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A Literature Review of the Use of GIS-Based Multi-Criteria AHP Technique for Optimal Siting of Wind Energy Sources

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ABSTRACT

Over the last years of the era of the modern Egyptian state, we have witnessed a remarkable development in all different sectors. To be able to continue this development, it was necessary to pay attention to the energy sector and its development, by dispensing with the main dependence on fossil fuels and finding new sources of energy that are less harmful to the environment, less costly and more abundant. The interest of the Egyptian state, represented by the Ministry of Electricity and Renewable Energy, appeared in the search for various renewable energy sources such as wind energy, solar energy, and others. Our role as researchers is to assist the state in making decisions about determining the optimal sites for the establishment of renewable energy plants of various kinds, based on the criteria for each of these types of stations. This is indeed what has been worked on in several previous studies and research in recent years. In this research, we have reviewed the most important researches related to choosing the best renewable energy sites (specifically wind energy as a model) in the Arab Republic of Egypt and other countries. The results were reviewed, and comparisons were made between the different study areas and the methodology of each research to clarify the effectiveness of geographic information systems in completing the decision-making process to determine the best sites for energy harvesting, and accordingly choosing the best sites for constructing wind power plants. Note that the researches reviewed here is based on Multi-Criteria decision analysis (MCDA) by analytical hierarchy process (AHP) method using Geographic Information System (GIS).

1. Introduction

Renewable energy is the energy that can be produced indefinitely. The efficient utilization of energy resources is currently a hot topic of debate. It's crucial to figure out which energy source to use and why. Most factors, such as cleanliness, cost, stability, efficiency, and environmental repercussions, must be examined. Unfortunately, many businesses around the world continue to rely on fossil fuels for energy generation. These fuels are unquestionably effective in terms of power generating quality, but they are not cost-effective over time. Companies must convert to renewable energy sources as soon as possible because fossil fuels will run out at some time. Furthermore, fossil fuels pose a serious threat to environmental equilibrium and are to blame for a slew of ecological issues [1].

The global need for sustainable energy will grow in importance as the environmental repercussions of fossil fuels become more apparent in the coming

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years. Furthermore, the rapid population growth in emerging countries increases the demand for electricity generation and distribution. Wind and solar energy are examples of renewable energy that are rapidly becoming a major source of green energy around the world [2], [3].

Egypt's economic prosperity is dependent on the energy sector. To meet rising energy demand, the government's Integrated Sustainable Energy Strategy (ISES 2035) advocates for increasing renewable energy use and improving energy efficiency in the power sector. The government has set goals for renewables to account for 42 percent of the country's electricity mix by 2035, based on rapid wind and solar installations [4].

The multi-criteria method based on GIS has proven to be a helpful decision support tool for identifying ideal spatial areas, particularly for harvesting renewable energy such as wind energy. This is what we touched upon in this review by compiling the most important previous researches in this field with representing the study area, the methodology of each research and the results obtained from it.

2. Study Area

- Research No.1: Maklad et al. (2021) have utilized multi-criteria GIS techniques for optimal siting of wind energy sources in Egypt's entire territory "Figure 1". As it astronomically extends between Latitude 22° N and 32° N, and between longitudes 24° E and 37° E, the research area's geographical borders are confined between the Mediterranean Sea and Sudan from the north and south, and between the Red Sea and Libya from the east and west. This study's overall area is estimated to be around 1001840 km2 [5].

- Research No.2: Abdelrazek (2017), has utilized multi-criteria GIS techniques for optimal siting of wind energy production units in Peninsula of Sinai, Egypt "Figure 2". As it astronomically extends between Latitude 27˚43' N and 31˚19' N, and between longitudes 32˚19' E and 34˚54' E, the research area's geographical borders are confined between the Gulf of Aqaba and Gulf of Suez from the east and west, and between the Mediterranean Sea from the north. This study's overall area is estimated to be around 61000 km2 [7].

- Research No.3: Sadeghi and Karimi (2017) have utilized multi-criteria GIS techniques for optimal siting of wind turbines in Tehran, Iran "Figure 3". As it astronomically extends between Latitude 35° 34′ N and 35° 51′ N, and between longitudes 51° 6′ E and 51° 38′ E. This study's overall area is estimated to be around 1404.788 km2 [8].

