Methodology for offshore renewable energy site selection using economic decision factors

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Abstract: This paper presents a new methodology of Multi-Criteria Analysis for offshore renewable energy site selection. Rather than using only weighting and mixing geo-physical and non-geo-physical properties in a subjective way, it defines costs related from those properties (distances, depth, energy and environment), giving access to more objective and absolute suitability values for the studied areas.

Keywords: Multi-Criteria Analysis, Site selection, Offshore wind energy, Wave energy, Cost functions.

1. INTRODUCTION

The very limited experience in offshore renewable energy projects renders their development and exploitation challenging topics. Today, as the purpose is to reach an attractive sale price of electricity, it is fundamental to ensure that all aspects of the project are cost efficient. One of the fundamental aspects of an ORE project is to find the most suitable sites available for its development. Indeed, the location of the plant can have a significant impact on the overall economic viability.

In order to select the appropriate site, a technique commonly used is the Multi-Criteria Analysis (MCA), often based on GIS tools. Its purpose is to weight energy resource, technical and non-technical constraints, geographically dependent. But, as stated in [1], early methods of MCA use experts perception to reclassify and weight criteria, that may lead to subjective results, as they may consider differently how a given factor impacts the overall project feasibility.

To help overcome these limitations, this document, following recommendations of M. Silva & al [1], will describe a site selection methodology including objective economic factors or functions, related to geographical and geo-physical characteristics of studied areas.

This document will review the current common MCA methodologies from existing literature. Then, cost functions related to geographical and geo-physical parameters will be described, a methodology proposed and applied on a concrete case, using GIS software. The general idea being to be able to use this methodology for general assessment of sites, upon governments or developers’ requests, ensuring, at a pre-feasibility stage, that decision-makers are provided with an objective view of potentially viable sites and at the same time avoiding conflicts of marine space users.

Finally, the results will be discussed and improvements will be suggested.

2. STATE OF THE ART

In the available literature, site selection through multi-criteria analysis is performed in different ways, but a common procedure is often applied to analyse suitable areas regarding competition for space. Indeed, one of the key aspects of site selection, which should be considered as a first step in any site selection process, is to limit conflicts with existing offshore activities or restrictions, such as (non-exhaustive list):

- Conservation and protected areas,
- Fishery areas,
- Aquaculture areas,
- Military areas,
- Maritime routes or corridors,
- Other power plants,
- Oil rigs,
- Cables & pipelines.

The multi-criteria analysis is then performed on the region of interest, generally resorting to two different methodologies, based on geophysical properties and local wind and wave climates. The most commonly used is closer to a qualitative analysis [1]:

Geophysical factors are reclassified into a common scale \( s_i \), usually from 0 to 100, 0 being the least preferable value. The reclassification is not always linear or direct. As an example, for depth reclassification, lower depth levels will be reclassified with a higher value.

A percentage weight \( w_i \) is then assigned to the criterion depending on its overall importance. The total sum of weights shall add up to 100%. The suitability indexes for the considered region are then derived using a simple linear combination:

\[
\sum_{i=1}^{n} w_i \cdot s_i
\]

Basically, the higher the value, the better is the location. An example of this kind of analysis can be found in the ORECCA project [2] or TROPOS project [3]. This approach, however, faces limitations at every step of the process: both reclassification and weighting of criteria are highly dependent on the sensitivity, experience and perception of the person(s) performing the analysis. Added to the general lack of experience in offshore plants development, this may lead to biased results, and project stakeholders’ misinterpretation.

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1 Offshore Renewable Energy
2 Geographical Information System
The second, more recent approach, consists in avoiding reclassification and weighting, but rather assessing costs related to some geophysical parameters, based on a particular farm and technology (e.g., [4], [5] and [6]).

For the UK REZ assessment [6], most of the costs associated with the CAPEX and eventually the OPEX are assessed and applied, in order to map the LCOE over a studied area, meaning that the energy production is assessed too. Some costs related to locations are assessed, such as costs of transportation, costs of foundations and costs of electrical connection, finally providing with a quantitative assessment of suitable areas.

On the other hand, the Galicia region’s study (4, 5), based on costs functions and assumptions, outputs the share on the final LCOE related to some of the sites geophysical characteristics (wave height, wave period, current speed, wind climate, depth, distance from farm to shore, distance to the floating platform construction location and distance to the components storage location).

These methodologies, rather than using reclassification and weighting, try to eliminate personal subjectivity, and present a quantitative assessment, which may be used as a basis for a more complete and complex analysis.

