Multi-Criteria Evaluation of the Appropriate Offshore Wind Farm Location in Nigeria

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Abstract - This paper presents a multi-criteria evaluation of the appropriate offshore wind farm location in Nigeria. The proposed site selection criterion takes into consideration the technical aspect of the Environment consideration. The four attributes considered in this work are proximity to power demand, Distance from Airport, Average wind speed and Interference with existing shipping route. These attributes were analyzed for three alternative locations (Victoria Island, Koko and Abbonema in Lagos, Warri and Port-Harcourt respectively) using Analytical Hierarchy Process to assign weight through pair-wise comparison and fuzzy TOPSIS Multi-criteria decision-making tool to make an appropriate selection. The results from this work showed that Victoria Island (Lagos) has the highest figure cumulative value of 894.23, Koko (Warri) has 740.04 and Abonnema (Port-Harcourt) with a value of 756.96.

1. Introduction

Energy provides an essential ingredient for almost all human activities: such as cooking and space/water heating, lighting, healthcare, food production and storage, education, mineral extraction, industrial production and transportation [1]. Nigeria’s energy is supplied from different hydro-power and thermal power stations. The extent of water available at these different hydro-power stations varies due to change in seasonality and this causes irregular supply at low water levels periods. The thermal power stations are also affected by lack of adequate supplies of natural gas [2]. The solution for the country is energy diversification. Harnessing offshore wind power was talked about as early as the 1930s, not until 1990, when the first modern offshore wind turbine was constructed 250 m offshore of Northern Sweden [3]. According to Okokpujie et al [4] and Odia et al. [5] the authors stated that wind turbine will serve as one of the major ways to resolve the issue of energy supply in Nigeria. Multiple-criteria decision making (MCDM) or Multiple-criteria decision analysis (MCDA) is a sub-discipline of operations research that explicitly evaluates multiple conflicting criteria in decision making (both in daily life and in settings such as business, government and medicine) [6]. Conflicting criteria are typical in evaluating options: cost or price is usually one of the main criteria, and some measure of quality is typically another criterion, easily in conflict with the cost. There have been important advances in this field since the start of the modern multiple-criteria decision-making discipline in the early 1960s [7]. The MCDM problem can be represented in the criterion space or the decision space. Alternatively, if different criteria are combined by a weighted linear function, it is also possible to represent the problem in the weight space. The analytic hierarchy process (AHP) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then. It has particular application in group decision making [8] and is used around the world in a wide variety of decision situations, in fields such as government, business, industry, healthcare, ship building and education, [9]. Once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them to each other two at a time, with respect to their impact on an element above them in the hierarchy. In making the comparisons, the decision makers can use concrete data about the elements, but they typically use their judgments about the elements' relative meaning and importance. It is the essence of the AHP that human judgments, and not just the underlying information, can be used in performing the evaluations [9].


AHP converts these evaluations to numerical values that can be processed and compared over the entire range of the problem. A numerical weight or priority is derived for each element of the hierarchy, allowing diverse and often incommensurable elements to be compared to one another in a rational and consistent way [10].

2. Data Collection

This study is limited to technical attribute required for the location of a wind farm. The considered data are Power Demand, Distance from Airport, Average wind speed and Shipping route. These data were collected for the three states i.e. Lagos, Warri and Port-Harcourt, which are the alternatives for which their attributes were analysed. The required Average Wind Speed was collected from the Nigerian Meteorological Agency (NIMET), while the quantitative attributes were sourced for and qualitative attributes were obtained using Questionnaires.

| Alternatives  | Years       | Average |     |
|---------------|-------------|---------|-----|
|               | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
| Lagos         | 7.21 | 6.49 | 7.27 | 7.32 | 7.21 | 7.6  | 5.88 | 4.83 | 4.7  | 4    |
| Warri         | 7.38 | 7.46 | 7.35 | 7.32 | 7.32 | 7.17 | 7.48 | 7.07 | 7.2  | 7.19 |
| Port Harcourt | 7.3  | 7.37 | 6.89 | 7.13 | 7.38 | 7.06 | 7.54 | 7.3  | 7.56 | 7.94 |

