Geographic Information Systems (GIS) Application in Wind Farm Planning

Almoataz Y. Abdelaziz Said F. Mekhamer
Electrical power and machines Department, Faculty of engineering, Ain Shams University, Cairo, Egypt

Amany B. Mohamed
IT Department, Egyptian Taxes Authority

Abstract - **This paper presents a review of the factors affecting the selection of wind farm sites and the application of the Geographic Information Systems (GIS) in studying these factors in the light of the relevant published literature within the last decade.**

Index Terms - **wind energy, wind farms, geographical information system, planning**

I. WIND ENERGY

Since the beginning of the 1990's, wind energy gained an escalating momentum due to the hazardous effects of fossil fuel plants and nuclear power plants as well as the expected depletion of fossil fuel resources within the next 50 years.

At the end of 2009, the installed capacity of wind-powered generators was about 160 GW producing 340 TWh of electrical energy. This amount of energy is equal to 2% of global electricity consumption.

World wind generation capacity increased more than 4 times between 2000 and 2006. Since 2004, the average growth in new installations has been 27.6% each year.

In terms of economic value, the wind sector had a turnover of 70 billion US$ and employed 550,000 persons worldwide in 2009. Wind power share in the energy generation market is expected to reach 3.4% by 2013 and 8% by 2018 [1].

The improved turbine designs and plant utilization have contributed to decline costs from 27 cents/kWh in 1980 to 3.5 cents/kWh in 2005. Thus, wind energy has become a competitive alternative to fossil and nuclear fuel plants. Table 1 compares the production costs per kWh from different plant technologies [2].

II. THE EGYPTIAN APPROACH TO WIND ENERGY

In Egypt, there exist several regions with high wind speed. The red sea shores and the Gulf of Suez are the most prominent of these regions. It was estimated that 20 GW of wind farms can be housed in the Gulf of Suez area. Other candidate areas for wind farm construction are located at Faiyoum, Beni sweif, Minya and Kharga oasis.

Egypt has already built a 425MW wind farm near the city of ZAFARANA; this plant is connected to the transmission network and has produced 931GWh of electrical energy in 2009 [3].

South of Zaafarana at Gabal Al-Zayt, an area of 700 square kilometers has been earmarked to house wind energy projects, mostly planned to be funded by private investments. A 250MW wind farm is already contracted in that region. This wind farm is expected to join service in 2012 [4]. It will be expanded in phases to reach a final capacity of 420MW [3].

Egypt is planning to have 7200MW of wind power capacity by 2020 constituting 12% of national generation capacity. More than 1000MW of wind energy projects are already planned.

Table 1: Cost of electricity with various power technologies

Plant Technology	Generation Cost[1] = Fuel + Capital ($/ kWh)	Indirect External Costs[2] ($/ kWh)	Total Cost ($/ kWh)
Wind turbine	3–5	0.1–0.3	3.1–5.3
Solar Photovoltaic	15–25	0.5–1	15.5–26
Solar Thermal (concentrated solar)	8–10	0.1–0.3	8.1–10.3
Biomass	7–9	0.2–3	7.2–12
Hydro	3–7	0–1	3-8
Coal Fired Steam	3–4	2–15	5–19
Nuclear	10–14	0.2–1	10.2–15
Natural Gas	3–5	1–4	4–9
Combined Cycle	5–7	2–6	7–13

III. GEOGRAPHIC INFORMATION SYSTEMS

A Geographic Information System (GIS) is a tool for displaying and analyzing information as it relates to a geographic location. GIS software programs provide the ability to organize, query, and analyze data, and to determine the answers required for informed decision making and comprehensive research.

Typically, a GIS is created by collecting available and appropriate data, processing it into a usable form, and overlaying the resulting layers on a base map for a given area. This data may be derived from field-collected GPS log files,

[1] Generation cost estimates are for the U.S. and Europe
[2] External costs are for meeting the U.S. and European environment and health standards

an existing spatial database, a list of objects with a known location or address, published GIS data layers, or by using object drawing and attribution tools within the GIS software.

