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Published in:
2023 IEEE 32nd International Symposium on Industrial Electronics, ISIE 2023 - Proceedings

DOI:
10.1109/ISIE51358.2023.10227990

Published: 01/01/2023

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:

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Mapping the Optimal Sites for Offshore Wind Power Plants and Green Hydrogen Production: South and Southeast Brazilian Case Study

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Abstract—The demand for renewable energy solutions has become a global trend due to the current climate change scenario and the increased demand for electricity. Hence, in several countries, the share of renewable sources in the electric matrix has grown with the insertion of new energy sources, such as offshore wind. Brazil presents optimal conditions for the construction of offshore wind farms. The Brazilian 10-year Energy Expansion Plan 2029, in addition to placing this source as an expansion for the coming years, intensely focuses on hydrogen. For this reason, this study aims to assist planners and agents interested in running new construction projects of offshore wind farms with green hydrogen production. Such a study case seeks better use of the available wind resources in the high energy consumption regions of Brazil's South and Southeast, assessing the wind resource considering technical, environmental, social, and economic restrictions to identify the best locations for installing wind farms. As such, it processes the data within a geographic information system, and then a fuzzy logic-based model is used for the joint evaluation of constraints. Results show that Rio de Janeiro and Espírito Santo are the most favorable places.

Index Terms—Fuzzy Logic, Geographic Information System, Green Hydrogen, Offshore Wind Energy

I. INTRODUCTION

Currently, the global trend focusing on environmental issues has led many countries to become responsible for increasing the quality of their energy supply by replacing, whenever possible, fossil fuels with renewable energy sources, in order to reduce the emission of greenhouse gases [1]. In this scenario, the offshore wind source has been gaining prominence due to the great availability of winds on the planet, the possibility of more robust ventures than those on land, and the maturity of wind technology in terms of efficiency and cost [2], [3].

Brazil has an electric energy matrix composed mainly of hydraulic sources, which poses a fragility in the energy supply when it is subject to climatic weather, which culminates in using more polluting and expensive energy sources [4]. The periods when the best wind speeds are recorded are when the drought seasons occur [2]. Aside from that, according to the National Electric Energy Agency (ANEEL), the country’s location provides a wind regime twice the world average and with an oscillation of only 5%, which provides greater predictability of supply [5]. The use of wind sources can complement the energy matrix in a clean and sustainable way. This source has been recently inserted in the medium-term horizon and considered for the first time as a candidate source for expansion in the analyses conducted on the 10-year Energy Expansion Plan, namely PDE 2029 [6]. According to IBAMA, there are 70 ongoing environmental licensing processes for offshore wind turbines at this institute until December 5, 2022 [7]. Among those, 13 projects are located in the Southeast Region, between the states of Espírito Santo and Rio de Janeiro, and 22 projects are located in the South Region, between the states of Santa Catarina and Rio Grande do Sul.

For the approval of offshore wind plant projects by IBAMA, it is essential to evaluate the offshore wind potential of the region of interest, considering environmental and social factors, with the purpose of mitigating impacts. The input of technical factors in this evaluation is also important to identify the locations with the best characteristics of wind speed and water depth in order to determine the layout of the wind farm.
As such, this study case aims to show the evaluation of favorable sites for implementing offshore wind power plants in the Brazilian regions with higher electricity consumption, which are in the South and Southeast. By such evaluation, we seek a better use of the wind resource available for energy generation and green hydrogen production, respecting technical, environmental, and social restrictions. Considering these constraints present a high spatial dispersion in the study zone, the study uses the Geographic Information System (GIS) for information processing. Data is then processed, through Python programming language, using fuzzy logic to perform a joint evaluation of constraints.

According to [8], hydrogen enables efficient energy storage for long periods and can be used for mobility and distributed energy generation. In [9], modeling of hydrogen production through offshore wind energy was presented. A georeferenced analysis of the potential of technical and theoretical production was performed considering technical, environmental, and economic restrictions. The study also showed the mapping of economic indicators, such as Levelized Cost of Electricity (LCOE) and Levelized Cost of Hydrogen (LCOH).

In [10], the authors developed a methodology to evaluate the viability of hydrogen production from offshore wind farms. The study demonstrates how to calculate wind energy production, electrolysis plant size, and hydrogen production from wind time speed. The costs are projected for the year 2030, by means of the Net Present Value (NPV) and the Discounted Payback.