Table 1: Ten years’ average wind speed for Lagos, Warri and Port-Harcourt

| Attributes                  | Alternatives | Lagos | Warri | Port-Harcourt |
|-----------------------------|--------------|-------|-------|---------------|
| Power Demand                | 4.5          | 3.875 | 4.375 |
| Distance from Airport       | 533          | 438.5 | 448.23|
| Average Wind Speed          | 6.25         | 7.29  | 7.35  |
| Shipping Route              | 1.75         | 3.875 | 4.375 |

Table 2: Attributes Value for the three Alternatives

3. Multi-criteria Evaluation Process

The pair-wise element matrix is the first step to the application of Analytical Hierarchy Process: The matrix if formed by comparing one criterion against another. Two criteria with same level of importance will have a score of 1, a criterion that is more important than that which it’s been compared with will have its actual value on the Effective Criteria and Pair Wise Comparison while a criterion less important than that which it is been compared to will be score the inverse of its actual value on the Effective Criteria and Pair Wise Comparison as shown in Table 2.

\[
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & C_{14} \\
C_{21} & C_{22} & C_{23} & C_{24} \\
C_{31} & C_{32} & C_{33} & C_{34} \\
C_{41} & C_{42} & C_{43} & C_{44}
\end{bmatrix}
\]

Having completed the comparison matrix next is to normalize the matrix: The sum of the pair-wise criteria matrix column was calculated. Each entry in the column is then divided by the column sum to yield its normalized score, the sum of each column of the normalized matrix. These procedures are done with the equations (1) and (2).

\[
C_i = \sum_{j=1}^n C_{ij}
\]
\[ X_i = \frac{C_i}{\sum_{i=1}^{n} C_i} \]

(2)

**Consistency Analysis**

Consistency analysis involves the calculation of the Consistency Ratio (CR), Consistency Index (CI): while the Random Index has already been generated by Satty, 2008 as

| N  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|----|----|----|----|----|----|----|----|----|----|----|
| RI | 0.00 | 0.00 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.46 | 1.49 |

Notes: \( n = \) order of Matrix

To calculate the CI and CR the Matrix Multiplication Function was calculated using the EXCEL (=MMULT()) function.

\[
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & C_{14} \\
C_{21} & C_{22} & C_{23} & C_{24} \\
C_{31} & C_{32} & C_{33} & C_{34} \\
C_{41} & C_{42} & C_{43} & C_{44}
\end{bmatrix}
\times
\begin{bmatrix}
W_{11} \\
W_{21} \\
W_{31} \\
W_{41}
\end{bmatrix}
=
\begin{bmatrix}
C_{v11} \\
C_{v21} \\
C_{v31} \\
C_{v41}
\end{bmatrix}
\]

(3)

\[
Average(\mu) = \frac{\sum_{i=1}^{n} C_i}{n} 
\]

(4)

\[
\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (C_i - \mu)^2} 
\]

(5)

Below are the results for the Multi-criteria analysis of four (4) criteria for a 3 alternatives. Rating scale is as shown in Table 1.

| Table 4 Effective Criteria and Pair Wise Comparison |
|----------------------------------|-----------------|-----------------|-----------------|
| Factor                          | More Important than | Equal | Less Important than | Factor |
| C1                              | 1 2 3 4 5        | 1 1 2 3 4 5    | C2              |
| C2                              | 1 2 3 4 5        | 1 1 2 3 4 5    | C3              |
| C3                              | 1 2 3 4 5        | 1 1 2 3 4 5    | C4              |
| C4                              | 1 2 3 4 5        | 1 1 2 3 4 5    |                 |
Table 5 Pair Wise Comparison Matrix

| Factor | C1 | C2 | C3 | C4 |
|--------|----|----|----|----|
| C1     | 1  | 3  | 2  | 2  |
| C2     | 0.3333 | 1  | 0.5 | 0.5 |
| C3     | 0.5 | 2  | 1  | 1  |
| C4     | 0.5 | 2  | 1  | 1  |