When these data layers are in place, they provide a visual perspective that can help answering fundamental questions about the areas of greatest average wind speed, properties adjacent to the project site, the nearest access roads… etc.

IV. GIS AND WIND FARMS SITE SELECTION

The selection of wind farm sites and the spotting of wind turbines depend on the following factors:

- Wind Resources
- Roughness of the terrain and obstacles
- Road Access
- Orography of the region
- Accessibility to transmission and/or distribution networks
- Soil Conditions
- Environmental impacts

Obviously, the factors listed above are best modeled and studied through appropriate mapping. A GIS system, being capable of processing map related data, is the best alternative for decision making when wind farm planning is considered. Hereafter, the factors affecting the selection of wind farm sites are briefly discussed.

1. Wind Resources

As a general rule, wind generators are practical if wind speed is 4.5 m/s or greater. An ideal location would have a near constant flow of non-turbulent wind throughout the year with a minimum likelihood of sudden powerful bursts of wind. Usually sites are preselected on basis of a wind atlas, and validated with wind measurements.

The complete wind atlas of Egypt was issued in 2006 as shown in Fig. 1. GIS can be easily applied to the wind atlas to create a layer of the most favorable wind energy sites.

2. Roughness of the terrain

In the lower layers of the atmosphere, wind speeds are affected by the friction against the surface of the earth. Therefore, the more pronounced the roughness of the earth's surface, the more the wind will be slowed down. Forests and large cities slow the wind down considerably, while concrete runways in airports will only slow the wind down a little. Water surfaces are smoother than concrete runways, and will have less influence on the wind.

The areas surrounded by cities, forests and rough terrains are excluded using the GIS software and a new layer is created.

3. Road Access

It is also necessary to confirm that road access is available, or can be developed at reasonable cost, for transporting the turbines and other equipment. Blades of large wind turbines can pose difficulties for transport on minor roads. For a large wind farm, the heaviest piece of equipment is likely to be the main transformer if a substation is located at the site.

The GIS is capable of analyzing the ability of the road and network transportation system to serve the wind farm project during construction and after commissioning. The GIS can also suggest solutions to the deficiencies detected during the analysis phase.

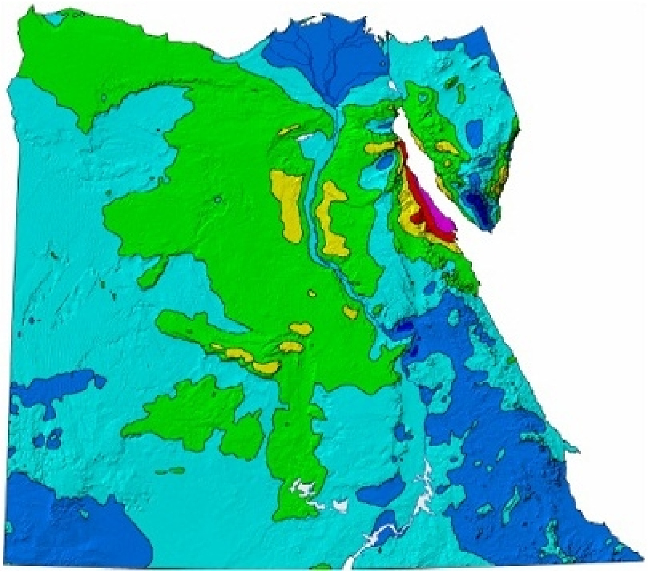

Figure (1): The wind atlas of Egypt. Map colors show mean wind speeds in [ms^{-1}] at a height of 50 m over the actual land surface: blue 4-5, cyan 5-6, green 6-7, yellow 7-8, red 8-9, magenta 9-10 ms^{-1}. The horizontal grid point resolution is 7.5 km.