- Research No.4: Höfer et al. (2016) have utilized multi-criteria GIS techniques for optimal siting of wind farms in Städteregion Aachen, Germany "Figure 4". The area is estimated to be around 707 km2 and is bordered by Belgium and the Netherlands, stretches 50 kilometers north to south and 10–25 kilometers east to west [9].

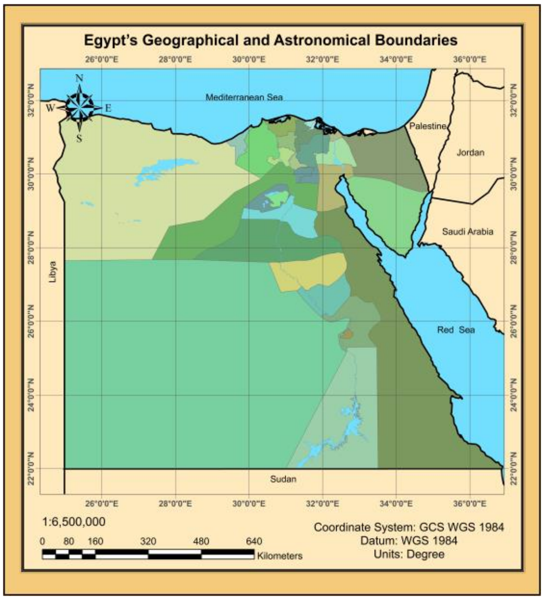

Fig. 1. Egypt Latitude & Longitude Map and Geographical Boundaries [6]

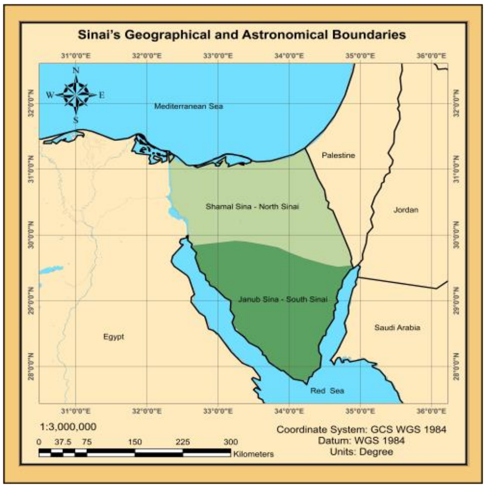

Fig. 2. Sinai Latitude & Longitude Map and Geographical Boundaries [6]

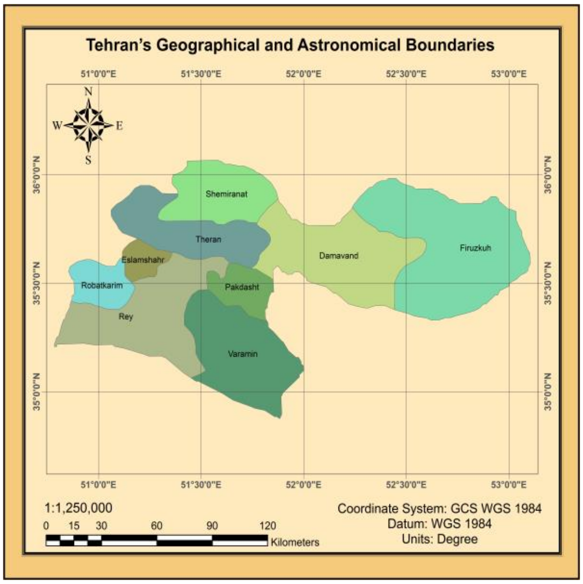

Fig. 3. Tehran Latitude & Longitude Map and Geographical Boundaries [6]

