Determination of Optimal Locations for Offshore Wind Farms Using the Analytical Hierarchy Process

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ABSTRACT


The ocean is one of the largest renewable energy sources. Offshore wind energy has attracted considerable attention owing to the increasing adoption of renewable energy technologies; therefore, it is vital to select the most appropriate sites for offshore wind farms. This study aims to select the optimal sites for offshore wind farms based on the analytical hierarchy process (AHP). This study considered 11 criteria: wind speed, water depth, distance from the shore, ship route density, military operations areas, marine ecosystem protection areas, marine biodiversity protection areas, special protected islands, protected areas for wildlife, cultural heritage sites, and national parks. The feasibility of potential sites for offshore wind farms was evaluated across the Korean Peninsula. The southern coast between Goheung and Yeosu is the most optimal area for installing offshore wind farms, followed by the west coast of Taean.

ADDITIONAL INDEX WORDS: Offshore wind farm, analytical hierarchy process, renewable energy.

INTRODUCTION

Renewable energy sources have attracted considerable interest worldwide. Among them, offshore wind power generation is considered a very efficient energy source. Wind power can replace existing fossil fuel power generation because it can produce electricity using only wind density without carbon dioxide emissions. Although offshore wind power generation requires a higher initial investment cost than onshore wind power, it does not have a limitation on the size of the power generation complex. The noise problem, which is a significant factor in civil petitions against wind power generation, can also be naturally avoided, thus facilitating the installation of a large-capacity power generation complex. Thus, price competitiveness increases. In particular, the Republic of Korea has a considerable interest in wind power generation. It is surrounded by the sea on three sides and has abundant offshore wind resources.

However, various factors such as economic standards (e.g., distance from the shoreline), technical standards (e.g., water depth), and social standards (e.g., sea routes) need to be considered for the feasibility of offshore wind power farms. Despite the wide acceptance of renewable energy, some concerns regarding the optimal locations of offshore wind farms exist.

Therefore, this study aims to determine the optimal locations for offshore wind farms across the Korean Peninsula. First, some areas, such as military operations areas, marine ecosystem protection areas, marine biodiversity protection areas, special protected islands, protected areas for wildlife, cultural heritage sites, and national parks, have been excluded using geographic information system (GIS) technology. Then, the AHP is used to solve complex decision-making problems by considering the wind speed, water depth, distance from the shoreline, and route density.

The remainder of this paper is organized as follows. Previous studies on the optimal locations of wind farms are reviewed in the Background section. Then, the proposed method based on AHP is presented in the Methods section. The Results section presents an experimental evaluation of the proposed method. The final section concludes the paper with a discussion on the limitations of the approach and future work.

BACKGROUND

Offshore wind power generation is more advantageous than onshore wind power generation owing to the relative abundance of wind energy. However, various factors must be considered when selecting a location for offshore wind power farms.

The selection of locations for offshore wind farm considering various factors has been studied using GIS technology. Elsner and Suarez (2019) identified the potential of offshore wind energy in high seas due to technological advances through geospatial models and discussed the related laws and policies. Mekonnen and Gorsevski (2015) analyzed the suitability of offshore wind power through the design of a web-based participatory GIS framework that can engage various stakeholders and the public. Cradden et al. (2016) used data and GIS for marine renewable energy (2001–2010) from all the European coasts to select locations accordingly. In addition, related issues such as the water depth for foundations, environmental restrictions, and port location were investigated and presented. Yamaguchi and
Ishihara (2014) investigated the wind climate in the coastal area of Japan’s Kanto region using a mesoscale model and estimated the offshore wind potential energy considering economic and social standards through GIS.

Furthermore, several studies have focused on economic evaluation. For example, Cavazzi and Dutton (2016) used GIS to evaluate the offshore wind energy potential of the UK economically. The renewable energy zone of the UK is divided into 10 km × 10 km grid squares, and the levelized cost of energy (LCOE) value of each grid cell is calculated and mapped to evaluate the wind energy potential economically. The result shows the highest energy potential in the open sea off the Scottish coast and the lowest energy potential near the coast with low average wind speeds. Kim et al. (2013) determined an optimal site for the first offshore wind farm on the Korean Peninsula (2012). The cost–benefit analysis was performed by the Korea Energy Research Institute (KIER) for each cell using the national wind resource map, water depth, and distance from the shoreline, and the optimal location was selected accordingly. Nagababu, Kachhwaha, and Savsani (2017) estimated the technological and economic potential of offshore wind in India, considering a levelized production cost map and human impact index.

