Using Multi-Criteria Evaluation to Determine Suitable Sites for Developing Wind Farms in Massachusetts

R U M I K A    C H A U D H R Y
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1. Project Introduction

The production and use of energy has more impact on the environment than any other human activity. Massachusetts like many other states through United States has just started to diversify its electricity generation portfolio by opting for wind power, which is one of the lower-impact forms of electricity available to us in terms of its benefits outlined at the regional and global level.

At present, there are number of wind power projects in Massachusetts, which are at various stages of operation and development. Table 1.1 on the next page gives a snapshot of these projects. Overall, Massachusetts ranks 32nd in United States in terms of its existing wind power generation capacity; estimated to be at 5.32 MW. With number of projects in pipeline, this figure is expected to increase by 860 MW in coming years. Massachusetts has a potential capacity of producing 2880 MW electrical energy by wind power that could bring its rank to 25th amongst all the other states in the United States.¹

Increasing Massachusetts’s potential would mean indentifying new sites for locating wind farms. According to the Renewable Energy Research Lab’s, Community Wind Fact-Sheet Series, the best wind power sites in Massachusetts are along the coast and on top of ridgelines in the western and central parts of the state. This assessment however, is based on a simple premise that areas receiving high annual wind speed can be the best candidate for developing wind farms too. But while wind energy is a real renewable energy resource it still has implications at local levels and far-reaching effects on natural and human environment. This means that planning and environmental restrictions and conflicts inevitably accompany the extension of wind energy.

This inevitably means that site location study for wind farm is not wind speed dependent and that there are in fact many underlying variables involved. It also means that different variables might not be of equal importance. Hence, we can say that decision-making on wind farm siting is a process characterized by complexity, uncertainty, multiple and sometimes conflicting management objectives, as well as integration of numerous and different data types.

¹ Source: http://www.awea.org/projects/Projects.aspx?s=Massachusetts
## Table 1.1 Wind Power Projects in Massachusetts, as of 2008

<table>
<thead>
<tr>
<th>Project</th>
<th>Status</th>
<th>Type</th>
<th>Location</th>
<th>Size</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hull Wind 2</td>
<td>Operating</td>
<td>Community Scale</td>
<td>Hull</td>
<td>1.8 MW</td>
<td>2006</td>
</tr>
<tr>
<td>Hull Wind 1</td>
<td>Operating</td>
<td>Community Scale</td>
<td>Hull</td>
<td>660 kW</td>
<td>2001</td>
</tr>
<tr>
<td>IBEW</td>
<td>Operating</td>
<td>Customer Sited</td>
<td>Boston</td>
<td>100 kW</td>
<td>2005</td>
</tr>
<tr>
<td>Mass Maritime Academy</td>
<td>Operating</td>
<td>Customer Sited</td>
<td>Bourne</td>
<td>660 kW</td>
<td>2006</td>
</tr>
<tr>
<td>Jiminy Peak</td>
<td>Operating</td>
<td>Customer Sited</td>
<td>Hancock</td>
<td>1.5 MW</td>
<td>2007</td>
</tr>
<tr>
<td>Forbes Park Wind Project</td>
<td>Operating Windfarm</td>
<td>Chelsea</td>
<td>600 kW</td>
<td>2008</td>
<td></td>
</tr>
<tr>
<td>Mass Planned Customer-Sited</td>
<td>Planned Community Scale</td>
<td>-</td>
<td>1.5 MW</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Mass Planned Community-Scale</td>
<td>Planned Community Scale</td>
<td>-</td>
<td>600 kW</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Hull Offshore</td>
<td>Planned Windfarm</td>
<td>Hull</td>
<td>12-14 MW</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Minuteman Wind</td>
<td>Seeking Permit</td>
<td>Windfarm</td>
<td>Savory</td>
<td>12.5 MW</td>
<td>-</td>
</tr>
<tr>
<td>Hoosac Wind Energy Project</td>
<td>Seeking Permit</td>
<td>Windfarm Florida and Monroe</td>
<td>30 MW</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Cape Wind</td>
<td>Seeking Permit</td>
<td>Windfarm</td>
<td>Nantucket Sounds</td>
<td>468 MW</td>
<td>-</td>
</tr>
<tr>
<td>PMLD Wind Farm</td>
<td>Construction Community Scale</td>
<td>Princeton</td>
<td>3 MW</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Berkshire Wind Power</td>
<td>Construction Windfarm</td>
<td>Brodie Mountain</td>
<td>15 MW</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>South Coast Offshore</td>
<td>In Development Windfarm</td>
<td>Buzzard’s Bay</td>
<td>300 MW</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Bog Wind</td>
<td>In Development Community Scale</td>
<td>Wareham</td>
<td>10-16 MW</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Projected coordinate system name: NAD_1983_StatePlane_Massachusetts_Mainland_FIPS_2001
Geographic coordinate system name: GCS_North_American_1983

Overarching Project Question

This project used Multi-Criteria Analysis to locate suitable wind farms sites in Massachusetts and then using the model developed, compare and assess how suitable for development, are these existing wind farms in Massachusetts.

