA methods (AHP and PROMETHEE) and the research depicted the gravity of criteria determining social acceptance of an RES investment in a given region. The necessity of using complementary approaches was dictated, on the one hand, by the possibility of an intuitive dialog with the decision-maker and the simplicity of structuring and expanding the model (the AHP method), and, on the other hand, the possibility of taking into account several different types of data (forms of preference information) in one model, which was the domain of the model prepared with the use of the PROMETHEE method.

While this paper was focused on the problem of identifying conditions that should take place so that a potential investor could chose the Szczecin region as a construction area of wind farms, the selected approach can be generalized towards other areas in the field of decision making. In the situations when it is possible to adjust parameters during the search for compromise solutions, the use of the proposed approach extends typical areas of MCDA models applications beyond the classic Roy problematics [52] and can be used as a generalized framework.

In the course of the research, it has been found that there are possibilities of developing and completing the prepared model. Undoubtedly, taking into consideration real interest groups and adapting the decision model to these conditions seem to be an interesting direction. The use of the Novel Approach to Imprecise Assessment and Decision Environments (NAIADE) or group development of the PROMETHEE method can be a suggested direction.

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