A hybrid method of quantitative analysis has been described in [1], providing a suitability index, based on some figures of costs, weighted by the relevant geophysical specificities, as shown below:

\[ I_{suitability} = \left\{ \frac{\left( \cos \text{cost} \_ \text{moorings} + \cos \text{cost} \_ \text{cable} + \cos \text{cost} \_ \text{mooring} \_ \text{device} + \cos \text{cost} \_ \text{device} \right) + \left( \cos \text{cost} \_ \text{cable} + \cos \text{cost} \_ \text{anchor} + \cos \text{cost} \_ \text{foundation} \times \text{seabed \_ \text{modifier}} \right)}{\text{AEP}} \right\}

\[ I_{suitability} = \left\{ 1 - \frac{\text{AEP}}{\cos \text{cost} \_ \text{cable} + \cos \text{cost} \_ \text{anchor} + \cos \text{cost} \_ \text{foundation} \times \text{seabed \_ \text{modifier}} / \text{AEP} \right\}

- AEP being the annual energy production,
- seabed\_modifier being a reclassified value of seabed composition, related to the complexity of the installation in a given seabed substrate (sand = 1, less complex, rock = 10, most complex).

With this method, the quantitative index \( I_{suitability} \) is computed, avoiding subjectivity, and applying some weighting factors on the relevant costs. By applying this method to several components of the project, different sites may be objectively compared through multi-criteria analysis.

3. COST FUNCTIONS

3.1 Depth related

For depths below 60 meters, station keeping systems are likely to be used (mooring and anchoring), for both wave energy converters (such as point absorbers) and floating offshore wind turbines.

Station keeping system - Mooring lines

Mooring lines come with various types of materials, such as synthetic fibres or steel. Only some of those will be covered, mostly because of the lack of availability of prices. Nevertheless, candidate materials for offshore energy devices’ mooring lines will be covered, notably chains, as described for the Hywind Scotland project [7]. The mooring line properties will be defined depending on their maximum breaking load, the chosen value being directly related to the extreme loads expected on the platform. Note that, at design stage, a safety factor has to be applied, following DNV-GL recommendations [8].

Functions to derive costs and diameters are provided for a range of maximum breaking loads (MBL) from 500kN to 12000kN, in Table 1 - Mooring lines materials costs.

The necessary length of mooring lines depends not only on the depth but also on the mooring lines’ design: either catenary or taut (spread or not). In order to derive the mooring lines’ cost functions, two designs will be studied: catenary mooring and taut (vertical) mooring, made only of one material, even if today’s designs might combine different materials.

The catenary design is adapted for chains and steel wire, as their weight provides restoring force - synthetic materials alone would not provide restoring force at equilibrium position as most of them have a positive buoyancy, i.e. their specific gravity is quite low. The required length, function of depth, is assessed considering a static inextensible cable approximation [11]:

\[ L_{min} = \text{depth} \cdot \frac{2 \times \text{MBL \_w} \_\text{depth}}{\text{w} \_\text{depth} - 1} [m] \] (1)

- MBL: Maximum Breaking Load in Newton, depth the local depth in meters, w the submerged weight of the selected material in kg.

For the taut design, mooring lines are likely to be of the same order of magnitude as the local depth:

\[ L_{min} \approx \text{depth} \]

Station keeping system - Anchoring system

Even if the anchoring system is not directly related to the local depth, it is directly related to the extreme loading on mooring lines and the holding capacity of the anchors must be taken into consideration to ensure proper station keeping of the floating platform. The anchor selection must be made depending on the local seabed slope, seabed substrate and holding capacity (vertical and/or horizontal, depending on the expected loading directions).

Indeed, there is a large choice in anchor types, with their own pros and cons, specific to the intended usage. Comparisons can be found in the US Navy Salvor’s Handbook [12], chapter 3-5.

An order of magnitude of the costs is to be found in [13], for two types of anchoring systems and described in Table 2 - Anchors cost functions.

Note: The vertical breaking load, VBL, provided in kN, can be approximated from the MBL, the depth and the mooring line length.

Bottom Fixed (Offshore Wind)

In offshore wind farms, fixed foundations and substructures are used at depth above 60 meters.
Monopile and jacket are commonly used. The depth related costs are found in [6] and available in Table 3 - Foundation cost functions.