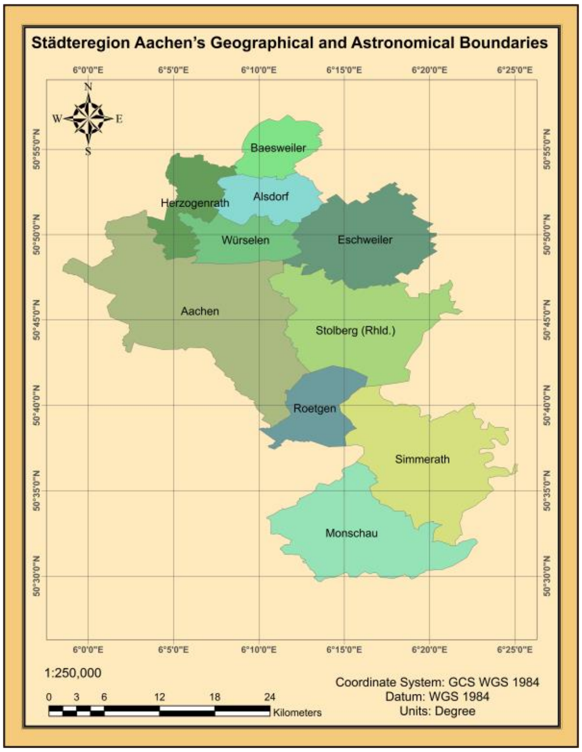

Fig. 4. Städteregion Aachen Latitude & Longitude Map and Geographical Boundaries [6]

3. Data and Methodology

3.1. Input Data

In order to integrate the multi-criteria technique inside a GIS framework, the previously mentioned researches went through a number of processing phases. Multi-criteria analysis essentially aims to define geographical locations to fulfil a set of requirements or restrictions. Therefore, the input datasets are made up of a variety of geographic databases, each reflecting a different criterion [2].

The input data includes a Digital Elevation Model (DEM) for the study area to extract the slopes, mean wind speed map at specific height, roads, and electricity network maps, and other several topographic and remote sensing imageries to construct shapefiles for coastlines, cities, airports, and land use.

3.2. Methodology

MCDA is a set of techniques for comparing, ranking, and selecting alternatives based on quantitative and non-quantitative criteria. MCDA was created to handle various problems. One of these problems is the problem of choice, which our review focuses on, in which MCDA is used for choosing the best option from a set of substitutes, Specifically, selecting the optimal site of renewable energy sources (wind energy sources as model) [10], [11].There are many used methods for applying MCDA, such as:

- **Ordinal combination method:** The region is mapped according to land attributes such as slope, soil type, vegetation, climate, and so on, with each quality having a rating equal to its importance. As a result, the land use is defined by the appropriateness grade assigned to it based on other places' equivalent attributes. Some flaws include the fact that the expert's evaluation is subjective, and that each rating must be done on the same scale to be comparable [12].

- **Gestalt method:** Similar areas are discovered, and the area is plotted. Additional maps depicting each alternative land use are made for each homogenous site, which are compared and studied to determine the optimum feasible land use. This strategy, however, is not often employed since it necessitates in-depth knowledge of the location in question, which is generally gained only when the planner has the opportunity to live in the area and devote a

- significant amount of time to it. It's also more difficult to adequately express it [12].

- **Linear combination method:** The ordinal combination method's rated attributes are compared with various weights, with the greatest weight given to the most important value and the least weight given to the least important, even though each rating is on the same interval scale [12].

- **Values suitability analysis:** In determining land appropriateness, human values (such as aesthetic preferences) are given equal weight to measurable costs and benefits. This is done often while selecting whether or not to incorporate open areas and how to manage them [13].

- **Analytic network process (ANP):** Pairwise comparisons are used to construct linkages within the structure, as well as hierarchical or network structures to describe the problem [14].

- **Analytic Hierarchy Process (AHP):** Based on mathematics and psychology, it is an organized method for organizing and understanding difficult decisions. It was created in the 1970s by Thomas L. Saaty, who collaborated with Ernest Forman to create Expert Choice software in 1983. Since then, AHP has been widely investigated and enhanced. It is a precise method of measuring the weights of choice criteria. Pair-wise comparisons are used to evaluate the relative magnitudes of variables based on individual experts' experiences. Using a carefully constructed questionnaire, each responder compares the relative value of each pair of elements [15], [16].

In our review we have focused on analytical hierarchy process (AHP) method. The following figure shows a general hierarchical Tree of applying AHP method.

3.3. Weighting

In AHP method, to elicit preferences, it divides the choice into a hierarchy of criteria and employs pairwise comparisons provided by expert assessments. The preferences are then combined to provide recommendations [18]. According to the consideration of several criteria in MCDA, identifying and selecting criteria is crucial for decision-making. The first step of applying AHP method for the optimal siting of wind energy sources is develop The three-level hierarchical framework as shown in "Figure 5", where the first level represent the goal (optimal wind energy sources sites), the second level state the different criterion (Average wind speed, Slope, Distance to transmission lines, Land use,……etc.), and the third level shows the alternatives (various deduced suitable sites). Then, Construct the pairwise comparison matrix (Saaty's matrix) to show Preferences between individual criteria according to importance scale of variables shown in "Figure 6".