In addition, studies have used AHP and GIS to resolve complex decision-making problems, such as optimal location selection. Vagiona and Karanikolas (2012) proposed an efficient method of locating an offshore wind power plant in Greece using AHP and GIS. All the coastal areas that do not satisfy specific criteria (wind speed, protected area, and water depth) were excluded using the GIS. The areas that were not excluded were selected through AHP. Ali, Lee, and Jang (2017) selected the optimal location by using GIS and AHP combined with fuzzy triangular number for onshore wind power plants in Korea. Ayodele et al. (2018) proposed a GIS-based model for the selection of locations for land wind power plants using the type-2 fuzzy AHP in Nigeria. The model focused on fuzzy sets to solve the uncertainty, ambiguity, and inconsistency problems in the selection of optimal wind-power plant locations. Mahdy and Bahaj (2018) selected offshore wind farms in Egypt using AHP and weighted linear combination. Table 1 summarizes the factors influencing the optimal locations of offshore and onshore wind farms.

This study focuses on the selection of optimal locations for offshore wind farms without considering economic factors. The study selects significant factors based on previous studies and utilizes AHP to find the optimal locations for offshore wind farms.

### METHODS
This study uses the AHP technique to find the optimal locations for offshore wind farms. The AHP technique, first formulated by Saaty (1994), has been used by scientists and decision makers for decades as a multiple-criteria decision analysis tool for solving complex decision problems. AHP has been used in various decision-making processes, including prioritization, planning and development, selection, and evaluation. AHP assists decision makers through a pairwise comparison of complex decision-making problems with various criteria, and GIS assists decision makers by analyzing, reporting, modeling, and mapping geographic information. Thus, the combination of AHP and GIS is an attractive tool for complex decision-making problems, such as selecting the locations of offshore wind power plants.

<table>
<thead>
<tr>
<th>Previous research</th>
<th>Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elsner and Suarez (2019)</td>
<td>Wind, water depth</td>
</tr>
<tr>
<td>Mekonnen and Gorsevski (2015)</td>
<td>Bird habitat, fish habitat, sport fishery effort, commercial fishery effort, distance from utilities, population density, distance from navigable waterways, distance from the shore.</td>
</tr>
<tr>
<td>Cradden et al. (2016)</td>
<td>Wind, wave, tidal current, electricity networks, logistics, shipping traffic, environmental protection</td>
</tr>
<tr>
<td>Yamaguchi and Ishihara (2014)</td>
<td>Wind, water depth, distance from the shore, national parks, fishery right, harbor and port</td>
</tr>
<tr>
<td>Cavazzi and Dutton (2016)</td>
<td>Wind speed, sea depth, slope of sea bottom, cable distance to the shore, distance to the nearest grid connection point, nature reserves, trade and shipping routes, military testing zones</td>
</tr>
<tr>
<td>Kim et al. (2013)</td>
<td>Wind, sea state, condition of location, environment</td>
</tr>
<tr>
<td>Nagababu, Kachhwaha, and Savsani (2017)</td>
<td>Wind, water depth, distance from the shore, human impact on marine ecosystem</td>
</tr>
<tr>
<td>Vagiona and Karanikolas (2012)</td>
<td>Wind, distance to protected areas, distance to ship routes, distance from the shore, connection to the electricity network</td>
</tr>
<tr>
<td>Ali, Lee, and Jang (2017)</td>
<td>Military zones and protected areas, land under use (tourism, historic, cultural, and religious places), natural and federal areas, railway and subway networks (wetlands, rivers, lakes, water reservoirs, and streams), public and community interest places, electric power stations, electricity lines and cables, road network, cities and towns with population greater than 10k, railway network, land slope (%), wind speed (m/s).</td>
</tr>
<tr>
<td>Ayodele et al. (2018)</td>
<td>Wind speed (m/s), slope (%), proximity to gridlines (m), proximity to roads (m), land cover, protected areas, rivers/water bodies, airport, urban areas, bird areas</td>
</tr>
<tr>
<td>Mahdy and Bahaj (2018)</td>
<td>Wind, water depth, cables, oil, parks, shipping routes, national grid, military areas, soil, distance to the shore, fishing areas</td>
</tr>
</tbody>
</table>