4. Accessibility to local demand and/or transmission networks

The transmission network operator carries out studies to determine the amount of generation that can be injected into the transmission system without impairing its stability, security and quality. Depending on the technical status of the distribution network, the local distribution company may also allow direct power injections from the wind turbines into the medium voltage networks [5]. Once it is found that the energy produced from a wind farm can be absorbed by a nearby power system, the GIS software can determine the optimal routing for transmission lines and/or the distribution feeders. The routing criteria may include shortest path, minimum loss and minimum voltage drop.

5. Effects of Orography

Orography is the study of the formation and relief of mountains, and can more broadly include hills, and any part of a region's elevated terrain. Mountains and hills can be used to improve the power output from a wind farm. On the other hand if the effects of the existing mountains and hills are not carefully studied, the wind turbines may experience detrimental wind forces as well as considerable loss of efficiency.

a) The hill effect

On hills, wind speeds are higher than in the surrounding area. As a result, wind turbines are commonly placed on hills or ridges overlooking the surrounding landscape. If the hill is steep or has uneven surface, significant amounts of turbulence occur and the advantage of higher wind speeds may be lost.

b) The tunnel effect

The air becomes compressed on the windy side of hills or mountains, and its speed increases considerably between obstacles. This is known as "the tunnel effect".

Placing a wind turbine in a natural tunnel is one way of obtaining higher power outputs. To obtain a good tunnel effect the tunnel should be "softly" embedded in the landscape. Rough and uneven hills produce wind turbulence that may negate the wind speed advantage; the changing winds may inflict a lot of useless tear and wear on the wind turbine.

Both tunnel and hill effects can be exploited by applying the GIS software to a topographic map of the region under interest. The result will be a layer contouring the mountain or hill tops where wind turbine can make use of the hill effect and the valleys where the tunnel effect boosts the wind speeds.

6. Soil Conditions

The soil conditions at the site also need to be investigated to ensure that the turbine foundations, access roads and construction areas can be provided at reasonable cost. Local ground conditions may also influence the position of turbines in order to reduce foundation costs [5]. GIS software can study geological maps and locate land clusters where the construction of wind farms is not economical due to unsuitable soil conditions.

7. Environmental Impacts of Wind Farms

Electromagnetic interference caused by wind farms affects radar and flight paths to airfields close to the proposed sites. In addition, a large wind turbine can produce an aggregate noise level of up to 100 dB (A), which weakens to a normal level within a 1.5 km distance. Wind farms are also harmful to local birds and may interrupt the immigration paths of immigrant birds. Therefore, sites restricted due to defense, communication and ecological considerations have to be reflected on an additional GIS layer.

V. WIND TURBINE ARRANGEMENTS AND TURBINE SPOTTING

In a wind farm, turbines located too close together will result in upwind turbines interfering with the wind received by those located downwind; this effect is known as “*the park effect*”.

Theoretical studies of square arrays with uniform, equal spacing illustrate that this interference becomes marginal if the spacing between turbine towers is more than 9 rotor diameters for square arrays. Practical experience has yielded some rules of thumb for tower spacing in rectangular arrays. Recommended spacing is 3 to 5 rotor diameters separating towers within a row and 5 to 9 diameters between rows [6]. More conservative approaches suggest that the optimum spacing shall be 8 to 12 rotor diameters apart in the wind direction [2]. The offsetting, or staggering, of one row of towers behind another, as illustrated in Fig. (2) is also common [7, 8].

The GIS program can optimize turbine spotting within the selected project area so that maximum power can be installed or produced.

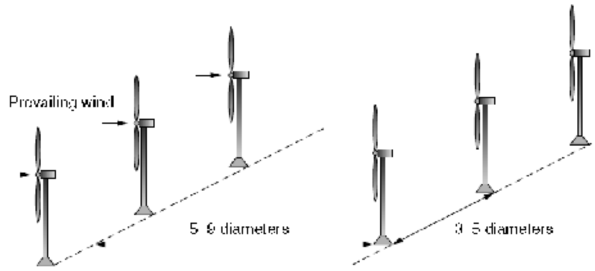

Figure (2): Optimum spacing of Wind Turbine towers

VI. APPLICATION OF GIS TO WIND FARM PLANNING

As the interest in renewable energy projects escalates, many contributions have been devoted to the planning of wind farm projects. However, few authors addressed the application of geographic information systems to wind farm planning.