Table 6 Column Total For Pair Wise Comparison Matrix

| Factor | C1 | C2 | C3 | C4 |
|--------|----|----|----|----|
| C1     | 1  | 3  | 2  | 2  |
| C2     | 0.3333 | 1  | 0.5 | 0.5 |
| C3     | 0.5 | 2  | 1  | 1  |
| C4     | 0.5 | 2  | 1  | 1  |
| Total  | 2.3333 | 8  | 4.5 | 4.5 |

Table 7 Row Total For Normalized Pair Wise Comparison Matrix

| Factor | C1 | C2 | C3 | C4 | Total | Average | Consistency Measure |
|--------|----|----|----|----|-------|---------|--------------------|
| C1     | 0.4285776 | 0.375 | 0.4444444 | 0.4444444 | 1.6924664 | 0.4231166 | 5.014431 |
| C2     | 0.1428449 | 0.125 | 0.1111111 | 0.1111111 | 0.4900671 | 0.1225168 | 5.030388 |
| C3     | 0.2142888 | 0.25  | 0.2222222 | 0.2222222 | 0.9087332 | 0.2271833 |
| C4     | 0.2142888 | 0.25  | 0.2222222 | 0.2222222 | 0.9087332 | 0.2271833 |
| Total  | 1  | 1  | 1  | 1  |       |         | 4.0978367 |

Table 8 Consistency Analysis For Normalized Pair Wise Comparison Matrix

| Factor | C1 | C2 | C3 | C4 | Total | Average | Consistency Measure |
|--------|----|----|----|----|-------|---------|--------------------|
| C1     | 0.4285776 | 0.375 | 0.4444444 | 0.4444444 | 1.6924664 | 0.4231166 | 5.014431 |
| C2     | 0.1428449 | 0.125 | 0.1111111 | 0.1111111 | 0.4900671 | 0.1225168 | 5.030388 |
| C3     | 0.2142888 | 0.25  | 0.2222222 | 0.2222222 | 0.9087332 | 0.2271833 |
| C4     | 0.2142888 | 0.25  | 0.2222222 | 0.2222222 | 0.9087332 | 0.2271833 |
| Total  | 1  | 1  | 1  | 1  |       |         | 4.0978367 |

Table 9 Criteria Weight from AHP analysis

| Criteria   | C1   | C2   | C3   | C4   |
|------------|------|------|------|------|
| Weight     | 0.48405 | 1.659624 | 0.933539 | 0.933539 |

Table 10 Decision Matrix

| Criteria       | Lagos | Warri | Port-Harcourt | Criteria Weight |
|----------------|-------|-------|----------------|-----------------|
| C1 Power Demand| 4.5   | 3.875 | 4.375          | 0.48405         |
| C2 Distance from Airport | 533 | 438.5 | 448.23 | 1.659624 |
| C3 Average Wind Speed | 6.25 | 7.29 | 7.35 | 0.933539 |
| C4 Shipping Route | 1.75 | 3.875 | 4.375 | 0.933539 |

Table 11 Result of Decision Matrix analysis

| Attributes     | Alternatives     |
|----------------|------------------|
|                | Lagos | Warri | Port-Harcourt |
|                | 4.5   | 3.875 | 4.375         |
| Power Demand     | 2.178225 | 1.875694 | 2.11771875 |
|------------------|----------|----------|------------|
| Distance from Airport | 884.5796 | 727.7451 | 743.8932655 |
| Average Wind Speed | 5.834619 | 6.805499 | 6.86151165 |
| Shipping Route    | 1.633693 | 3.617464 | 4.084233125 |
| **Total**         | 894.226  | 740.044  | 756.95673  |

Figure 1 Bar chart of the cumulative result for the three alternatives

4. Conclusions

Nigeria has a great potential for offshore wind farm projects and this should be considered to solve the issue of epileptic power supply in the country and the Analytic Hierarchy Process and fuzzy TOPSIS are applicable for the multi-criteria selection of the appropriate offshore wind farm location in Nigeria. The collected wind farm siting attributes revealed that the three alternatives showed a good wind speed characteristic and this was shown by the 10 years’ average wind speeds collected for three locations. The application of Analytic Hierarchy Process gave a normalized column total of 1, consistency index and consistency ratio within the expected range as stated by Satty, [10] and finally from the multi-criteria analysis, Victoria Island was found to show the highest consideration value.

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