The AHP algorithm consists of five steps. The first step is the problem definition (e.g., determining the optimal location of offshore wind farms). The second step is to create a hierarchical structure for establishing standards and alternatives to achieve the objectives as shown in Figure 1. It is necessary to define the criteria for this purpose. The criteria in this study were determined to be wind speed, water depth, distance from the shore, and ship route density, based on the literature review.
The subsequent step is to conduct pairwise comparisons between different criteria. Equation (1) shows the matrix for pairwise comparisons. For example, \( a_{ij} \) represents the relative importance of \( A_i \) versus \( A_j \). The relative importance is usually assigned to \( a_{ii} \) on a nine-value scale ranging from 1 to 9. Here, “1” indicates that \( i \) is equally important as \( j \) and “9” indicates that \( i \) is much more important than \( j \). The definition of the AHP scale is presented in Table 2. Then, each element is divided by the sum of each column in Equations (2) and (3). Thus, the pairwise matrix comparisons can be generalized:

\[
\begin{bmatrix}
A_1 & A_2 & \ldots & A_n \\
A_1 & a_{11} & a_{12} & \ldots & a_{1n} \\
A_2 & a_{21} & a_{22} & \ldots & a_{2n} \\
A_3 & a_{31} & a_{32} & \ldots & a_{3n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
A_n & a_{n1} & a_{n2} & \ldots & a_{nn}
\end{bmatrix}
\]  

(1)

Table 2. Definition of the AHP scale.

<table>
<thead>
<tr>
<th>AHP Scale</th>
<th>Linguistic Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equally important</td>
</tr>
<tr>
<td>3</td>
<td>Weakly important</td>
</tr>
<tr>
<td>5</td>
<td>Fairly important</td>
</tr>
<tr>
<td>7</td>
<td>Strongly important</td>
</tr>
<tr>
<td>9</td>
<td>Absolutely important</td>
</tr>
<tr>
<td>2,4,6,8</td>
<td>Interpolation scale</td>
</tr>
</tbody>
</table>

The fourth step is to calculate the weights using Equation (4). The following step is used to calculate the consistency index (CI) using Equations (5)–(7):

\[
\omega_1 = \sum_{x=1}^{n} m_{1x} \cdot \frac{1}{n}
\]

(4)

A consistency check is required to verify the logical validity of the pairwise comparison. Saaty (1994) defined the CI as \((\lambda_{\text{max}} - n) / (n - 1)\) and the consistency ratio (CR) as CI/RI. Here, RI represents the random index for the corresponding matrix size, summarized in Table 3. If the CR is less than 0.1, the pairwise comparison is logically valid.

\[
\begin{bmatrix}
\omega_1 \\
\omega_2 \\
\omega_3 \\
\vdots \\
\omega_n
\end{bmatrix}
=
\begin{bmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\vdots \\
\sigma_n
\end{bmatrix}
\]

(5)

\[
\begin{bmatrix}
\lambda_1 \\
\lambda_2 \\
\lambda_3 \\
\vdots \\
\lambda_n
\end{bmatrix}
=
\begin{bmatrix}
\sigma_1/\omega_1 \\
\sigma_2/\omega_2 \\
\sigma_3/\omega_3 \\
\vdots \\
\sigma_n/\omega_n
\end{bmatrix}
\]

(6)

\[
\lambda_{\text{max}} = \frac{\lambda_1 + \lambda_2 + \lambda_3 + \ldots + \lambda_n}{n}, \quad \text{CI} = \frac{\lambda_{\text{max}} - n}{n - 1}, \quad \text{CR} = \frac{\text{CI}}{\text{RI}} < 0.1 \ (10\%)
\]

(7)

Table 3. Random index obtained from Saaty (1994).

<table>
<thead>
<tr>
<th>n</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
<td>0</td>
<td>0</td>
<td>0.52</td>
<td>0.89</td>
<td>1.11</td>
<td>1.25</td>
<td>1.35</td>
<td>1.40</td>
<td>1.45</td>
<td>1.49</td>
</tr>
</tbody>
</table>

The final step is to derive the priority of the potential locations. This process calculates the weight of the alternative by comparing each criterion. For instance, if there are 20 potential locations for offshore wind farms, the weights per criterion are compared among the potential locations.