The overarching questions for this project are:

1. Using the results of the Multi Criteria Analysis developed for this project; explain how suitable are the existing wind farm sites in Massachusetts?
2. How can Multi Criteria Analysis be used to locate suitable sites for wind farms in Massachusetts?
3. What process could be followed to set aside 19,000 hectares of the best sites for wind farm development?

Objectives

I. To develop criterion maps for the project, that could be used in running the Multi Criteria Analysis.
II. To develop a set of weights to establish the relative importance of the criteria maps to the objective under consideration.
III. To come up with the most suitable sites for wind farm development in Massachusetts using Multi Criteria Analysis.
IV. To investigate a procedure in Idrisi which can help locate areas of 19,000 hectares of the suitable sites acquired through Multi Criteria Analysis.
V. To perform an analysis which can help determine the suitability of the present wind farm sites in Massachusetts.
2. Data and Methodology

In order to achieve the objectives and answer the overarching questions of the project a spatial decision support system with multi-criteria capabilities, where decision will be derived from an assessment of suitability, the degree, to which a location belongs to the suitable or not suitable set, will be considered. Therefore, suitability of developing a wind farm site will not be Boolean in character, but rather expressed as varying degrees of set membership.

Multi-Criteria Decision Support

Two types of criteria support decision-making: constraints and factors. These criteria represent conditions possible to be quantified and contribute for the decision making (Eastman et al., 1993).

The constraints are based on the Boolean criteria, which limit the analyses to specific regions. The factors are criteria, which define some degree of suitability for all the geographic regions. They define areas or alternatives according to a continuous measure of suitability, enhancing or diminishing the importance of an alternative under consideration in the geographic space resulting after the exclusion of the areas defined by the restrictions. The factors indicate continuous degrees of fuzzy membership in the range between 0 and 255.

In order to locate suitable sites for developing wind farm in Massachusetts, we need to consider both kinds of criteria. The criteria selected for this project was based on reviewing planning and research literature developed specifically for siting wind farms in Massachusetts. Below are some basic guidelines that were considered while selecting criteria:

1. The criteria should represent national, regional and state-wide legislation related to wind farm development.
2. The criteria must also take into account local restrictions such as master plan and zoning ordinance.
3. The criteria should also incorporate local conditions such as site topology, hydrology, infrastructure and amenities, cultural, historical and social significance of the potential site amongst other things.
4. The criteria should consider some initial thought on the economic viability of the project and should take into account available wind resources.
Creating the Constraints Maps

For the constraints, all that is required is the development of Boolean, zero and ones, images. Zeros signifies areas where wind farm development is excluded and ones where it is permitted. In this case, six constraints were developed by considering the restrictions put forth by the Local, State and Federal agencies in Massachusetts for wind projects. The details can be found in the literature developed by Renewable Energy Research Laboratory, University of Massachusetts, Amherst\(^2\).

Table 2.1 Constraints identified for Developing Wind Farm Sites in Massachusetts

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Developable Land</td>
<td>Wind farms can only be sited on lands which are available for development.</td>
</tr>
<tr>
<td>(develandBOOL)</td>
<td></td>
</tr>
<tr>
<td>2. Wetlands</td>
<td>Wetlands are protected to various degrees at federal, state and local levels. In most cases they can not be altered, discharged into or built on to. They are not recommended for wind farm sitings.</td>
</tr>
<tr>
<td>(wetlandBOOL)</td>
<td></td>
</tr>
<tr>
<td>3. Slope</td>
<td>Slopes greater than 30(^{0}) should be avoided as they create undesirable wind turbulence, decrease accessibility through roads and increase construction costs.</td>
</tr>
<tr>
<td>(slopeBOOL)</td>
<td></td>
</tr>
</tbody>
</table>

\(^2\) Refer to Community Wind Power Fact Sheet # 7 for details on the considerations.
4. **Rare Species (rarespeciesBOOL)**

Federal, State and local Conservation Commissions laws requires that a new project must not “take” any federal or state rare or endangered species. Such areas must be avoided.

5. **Historical Landmarks (historicBOOL)**

Federal and Massachusetts Historic Commission protect National and State Historical Landmarks. These sites should be avoided.

6. **Areas of Critical Environmental Concern (ACEC) (ACECBOOL)**

Federal and State laws require that a new project must not fall within or disturb ACEC. Such areas must be avoided.