Finally, accomplish judgment for pairwise comparison to determine the weights of individual criteria. The tables (1~4) show the different criteria and their weights which have been determined using AHP [19].

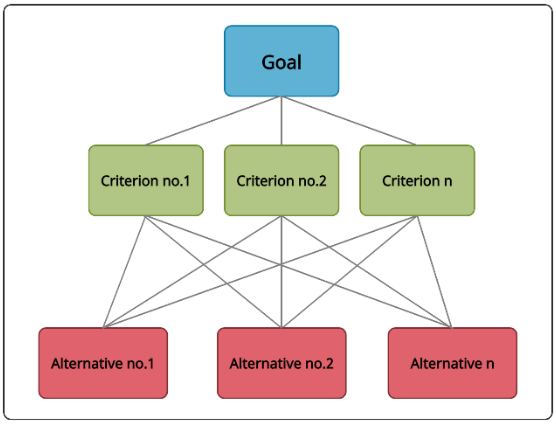

Fig. 5. General hierarchical framework [17].

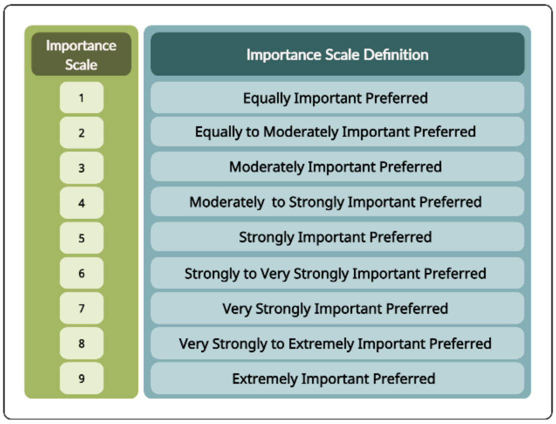

Fig. 6. Variables importance scale [17].

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Table 1. Research No.1 (Egypt) Criteria weights [5].

No.	Criteria	Cat.	Suit.	Weight
1	Average wind speed (50 m) high (m/s)	< 1 1 - 4 4 - 7 > 7	R. L. M. H.	0.30 (30%)
2	Slope (degree)	> 30 27 - 21 21 - 12 < 12	R. L. M. H.	0.15 (15%)
3	Distance to transmission lines (Electrical network) (Km)	> 20 20 - 10 10 - 5 < 5	R. L. M. H.	0.15 (15%)
4	Distance from roads (Km)	> 10 10 - 7 7 - 4 < 4	R. L. M. H.	0.15 (15%)
5	Distance from coastlines (Km)	0 - 0.5 0.5 - 5 5 - 10 > 10	R. L. M. H.	0.05 (5%)
6	Distance from cities (Km)	< 2 2 - 5 5 - 10 > 10	R. L. M. H.	0.05 (5%)
7	Distance from airports (Km)	< 3 3 - 10 10 - 20 > 20	R. L. M. H.	0.05 (5%)
8	Land use	Ag. Urban. Water Classes. Terrestrial and Aquatic Natural Vegetation. Barren.	R. L. H.	0.10 (10%)

Table 2. Research No.2 (Sinai) Criteria weights [7].

No.	Criteria	Cat.	Suit.	Weight
1	Average wind speed (50 m) high (m/s)	< 5 5 - 6 6 - 7 > 7	R. L. M. H.	0.25 (25%)
2	Slope (degree)	> 10 5 - 10 3 - 5 < 3	R. L. M. H.	0.15 (15%)
3	Distance to transmission lines (Electrical network) (Km)	> 20 0 - 0.5 5 - 20 0.5 - 5	R. L. M. H.	0.20 (20%)
4	Distance from roads (Km)	> 20 0 - 0.5 5 - 20 0.5 - 5	R. L. M. H.	0.10 (10%)
5	Distance from coastlines (Km)	0 - 0.5 0.5 - 5 5 - 10 > 10	R. L. M. H.	0.05 (5%)
6	Distance from cities (Km)	< 2 2 - 5 5 - 10 > 10	R. L. M. H.	0.05 (5%)
7	Distance from airports (Km)	< 3 3 - 10 10 - 20 > 20	R. L. M. H.	0.05 (5%)
8	Land use	Barren.	H.	0.10 (10%)
9	Distance from protected areas (Km)	< 0.5 0.5 - 5 5 - 1 > 1	R. L. M. H.	0.05 (5%)

Cat.: Categories – Suit.: Suitability - R.: Restricted - L.: Low – M.: Medium – H.: High

Table 3. Research No.3 (Iran) Criteria weights [8].