In [11], an evaluation was performed from the technical and economic point of view on the electricity supply generated by offshore wind turbines to an electrolyzer. The simulation was made in the hybrid optimization model for Electric Renewable software - Hybrid Optimization of Multiple Energy Resources (HOMER). Criteria for analysis were: comparison of generation curves, financial impacts of energy storage, and capacity factor compared to onshore wind.

In [12] and [13], some methodologies were presented for site evaluation in the state of São Paulo, with the potential for the implementation of wind generators with a focus on sustainable development. Both researchers considered social and environmental factors that can influence the development of onshore wind power plant projects. The authors in [13] used multi-criteria techniques, whereas in [12], GIS and Fuzzy-AHP were used for the selection of the most suitable municipalities for the installation of onshore wind power plants. Similar to [12], the GIS was also used in [14], but combined with fuzzy logic within the Python language, to develop a methodology for spatial and temporal analysis of the distribution of photovoltaic adopted by subarea (census tracts).

Over the years, with the development of technology and the beginning of the depletion of sites for the installation of onshore wind power plants, studies began to focus on evaluating sites conducive to the installation of offshore wind farms. In this scenario, [1] developed a study to evaluate the offshore wind potential of Brazil, with the purpose of mapping the best areas for source development and estimating the capacity that could be installed on the Brazilian coast. The analysis considered the theoretical offshore wind potential as well as technical, environmental and social limitations, which would economically enable the implementation of wind farms. The final choice of the best areas was made by multi-criteria spatial analysis. Also, in the Brazilian scenario, [5] elaborated a methodology using Excel software and data collected from ocean buoys and automatic weather stations, aiming at complementing the electrical matrix of the Southeast region from the identification of the best locations for the use of offshore wind energy.

In [15], an assessment of the Brazilian offshore wind potential was made through the mapping of potential at different levels - gross, technical, environmental and social-highlighting the most economically attractive areas for the implementation of offshore wind by means of a spatial analysis of Multi-Criterion Decision.

The author in [17] performed research on optimizing the layout of offshore wind farms, maximizing the extracted power, and minimizing the cost of the enterprise. Similarly, [18] followed the same line aiming to maximize power extraction and minimize electrical losses and cable costs in the construction of offshore wind farms. To determine the layout of wind farms, the author considered partial, multiple and total interferences of the wake effect. Different angles of wind incidence, mean speed and probability of occurrence were also considered. In [19], a new methodology was proposed to determine the optimal electrical connection point of offshore wind farms, with the aim of maximizing energy penetration, considering Benders’ decomposition approach.

In the global offshore wind scenario, in [20], the authors performed a study to identify marine areas in Greece that are best suited for deploying offshore renewable energy sources, wind and wave energy. The authors used GIS and analytical hierarchy processes to make the analysis, considering exclusion criteria related to economic, technical and social limitations. The GIS was also used in [21] combined with financial parameters and economic, technical and social criteria to assess the resource of economically accessible offshore wind energy to the UK.

As a summary of studies in the area of offshore wind power plants and GIS, [22] made a reference review that has brought out some trends: (1) less than 40% of the analyzed studies considered aspects of marine space planning and less than 20% mentioned requirements for environmental impact assessment; (2) the maximum viable depth of water constantly increases over time, driven by the advancement of technology; (3) spatial data resolutions vary dramatically between studies; (4) the analyses of the selection of sites are typified by the most frequent and significant deviations of global trends, both in relation to water depth and in relation to spatial resolutions; and (5) the number of parameters evaluated in GIS range from 2 to 14.

The literature review shows the tendency to use GIS in studies evaluating wind potential or determining favorable sites for
installing wind power plants. However, some studies also use multi-criteria decision analysis. As such, this paper identifies good areas for implementing offshore wind power plants in the regions with high energy consumption in the South and Southeast of Brazil. For this identification, a methodology based on fuzzy logic was performed to characterize better planners’ subjective evaluations concerning environmental, technical, and social dimensions. Furthermore, this study also evaluates the estimates and values of investments through capital expenditures (CAPEX) and operational and maintenance costs (OPEX) of the enterprises to indicate the best locations for investments in offshore wind plants and green hydrogen production.