*Sources:*

http://www.mass.gov/mgis/laylist.htm

http://www.clarku.edu/departments/hero/data.cfm
Creating the Factor Maps

The development of factor maps involves two distinct steps. In the first step the basic factor map was developed. In the second step, all the maps were standardized to a byte range, positive integers from 0 to 255. This was done through first using the DISTANCE module to calculate the distance between each cell and the nearest of a set of target features and then using the FUZZY module to standardize the distance values to a byte range, positive integers from 0-255 (indicating a continuous increase from non-membership to complete membership). Unlike conventional power plants, where a wind turbine is located has a major effect on the amount of energy captured from the wind and electricity produced. At the same time, it has implications on the natural and physical environment. The quality of wind site depends on many factors:

Table 2.2 Factors identified for developing Wind Farm sites in Massachusetts

<table>
<thead>
<tr>
<th>Factors</th>
<th>Fuzzy Classification</th>
<th>Factor Weight</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Wind Speed 100m</td>
<td>Sigmoidal, Monotonically increasing (6,15)</td>
<td>0.4399</td>
<td>Most critical site characteristic. Wind maps alone, may not accurately represent a specific site. Locations with annual average wind speed of 6m/s or more at hub height are considered.</td>
</tr>
<tr>
<td>2. Transmission Lines</td>
<td>Linear, Monotonically decreasing (0, 26600)</td>
<td>0.0986</td>
<td>Building new transmission lines are expensive, so sites near existing power lines are highly desirable.</td>
</tr>
<tr>
<td>3. Slope</td>
<td>Sigmoidal, Monotonically decreasing (0, 30)</td>
<td>0.0636</td>
<td>Gradual slopes cause increase in wind speed and road accessibility. Construction is also more feasible.</td>
</tr>
<tr>
<td></td>
<td><strong>Risks</strong></td>
<td><strong>Fuzzy Classification</strong></td>
<td><strong>Factor Weight</strong></td>
</tr>
<tr>
<td>---</td>
<td>-----------</td>
<td>--------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>4.</td>
<td><strong>Roads</strong></td>
<td>Linear Monotonically decreasing $(0, 2660)$</td>
<td>0.1356</td>
</tr>
<tr>
<td>5.</td>
<td><strong>Routes</strong></td>
<td>Linear Monotonically decreasing $(0, 2660)$</td>
<td>0.1864</td>
</tr>
<tr>
<td>6.</td>
<td><strong>Elevation</strong></td>
<td>Linear Monotonically increasing $(0, 100)$</td>
<td>0.0488</td>
</tr>
<tr>
<td>7.</td>
<td><strong>Airports</strong></td>
<td>Linear Monotonically increasing $(0, 109000)$</td>
<td>0.0272</td>
</tr>
</tbody>
</table>

**Sources:** [http://www.mass.gov/mgis/laylist.htm](http://www.mass.gov/mgis/laylist.htm), [http://www.clarku.edu/departments/hero/data.cfm](http://www.clarku.edu/departments/hero/data.cfm)
**Weighting the Criteria**

Once the criteria maps had been created, the next step was to develop a set of weights to establish the relative importance to the objective under consideration. The weights will be real numbers which will sum up to 1.0. The factor maps will then be multiplied by their weights and subsequently added together. Since the weight sum up to 1.0 and the factor maps all have a standardized range of 0-255, the final weighted linear combination (WLC) will also have a range of 0-255 (*Eastman, 2006*).

Clearly, a problem such as determining suitable sites for wind farm development involves a considerable degree of uncertainty concerning the quantitative values of the weights and for this purpose the procedure of pairwise comparisons associated with Analytical Hierarchy Process (AHP) is appropriate. Although, usually this is done in a group using input from different stakeholders but for this project pairwise comparison was determine through the relative important the referred literature gave to each of these factors. Next, **WEIGHT** module in Idrisi was used to get the best fit weights and an indication of the consistency of the judgments. The consistency ratio measured fro this project was 0.10, which indicated that the pairwise rating was developed on at random.

The eigenvector of weights is:

```
airportFAC: 0.0272
elevationFAC: 0.0488
rdmajorFAC: 0.1356
rdrouteFAC: 0.1864
slopeFAC: 0.0636
windspeedFCA: 0.4399
transmissionFAC: 0.0986
```

Consistency ratio = 0.10
Consistency is acceptable.

Once, the weights to apply to the factors have been determine, Multi Criteria Evaluation (MCE) of the variables considered important in siting wind farm in Massachusetts can be undertaken. The result for this process can be seen on page 10.
3. Results and Discussion

The Multi-Criteria Evaluation for wind farm siting used Weighted Linear Combination (WLC) method to develop a map indicating the suitable sites for this purpose. Along with full tradeoff, this combination procedure is characterized by an average level of risk, as it is exactly midway between the minimization (AND operation) and maximization (OR operation) of areas to be considered suitable in the final result (*Eastman, 2006*).