No.	Criteria	Cat.	Suit.	W.
1	Average wind speed (m/s)	> 3.5 2.75 – 3.5 2.2 – 2.75 < 2	B.S. S. M. L.	0.2828 (28.3%)
2	Land use	• Barren • cultivation • grass • orchard and woods	B.S. S. M. L.	0.6434 (64.3%)
3	Constraints	• Dist. to power lines = 250 m • Dist. from major roads = 500 m • Dist. to city = 500 m • Dist. from Airport = 250 m • Elevation more than 2000 m • Slope more than 15%	—	0.0738 (7.4%)

Table 4. Res. No.4 (Germany) Criteria weights [9].

No.	Criteria	Weight
1	Wind energy potential (m/s)	0.216 (21.6%)
2	Slope of terrain (%)	0.046 (4.6%)
3	Distance from electricity grid (m)	0.08 (8%)
4	Distance from road network (m)	0.074 (7.4%)
5	Landscape architecture	0.062 (6.2%)
6	Land cover type	0.06 (6%)
7	Distance from places of interest	0.072 (7.2%)
8	Distance from urban areas	0.185 (18.5%)
9	Distance from natural environments	0.204 (20.4%)

Cat.: Categories – Suit.: Suitability - Dist.: Distance - W.: Weight – B.S.: Best Suitable – S.: Suitable – M.: Moderate – L.: Low

As shown in the previous tables (1 ~ 4), the criteria taken into consideration differ from one research to another, and the weights of the common criteria may differ from one research to another, depending on the study area and its environmental and topographic conditions. Also, the previous studies and the consensus of previous researchers on the required criteria and their weights according to the study area using the AHP method is a reason for this diversity.

4. Results and Discussion

In the previous researches mentioned in this review, the researchers found the optimal sites for wind energy harvesting.

Maklad et al. (2021), found that the high suitable area for wind harvesting in Egypt is around 4100.22 km2, with most of them concentrated along the Red Sea coast, while the medium suitable area is approximately 76366.23 km2, whereas the low suitable area is about 5230.92 km2, and around 916142.63 km2 of restricted area. It has been recommended to use a high rise wind turbines (more than 50m height) to achieve higher wind speed and increase the suitable sites [5].

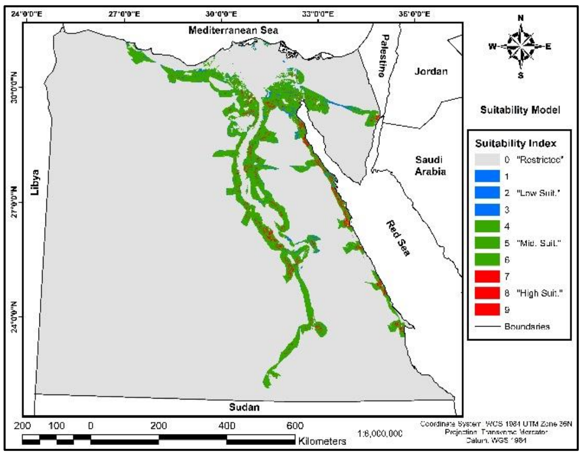

Fig. 7. Egypt, Model of Suitability. [After Maklad et al. (2021)] [5].

Abdelrazek (2017), found that the high suitable area for wind harvesting in Sinai is around 1485 km2, while moderate suitable area is nearly 22834 km2, whereas the low suitable area is about 892 km2, and around 34583 km2 of unsuitable area. It has been indicated that the suitable areas reduced progressively as the wind speed decreases towards the northern areas of Sinai [7].