RESULTS

The decision-making process for the optimal locations of offshore wind farms is divided into two main steps. The first step excludes the restricted areas using GIS. The restricted areas include military operations areas, marine ecosystem protection areas, marine biodiversity protection areas, special protected islands, protected areas for wildlife, cultural heritage sites, and national parks as shown in Figure 2.

In terms of water depth, areas with depth less than 15 m are excluded because of the difficulty of ship accessibility for the construction. Further, areas with depth more than 40 m are excluded because of a technical problem for offshore wind farm foundations. According to Figure 2, the military operations areas account for the largest proportion of the restricted areas, followed by national parks.
Figure 3 shows the potential sites for the offshore wind farms with a radius of 5 km based on national law. The potential sites for offshore wind farms are mainly located on the southwest coast. While the low depth or the presence of several islands prevents the installation of offshore wind farms across the west and south coasts, the deep water depth is a problem across the east coast.

GIS selects potential sites for offshore wind farms by excluding restricted areas. Then, the AHP determines the optimal locations for offshore wind farms. GIS selects 20 potential sites, as shown in Figure 3. The factors considered in AHP in this study are wind speed, water depth, distance from the shore, and ship route density. For example, Figure 4 illustrates the ship route density and distance from the shore. The ship route density is calculated using automatic identification system data, which is a self-reporting maritime system (Jeong et al., 2020).

The AHP determines the optimal sites as the order of locations listed in Table 4. For example, sites 14, 15, and 16 across the southern coast between Goheung and Yeosu are the most optimal for installing offshore wind farms, followed by sites on the west coast of Taean (i.e., 2 and 3).

DISCUSSION AND CONCLUSIONS
This study aimed to select the optimal locations for offshore wind farms across the Korean Peninsula. GIS was utilized to select the potential sites, and then, AHP was utilized to determine the optimal locations.

The experimental results show that various factors should be considered together. For instance, although the wind speeds of sites 16 and 18 are lower compared with those of the others, these sites are the 3rd and 4th optimal locations because of their favorable values of water depth and distance from the shore. Further, site 5 has a higher wind speed than the other regions, but it is ranked low because it is unfavorable in all the other aspects, such as water depth, distance from the shore, and route density.

The selection of the optimal offshore wind farm is a complex process because numerous factors must be considered. This study examined the optimal locations for offshore wind farms using GIS and AHP. However, further studies should focus on economic evaluations, such as LCOE analysis, for the selection of economical locations for offshore wind farms. In addition, the law on installing and managing renewable energy farms should be considered.

ACKNOWLEDGMENTS
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Table 4. Final prioritization of offshore wind farm sites (%).

| Weight | 14 | 15 | 16 | 18 | 2 | 10 | 13 | 9 | 7 | 3 | 12 | 1 | 17 | 4 | 8 | 5 | 19 | 20 | 11 CR |
|--------|----|----|----|----|---|----|----|---|---|---|----|---|----|---|----|---|----|----|     |
| Goal   | 100.0 | 8.2 | 7.3 | 7.3 | 6.7 | 5.6 | 5.5 | 5.1 | 5.1 | 4.8 | 4.6 | 4.4 | 4.4 | 4.1 | 4.0 | 4.0 | 3.9 | 3.7 | 3.2 | 3.1 | 1.2 |
| Wind speed | 46.7 | 3.0 | 3.0 | 1.7 | 0.5 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 1.1 | 3.0 | 1.1 | 3.0 | 0.7 | 0.6 | 1.7 | 0.5 |
| Water Depth | 27.7 | 3.3 | 3.3 | 4.4 | 4.4 | 1.8 | 0.3 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.3 | 0.8 | 0.8 | 0.8 | 1.8 | 0.3 | 1.2 | 0.4 | 0.4 | 0.3 | 2.2 |
| Distance from the shore | 16.0 | 1.7 | 1.1 | 1.1 | 1.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.4 | 0.2 | 0.3 | 0.3 | 0.3 | 1.1 | 0.4 | 1.1 | 0.2 | 1.7 | 1.7 | 0.2 | 1.5 |
| Route density | 9.5 | 0.2 | 0.4 | 0.2 | 0.1 | 0.1 | 1.3 | 0.9 | 0.9 | 0.8 | 0.9 | 0.9 | 0.3 | 0.8 | 0.3 | 0.7 | 0.2 | 0.1 | 0.1 | 0.9 | 3.5 |

LITERATURE CITED