The final suitability map for developing wind farms in Massachusetts, like factors, has a standardized range which shows suitability on a scale from (0-255). Higher numbers in this range indicates close to complete membership which means that the red pixels in the above analysis showed sites that are most suitable.
Research Question 1

Projected coordinate system name: NAD_1983_StatePlane_Massachusetts_Mainland_FIPS_2001
Geographic coordinate system name: GCS_North_American_1983

The next step of the analysis is to calculate percentage areas of highly suitable sites (defined as those sites with the suitability ranging from 155-255) within Massachusetts.

Calculation

Total Area of Massachusetts = 2,095,991.64 hectares
Total Area of highly suitable sites in Massachusetts
(Highly suitable sites are defined as those in the range between 155-255) = 189,409.59 hectares

Percentage area of the highly suitable sites in Massachusetts = 189,409.59 / 2,095,991.64 x 100
= 9.037 %
One of the research questions posed for this project was to assess the suitability of the already existing wind farm sites with the results of the investigation. This was achieved by overlaying (AND) the highly suitable sites for developing wind farm sites with the “wind power towns” layer in Massachusetts. The resulting image shows most of these towns do fall into the areas which have been identified as highly suitable sites for wind farm sites in Massachusetts. The result validates the accuracy of the model developed.

It will also be useful to investigate the percentage area of the highly suitable sites that have been used to some degree in Massachusetts (assumption here is that all the suitable site areas within a town have been used to full potential as of today)

Total Area of highly suitable sites in Massachusetts
(Highly suitable sites are defined as those in the range between 155-255) = 189,409.59 hectares
Total Area of highly suitable sites in “wind power towns” in Massachusetts = 5392.98 hectares

Percentage Area of highly suitable sites that have been used in Massachusetts for Wind Farms
= 5329.98 / 189,409.59 x 100 = 2.85 %
Research Question 2

Through the Multi Criteria Analysis, a comparative suitability of the wind farms siting in Massachusetts has been determined. In this phase of the analysis the result of MCE will be used to figure out sites which have the best 19,000 hectares to develop wind farms.

In order to achieve this goal data cells in the MCE diagram were rank order in terms of their suitability, and selected as many of the most highly ranked cell to total 19000 hectares. This will be achieved by the process in Idrisi as shown in the model diagram below.

Flow Diagram showing the process of locating 19,000 hectares of the best sites for wind farm development in Massachusetts

Projected coordinate system name: NAD_1983_StatePlane_Massachusetts_Mainland_FIPS_2001
Geographic coordinate system name: GCS_North_American_1983
Once the wind farm suitability map has been rank ordered, a given number of best cells can be isolated using RECLASS. The rank ordered image needs to be interpreted as cell numbers from the area. The following calculation will help achieve this.

Reclass

19,000 hectares of the best areas for wind farm development is needed

Each cell in the raster “ranked image” has an area of \(90\text{m} \times 90\text{m} = 8100\text{ sq. meter}\)

Or each cell has an area of \(0.81\text{ hectares}\)

Therefore, Wind farm sites adding up to 19,000 hectares would be equivalent of 23,457 cells

Projected coordinate system name: NAD_1983_StatePlane_Massachusetts_Mainland_FIPS_2001
Geographic coordinate system name: GCS_North_American_1983
Conclusions

The paper has described how to use fuzzy based Multi Criteria Analysis for the evolution of new wind farms. This process is able to handle the complexity, uncertainty, multiple and sometimes conflicting management objectives, which are characteristic for projects like wind farm sitings.

In this paper, number of constraints and factors are identified which can influence the decision of where wind farms could be sited in Massachusetts. There is a possibility that different localities and situations call for considering new criteria or eliminating old ones; MCE allows for easy integrating of new information into the analysis and assigning new weights when required. So, in this sense the process opted is flexible enough to account of adjustments arising for changes in situation, location, stakeholders, policies and bylaws concerning wind mill siting etc.

The model also includes and procures stakeholder and public participation in assigning weights to different factors; this increases the general likelihood of project acceptance by the stakeholders and general public.

The suitability of the model is further verified by looking at the overlay of the “present wind mill sites in Massachusetts” with “highly suitable sites Boolean” acquired from the MCE result. It shows that the towns using wind power at present also intersect with some of the best sites identified by the model. The present wind mill siting in Massachusetts were done through a through survey and hence, are quite a reliable source for cross examining the suitability of the model developed.
References

Resource Websites
   http://www.ceere.org/rerl/publications/published/communityWindFactSheets/
14. Massachusetts Division of Energy Resources, Model Amendment to a Zoning Ordinance or By-law: Allowing Wind Facilities by Special Permit.

Data Sources