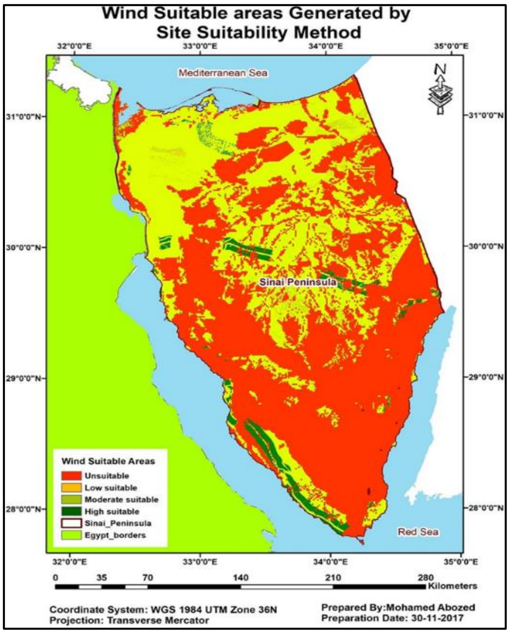

Fig. 8. Sinai Model of Suitability.
[After Abdelrazek (2017)] [7].

Sadeghi and Karimi (2017), found that the best suitable area for wind harvesting in Tehran is around 2680.70 km2, while the suitable area is approximately 4964.22 km2, whereas the moderate suitable area is about 37337.17 km2, and around 789939.63 km2 of low suitable area. It has been indicated that the eastern region of Tehran has the highest potential for harvesting wind energy [8].

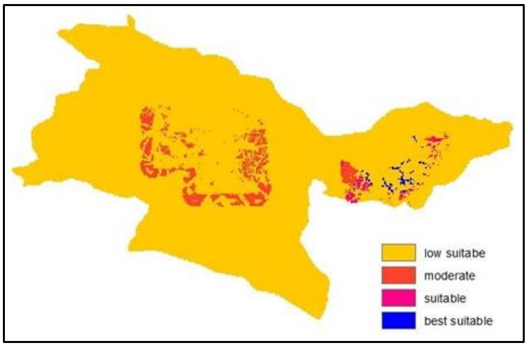

Fig. 9. Tehran Model of Suitability.
[After Sadeghi & Karimi (2017)] [8].

Höfer et al. (2016) found that the high suitable area for wind harvesting in Städteregion Aachen is around 1232 km2, while the medium suitable area is approximately 5210 km2, and the low suitable area is about 216 km2 [9].

The results of the above mentioned researches have been compared and summarized in table (5).

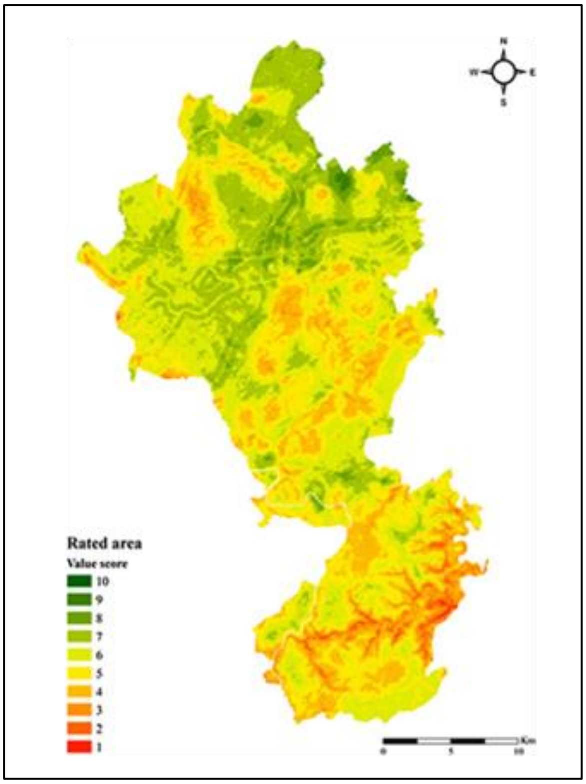

Fig. 10. Städteregion Aachen Model of Suitability.
[After Höfer et al (2016)] [9].

5. Conclusion

By the end of this review, it will be obvious how successful MCDA approaches based on GIS are in assisting decision-makers identifying the best locations for wind energy collecting and build wind turbines to provide clean renewable energy as a replacement for fossil fuels, among many other uses involving spatial suitability. As previously stated, this study was based on four prior studies that differed in terms of the spatial scope and the preparation time of the study. Suitability maps were produced to determine the optimal sites for harvesting wind energy, which in turn considered to be a clarification of the appropriate areas for that purpose.

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