II. MAPPING THE OPTIMAL SITES FOR OFFSHORE WIND POWER PLANTS AND GREEN HYDROGEN PRODUCTION

The performed methodology considers two information bases:
- Formed with data with geographic coordinates; and
- Formed by “IF-THEN” rules and Fuzzy inference parameters. In this research, the fuzzy inference technique used was the Mamdani method.

In the first stage, the data with geographic coordinates are as follows: wind speed, conservation units of integral protection and sustainable use, priority areas for conservation classified with extremely high priority, substations and water depth. At this stage, a GIS is used to select the sites of greatest interest for the study, excluding sites that do not meet environmental, technical and social restrictions. It is also at this stage that the distances from the study point to the coast and the nearest substations are calculated. The result of the first stage is a table that shows the values of wind speed, water depth and distances calculated in the places that comply with all technical, environmental and social restrictions.

In the second stage, estimated CAPEX and OPEX information is added for each study point. The output data of the first stage with the input data of the second stage have a membership relationship. In the fuzzy inference system, the data are represented by means of pertinence functions, which represent the linguistic variables - low, medium, high - and their respective interval ranges, which can be defined and modified within the fuzzy inference system. These functions can be triangular, trapezoidal, or Gaussian, among others. Through the defuzzifiers, the percentage of possibility of implementation of offshore wind power plants with green hydrogen production was obtained for each point analyzed.

The final result of the methodology presents the best-ranked sites for the installation of these plants. Fig. 1 shows the flowchart of the proposed methodology.

A. Case Study

1) Study area Characterization: The case study was developed for the Southeast region, where the largest states with the highest electricity consumption in Brazil are located. The data used were:

- Offshore wind speed at the height of 100 meters, data are taken from the Electric Power Research Center database [24];
- Power substations, data taken from the Operador Nacional do Sistema [26];
- Depth and bathymetry data are taken from the databases of the Geological Service of Brazil – Center for Technological Development [25];
- Location of the Full Protection and Sustainable Use Conservation Units (UCs), data taken from the database of the Brazilian Institute of Environment and Natural Resources [27];
- Priority Areas for Conservation, data taken from the database of the Ministry of Environment [28].

Fig. 2 shows the closest substations to the Brazilian coast. Through the power of the substations, it was possible to calculate the energy that would be delivered to the grid and the amount of hydrogen that could be produced with the energy produced by the offshore wind plant.

The wind speed points were selected considering a speed above 7 m/s, according to technical restriction, which is the minimum speed that enables generation, considering commercial wind turbines. Furthermore, points located less than 8 km from the coast were excluded in order to meet the social restriction, preventing wind turbines from causing visual impact or reaching pipelines [1]. For the wind speed points, adhering to technical, social and environmental restrictions
was analyzed, considering the water depth values in each position.

In order to avoid negative impacts on fishing activities and sensitive biological groups, an environmental restriction was used in areas of conservation units and priority areas for conservation [1]. These areas are shown in Fig. 3.

![Figure 3: Conservation Units and Priority Areas for Conservation.](image)

As a result, a table was generated with the geographic coordinates of each point and their respective wind speed values, water depth, distance from the coast and distance to the nearest substation.

To find the most favorable locations for implementing offshore wind power plants with green hydrogen production, we carry out an analysis, through fuzzy logic, of the result of this first step with the estimated values of CAPEX and OPEX, calculated following the methodology of [10].

First, the power output of a wind turbine, $P(t)$, is calculated according to (1), which is used then to calculate the time-varying power output of the entire wind farm, $P_{farm}$, Equation (2), where $\rho$ is the air density, $A$ is the rotor area, $C_{tot}$ is the overall efficiency coefficient (ranging from 0.3 to 0.5), $v$ is the wind speed, and $N$ is the number of turbines in the wind farm [10].

$$P(t) = 0.5 \cdot \rho \cdot A \cdot C_{tot} \cdot v^3$$  \hspace{1cm} (1)

$$P_{farm}(t) = \sum_{i=1}^{N} P(t)$$  \hspace{1cm} (2)

The following assumptions were considered:

- Each turbine uses the same wind power curve;
- Wind shear effects, change in air density, wake effect, and turbulence caused by other turbines are not considered;
- A 95% availability was considered for the wind farm.