3.2 Distance related costs functions (Shore, Ports)

Cost of distance to shore – Export cable

One of the most sensitive cost components related to the distance to shore is the cost of export cables(s) installation. Obviously, the further offshore is the site, the longer the cable(s) will be. Moreover, the cables need to be buried. Burial operations’ costs equally depend on the seabed substrate along the way to the shore. Because of that, the most straightforward path to shore may not be necessarily the cheapest path.

The market offers a wide variety of subsea cables, in terms of capacity (MVA\(^3\)), current type (AC/DC) and number of cores (1 or 3). Prices are not readily available to the public but the DTOcean project [14] provides some insights and the following cost function can be inferred for AC cables:

\[
   \text{Cost} = c_1 + c_2 \cdot e^{c_3 \cdot \text{MVA}} \quad [\text{€/m}] \quad (2)
\]

\(\text{MVA: cable rated power in MVA}\)
\(c_1, c_2, c_3: \text{cost coefficients provided in Table 4 - Export Cables - cost functions coefficients.}\)

Different techniques and equipment are used to bury the cables into different types of substrate. Daily rates of specialized vessels (commonly referred to as Cable Laying Vessels/Cable Laying Barges (CLV/CLB)), are available in the DTOcean database, and provided in Table 5 - Cable Laying Vessels&Barges Daily Rates.

Trenching in the seabed is performed with special equipment [15], depending on the seabed composition, before the cable laying and burial (1-2m deep). We can approximate the time, hence the cost, of burying a meter of cable, depending on the trenching/burial speed [15], provided in Table 6 - Trenching speeds. The type of seabed must be considered to select the appropriate trenching technique, according to [16].

Hence, by assuming the cable installation vessel works 24h a day, with trenching and burial capabilities, we can define the total cost of a meter of export cable and its installation:

\[
   \text{Cost} = c_1 + c_2 \cdot e^{c_3 \cdot \text{MVA}} + \frac{\text{dailyRate} \cdot \text{distanceFromPort}}{\text{installSpeed} \cdot 1440} \quad [\text{€/m}] \quad (3)
\]

dailyRate is the daily rate of candidate CLV/CLB.
installSpeed is the speed of trenching and burying cable in a given substrate type.

Cost of distance to suitable ports

The distance of a site from suitable ports will impact installation and O&M costs. Vessels’ mobilization & demobilization costs may not be known, as they are strongly dependent on their location, offer & demand on the market (SPOT market, short or long term charter [17], [18]). Nevertheless, cost functions can be defined related to vessels capacity, speed and distance from suitable ports to a particular location.

Indeed, installation-wise, we can assess necessary time and costs of transportation of plant devices (wind turbines or wave energy converters) & foundations (wind turbines floating/fixed platforms, mooring lines and anchors). The following speeds & daily rates for common installation vessels may be used, based on DTOcean’s database [19], provided in Table 7 - Installation vessels information.

The cost function for transportation of a particular plant element type, back and forth, can be derived:

\[
   \text{Cost}_{\text{transportation}} = \frac{2 \cdot \text{distanceFromPort} \cdot \text{dailyRate} \cdot \text{ceiling} (\frac{\text{nbComponents}}{\text{vesselCapacity}})}{\text{vesselSpeed} \cdot 24} \quad [\text{€/day}] \quad (4)
\]

distanceFromPort: distance from port in km.
dailyRate: daily rate of the candidate vessel that transports/tows the components in €/day.
vesselSpeed: candidate vessel speed in km/h.

nbComponents: total number of components of a particular type (wind turbines, WEC, floating platform, anchors) to be transported on site from the port.

vesselCapacity: number of components the vessel can transport/tow in one trip.

Typically, for an offshore wind farm, the components to be transported on site would be: the wind turbines, the floating platforms or fixed foundation, the anchors and the mooring lines. For a wave energy farm: wave energy devices, and anchors and mooring lines.

4. METHODOLOGY

This methodology can be applied with various GIS tools. ESRI ArcGIS [20] was used in the present study.

For that, it is necessary to define a couple of items, such as:

- The plant power output, in order to select the appropriate number and capacity of export cables, and obtain relevant costs for the export cable(s).
- The number of devices to be installed, in order to be able to obtain costs for installation vessels trips,
- Define vessels used to transport the plant equipment,
- If a floating technology is considered, the expected maximum loads on the platform (floating platform or floating wind turbine or buoy for a wave energy converter) must be known, as it defines station keeping system design (and costs).
- The characteristic dimension of the devices, such as rotor diameter or buoy diameter, in order to be able to assess the plant footprint, depending on the devices spacing. Indeed, depth is not constant over the entire area and must be averaged to estimate total costs of foundations or station keeping systems.