Monteiro et al. [9] developed a method based on a GIS system to detect high potential areas for wind farm location. The proposed method utilizes the GIS system in two phases. In the first phase, the topography and roughness of terrain are transferred from the GIS to special software that generates the annual wind distributions in the area of interest. The wind distributions are then fed back to the GIS system to create the wind grid. In the second phase, the GIS system performs geographic filtering in order to exclude unfeasible places for wind farm sitting. The filtering process uses a set of rules defined by the user and having technical, social or administrative nature. The list of exclusion rules included the following:

- All places with more than 1000 m height.
- Protected and restricted zones such as national parks, airports, lakes, water zones, forests and urban areas.
- Places with more than 10% slope.
- Places in a certain range from any housing.
- Places with unsuitable wind speeds.

Apart from these constraints, the authors also considered the voltage drop obtained if a certain location is to be connected to loads or to the existing network. This led to the elimination of all locations having a voltage drop larger than 5%.

In [10], D. Elliott describes the methods developed by the U.S. National Renewable Energy Laboratory (NREL) to assess the wind resources and produce detailed high resolution (1 km^2) wind maps for any place in the world. The methodology integrates the global terrain and climatic data sets, GIS technology, and analytical and computational modeling techniques. The NREL methodology does not utilize GIS as a direct wind energy planning tool, however

GIS is the basic platform for the geographical data analysis and is also the tool for wind resources representation all over the world.

In [11], Ramirez et al. devoted their work to describing the capabilities of GIS in distributed generation planning. The authors outlined the digital data models supported by GIS, namely: raster, vector and surface data models. They also discussed the geo-computation techniques which increase the capabilities of GIS by adding modern computational methods and high level computing hardware. Geo-computation techniques can be programmed into the GIS software to calculate and analyze all technical and economical aspects of DG even in the situations of uncertainty, nonlinearity and discontinuity.

In [12], the authors proposed a tool to deal with the case where groups of different interests are involved in the selection of a wind project site. The criteria applied by the GIS software differ according to the preferences of each group. For example, an environmentalist group can use maps with legal environment restrictions, distances to inhabited areas, distances to avian protected corridors, etc. On the other hand, an investor group may use map indicators for the expected energy production cost, municipality influences, economic risk of the investment, terrain slopes, etc. The proposed system also involves methods for criteria standardization, relative weight assessment for different criteria and aggregation of preferences within each group and between groups as well. The main advantage in this approach is that all feasible alternatives are ranked on a 0 to 1 scale so that a consensual decision is attained far from the traditional accepted/not accepted approach. The proposed methodology is actually a midway point between deterministic and fuzzy decision making.

The work presented in [13] is similar to that in [9] but it addresses the specific case of Lebanon and considers fewer constraints. The site selection criteria include: average wind speed, distance from urban areas and shortest path to transformer substations. The paper also addressed the selection of wind turbines for residential application. A simple visual basic program was created to interface the non-technical user to the GIS system.

Baban and Parry in [14], proposed a procedure resembling the work published in [12] but much simpler. The GIS approach considered the issues of land elevation, distances from urban areas, historical sites, woods, water bodies and electrical grids. Also the effect of assigning different weights to the criteria of interest is discussed. The resulting map locations were ranked on a 0 to 1 scale.

Hillring and Kreig in [15], explored the wind energy potential in Sweden. They also estimated the annual wind energy production from five different wind turbines.

In [16], the authors studied the case of the island of Crete. The filtering procedure eliminated urban areas, location with certain altitudes and unfeasible locations due to geographical, economic, legal and aesthetic conditions.

The U.S. NREL has developed a baseline offshore wind resource GIS database [17]. The database aims to study the effect of water depth, the distance from shore to a wind project on the type of technology needed for project development, project's physical visibility, and provides information on the potential cost of development based on underwater cable needed to connect the offshore wind project to land-based energy resource demands.