For the calculation of hydrogen production, equation (4), the electrolyzer manufacturer specifies the electricity consumed, $E_{elec}$, for the production of one unit of hydrogen (MWh/kg). The electricity consumed for water purification, hydrogen compression and other losses are also considered in the calculation, $E_{pel}$ in (MWh/kg) [10]. From this standpoint, based on the theoretical maximum hourly hydrogen production, the Rated Capacity of the plant, $P_{H2,plant}$, represented in the equation (3), was also calculated, where $W_{H2}$ is the amount of hydrogen produced per hour and $\eta_{conv}$ is the conversion efficiency.

$$P_{H2, plant} \leq \text{max} W_{H2}(t) \times E_{elec}[MW]$$\hspace{1cm} (3)

$$P_{H2}(t) = \frac{P_{farm}(t) \times \text{hour}}{\eta_{elec} \cdot H_{2}} + E_{pel}[kg/hour]$$\hspace{1cm} (4)

To calculate the CAPEX of the offshore wind plant, it is necessary to consider the capital expense of the plant and equipment - including electrical cables and substations [10]. Our case study looks at the nearest substation to be used and deletes this expense.

To calculate the CAPEX of the electrolysis plant, the capital expenditure on the platform, installation, water purification system and power supply system are considered. The total CAPEX ($C_0$) is calculated by adding the CAPEX of the offshore wind plant ($C_{0,wind}$), the electrolysis plant system ($C_{0,H2plant}$), together with the CAPEX of the hydrogen storage ($C_{0,storage}$), which includes construction and pipeline system, according to (5). It is important to consider that the storage capacity of the project should be aligned with the technological advance and the availability of maritime hydrogen transportation by tankers [10].

$$C_0 = C_{0,wind} + C_{0,H2plant} + C_{0,storage}$$\hspace{1cm} (5)

The OPEX for both the offshore wind plant and the electrolysis system is continuous. Therefore, to calculate the total OPEX ($OPEX_0$), the OPEX of the wind plant ($OPEX_{wind}$) is added together with the OPEX of the electrolysis system ($OPEX_{H2plant}$), including the costs for labor, water purification, hydrogen compression and pumping to the storage facility.

$$OPEX_0 = OPEX_{wind} + OPEX_{H2plant}$$\hspace{1cm} (6)

2) Fuzzy Logic Modeling: the table generated in the previous stage, along with the final values of CAPEX AND OPEX, was used as input data for the fuzzy inference system to determine favorable locations for offshore wind power plants with green hydrogen production.

Table I presents the classification used in the fuzzy inference system for the distance from the analyzed points as far as a substation or the coast. The distance from the coast also defines whether the transmission will be made through high voltage cables by alternating current or by direct current. Alternating current transmission is more common for small distances and direct current transmission is more suitable for long distances, as in wind farms located from 50 to 100 km from the earth [1], [30], [31]. This study considered that the shorter the distance to a substation, the more attractive it will be for the implementation of offshore wind farms.
TABLE I
Classification of the input data of distance about the site to the coast or the nearest substation.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near</td>
<td>0 - 75</td>
</tr>
<tr>
<td>Medium</td>
<td>65 - 105</td>
</tr>
<tr>
<td>Far</td>
<td>95 - 200</td>
</tr>
</tbody>
</table>

Table II presents the classification used in the system for wind speed. This data is considered the most relevant in the financial evaluation of wind projects since the electrical generation and the capacity factor depend on speed. For this criterion, the higher the wind speed at the analyzed site, the more attractive the implementation of wind power plants will be.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Wind speed [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>7.0 - 8.5</td>
</tr>
<tr>
<td>Average</td>
<td>7.5 - 10.0</td>
</tr>
<tr>
<td>High</td>
<td>9.0 - 15.5</td>
</tr>
</tbody>
</table>

Table III presents the classification used in the system for water depth. This is also considered a very important criterion, as the installation costs of the plants increase with lower depths. Foundation types for larger depths have high implementation costs [21]. Thus, the shallower the water depth, the more economically attractive the implementation of offshore wind farms will be.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Depth [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow</td>
<td>0 - 25</td>
</tr>
<tr>
<td>Medium</td>
<td>15 - 55</td>
</tr>
<tr>
<td>Deep</td>
<td>45 - 1000</td>
</tr>
</tbody>
</table>

Table IV presents the classification used in the system for values of the total CAPEX and OPEX value of the offshore wind plant with hydrogen production. For annual values and the rating is according to [9] and [10].