VII. CONCLUSION

Geographical information systems have been used for planning wind energy projects for more than a decade. Although Egypt has an ambitious wind generation program, the contribution of GIS systems in this program needs more light to be shed on. The reviewed literature in this paper utilizes GIS for both filtering and planning purposes.

The filtering approach aims to exclude unsuitable locations for wind power generation according to certain criteria. The planning approach is technically and economically oriented and serves the decision making process through some alternative ranking procedures. The works involving alternative ranking make use of fuzzy like approaches to evaluate the preferences of planners with respect to a certain alternative.

VIII. ACKNOWLEDGEMENT

The authors would like to thank Dr. Akram I. Aly, Design & Specification Sector, Egyptian Electricity Holding Company, for his valuable contribution to this paper.

REFERENCES

[1] *World Wind Energy Report*, Bonn, Germany: World Wind Energy Association WWEA, 2009.

[2] Mukund R. Patel, *Wind and Solar Power Systems Design, Analysis, and Operation*, Taylor & Francis, 2006.

[3] *Egyptian Electricity Holding Company Annual Report*, Cairo: Egyptian Electricity Holding Company, 2008-2009.

[4] *Arab Electricity Magazine*, January-March 2010, p. 4.

[5] Tony Burton, David Sharpe, Nick Jenkins and Ervin Bossanyi, *Wind Energy Handbook*, John Wiley & Sons Ltd., 2001.

[6] Gilbert M Masters, *Renewable and Efficient Electric Power Systems*, Wiley Interscience, 2004.

[7] D. L. Elliot, *Status of Wake and Array Loss Research*, Palm Springs, California, AWEA Windpower 91 Conference, September 1991.

[8] M. J. Grubb and N. I. Meyer, *Wind Energy: Resources, Systems, and Regional Strategies*, Washington, D.C., Island Press, 1993.

[9] Claudio Monteiro , Joao Tome Saraiva, and Vladimiro Miranda, *Evaluation of Electrification Alternatives in Developing Countries*, 9th Mediterranean Electrotechnical Conference, MELECON 98, Vol. 2, 18-20 May 1998, pp. 1037-1041.

[10] D. L. Elliott, *Assessing the Worlds Wind Resources*, IEEE Power Engineering Review, Vol. 22, No. 9, September 2002, pp. 4-9.
[11] I. J. Ramírez-Rosado, L. A. Fernadez Jimenez, C. Monteiro, V. Miranda, E. García-Garrido, and P. J. Zorzano-Santamaría, *Powerful Planning Tools*, IEEE Power and Energy Magazine, Vol. 3, No. 2, March/April 2005, pp. 56-63.
[12] I. J. Ramírez-Rosado, C. Monteiro, E. García-Garrido, V. Miranda, L. A. Fernández-Jiménez, P. J. Zorzano-Santamaría, *Negotiation Aid System to Define Priority Maps for Wind Farm Development*, IEEE Transactions on Power Systems, Vol. 20, No. 2, May 2005, pp. 618-626.
[13] Ali M. Bazzi and D. A. Fares, *GIS Based Wind Farm Site Selection in Lebanon*, IEEE International Conference on Electro/Information Technology, May 2008, pp. 201-204.
[14] S. Baban and T. Parry, *Developing and Applying a GIS-Assisted Approach to Locating Wind Farms in the UK*, Renewable Energy, Vol. 24, No. 1, September 2001, pp. 59-71.
[15] R. Kreig Hillring, *Wind Energy Potential in Southern Sweden - Example of Planning Methodology*, Renewable Energy, Vol. 13, No. 4, April 1998, pp. 471-479.
[16] Voivontas, D. Assimacopolous, A. Mourelatos, J. Corominas, *Evaluation of Renewable Energy Potential Using a GIS Decision Support System*, Renewable Energy, Vol. 13, No. 3, January 1998, pp. 333-344.
[17] D. Heimiller, S. Haymes, M. Schwartz and W. Musial, *Offshore Wind Resource Potential of the United States*, OCEANS 2007, Vancouver, October 2007, pp. 1-8.