<table>
<thead>
<tr>
<th>Classification</th>
<th>CAPEX+OPEX [M€/MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>1.65 - 2.35</td>
</tr>
<tr>
<td>Medium</td>
<td>2.25 - 3.10</td>
</tr>
<tr>
<td>High</td>
<td>2.95 - 3.55</td>
</tr>
</tbody>
</table>

In this study, 81 fuzzy rules were defined in Python to relate input data (antecedent) to determine output data (consequent). The number of rules is determined according to the number of input variables, 4, and linguistic variables, 3, so $3^4 = 81$. Taking Rule 1 as an example, we have: "IF total CAPEX + OPEX is cheap AND the substation is close AND the speed is low AND if it is shallow (depth) THEN the possibility of implementing offshore wind plant with hydrogen production will be medium." It can be noticed that the low wind speed influences the opportunity for implantation, thus reducing the possibility.

Fig. 4 shows the output fuzzy set, representing the linguistic variable of the percentage possibility of offshore wind power plants implementation.

![Fig. 4. Membership functions of output data.](image)

The values assumed by this linguistic variable - Low, Medium and High - are represented by fuzzy sets. The graphic representation of these sets is made by means of the trapezoid and triangular pertinence functions. For each input data, 3 pertinence functions are considered, representing each linguistic variable. Such functions and their intervals can be modified depending on the planner’s expertise and knowledge.

The classification shown in Table V refers to the output of the fuzzy inference system and shows the ranges of the membership functions.

<table>
<thead>
<tr>
<th>Classification</th>
<th>CAPEX+OPEX [M€/MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>0 - 50</td>
</tr>
<tr>
<td>Medium</td>
<td>40 - 80</td>
</tr>
<tr>
<td>High</td>
<td>From 70 up</td>
</tr>
</tbody>
</table>

III. RESULTS

The table generated as a result of the first step has 923 points. This table was inserted in the fuzzy inference system to perform the evaluation of the most favorable sites for the implementation of offshore wind power plants with hydrogen production. The points with classification above 60% are shown in Fig. 5, representing 67 sites with the possibility of implementing offshore wind plants. The points are located in the Southeast Region, between the coast of Rio de Janeiro and Espírito Santo. These sites are classified as Medium- or High-possibility of installation of offshore wind turbines with green hydrogen production.
IV. DISCUSSION

The locations found by the proposal and shown in Fig. 5 and show the following characteristics: (1) Distance from the substation: Near or Medium, presenting only 2 points classified as Far; (2) wind speed ranging between the Average and High ratings; (3) Water depth varying between shallow and medium ratings; and (4) CAPEX and OPEX ranging between the Low and Medium ratings.

The results obtained in this study present the same region of location as the results obtained in the proposal [4]. However, this proposal replaced transmission lines with power substations and added the analysis of green hydrogen production from the offshore wind plant, analyzing the annual investment through the insertion of CAPEX and OPEX in the analysis. In the analysis of the first stage, it was observed that many points located on the coast of the South and Southeast regions were excluded by the restrictions related to the areas of conservation units and priority areas for conservation with extremely high priority. As shown in Figure 3, these areas cover much of the Brazilian Southern and Southeastern coasts and, as a consequence, many points were excluded from the fuzzy analysis.

V. CONCLUSIONS

This paper has provided a tool to evaluate favorable sites for implementing offshore wind power plants with green hydrogen production in the Brazilian regions with higher electricity consumption, placed in the South and Southeast. For this evaluation, a Geographic Information System has been used in a fuzzy inference system set, programmed in Python language, to estimate the most favorable sites. It is noteworthy to mention that the premises used in the study add some uncertainties due to the perceptions defined based on rules, which may differ according to the perspective of different experts. The most favorable sites for implementing offshore wind power plants are between the states of Rio de Janeiro and Espírito Santo, as in the previous study. Other parts of the South and Southeast regions also present good conditions for implementing wind power plants; however, they were removed from the analysis due to the environmental restrictions considered in the study.

The results of the performed methodology are expected to assist in the decision-making process of planners and agents in expanding offshore wind power projects involving green hydrogen production. Furthermore, the results can serve as a basis for further studies not only in other regions of Brazil but also in other countries. Moreover, the proposed methodology can help decision-makers to identify green hydrogen production sites such that the byproduct heat can be efficiently used in the heating network of potential countries such as Finland, Denmark, Norway, and Sweden.

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