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\(^3\) MVA: Mega-Volt Ampere, unit of measurement of apparent power
Geographical information of the studied region will be necessary as well, to perform the analysis and avoid conflicts in marine spatial planning:
- Exclusion zones (subsea cables, protected areas, shipping routes, existing offshore activities, etc.) ([21], [22]),
- Bathymetry ([23]),
- Seabed substrates ([24]),
- Suitable ports coordinates ([25]),
- Shorelines,
- Offshore wind and wave energy resource information ([26]).

The steps of the methodology are:
1. Extract the depth range of interest, appropriated to the selected technology,
2. Compute station keeping system costs, based on bathymetry map, at any location, and use Focal statistics [27] to average the costs over an area of the size of the plant,
3. Perform a reclassification of the seabed from substrates to the actual cost of purchase and burial of a meter of cable in a particular substrate,
4. Compute the total cost of cable needed to go from shore to any offshore location using cost distance [28], the cost raster being the output of step 3,
5. Compute distances from suitable ports to any offshore location, and derive transportation costs from equation (4),
6. Compute annual energy production (AEP) of one device of the selected technology at any offshore location, and average the values over the farm area, using Focal statistics [27],
7. The suitability index can be derived using the following formula, at any offshore location:

\[
\text{Index} = \frac{(\text{Cost}_{\text{foundation}} / \text{NB}_{\text{devices}}) + \text{Cost}_{\text{transportation}} + \text{Cost}_{\text{exportCable}} / \text{NB}_{\text{exportCables}}}{\text{AEP} \cdot \text{NB}_{\text{devices}}} \quad (5)
\]

8. To increase clarity, the previously derived index should be normalized by its minimum value:

\[
\text{Index}_{\text{norm}} = \frac{\text{Index}}{\min(\text{Index})} \quad (6)
\]

9. Exclusion zones should then be overlayed on the index map, to provide a clear vision of the available areas in the studied region.

Note that, implicitly to its definition, the lower the value of the suitability index, the better the location.

### 5. RESULTS & DISCUSSION
The methodology was applied to the North Sea, considering offshore wind energy, bottom-fixed and floating.

<table>
<thead>
<tr>
<th>Bottom fixed</th>
<th>Floating</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Power Output</strong></td>
<td>496 MW</td>
</tr>
<tr>
<td><strong>NB_{devices}</strong></td>
<td>62</td>
</tr>
</tbody>
</table>

Results for the floating wind technology case and bottom fixed case are respectively shown in Figure 1 - Suitability Map - Floating Offshore Wind and Figure 2 - Suitability Map - Bottom Fixed Offshore Wind.

In the case of floating wind technology, we observe a rather expected result: the further offshore, the less suitable locations are. In that particular case, it indicates that the increase in energy production offshore is not enough to counterweight the increase in costs. The potentially available area seems to be less prone to spatial competition than in depths shallower than 60m (in respect with the data of human activities or protected areas available or considered).

In the case of bottom fixed wind technology, results are more relevant: distinct areas of suitability level appear, that wouldn’t have been necessarily expected. Indeed, attractive locations are found far offshore (more than 200km from shore).
The results of this particular analysis can be compared with characteristics of existing/in construction/planned wind farms in the region (blue circles in Fig. 2). Indeed, most of the wind farms are located in rather suitable areas, as identified from the application of the methodology.

The wind farms location suitability index can be plotted as a function of distance to shore (size of circles relative to plant power output):

![Figure 2 - Suitability Map - Bottom Fixed Offshore Wind](image)

**Figure 2**

Figure 3 demonstrates that going further offshore doesn’t necessarily mean a decrease in location suitability. The four orange circles (Dogger Bank wind farms projects) present interesting suitability indexes, which may be explained by a shallower depth and a higher available power density.

It could be interesting to apply the normalization based on the same minimum value for both technologies to get a better idea of locations suitability, whether the technology is fixed or floating. This was not possible in the present study due to the lack of available data on the specificities and costs of the floating platform.

However, applying this methodology, in regions willing to develop bottom-fixed technology, seems relevant. And based on the previous results, locations with suitability index ranging from 1 to 2.5 seem attractive, as proved by the existence of wind farms installed within these areas.

Note that, in this particular case, the suitability index of 1 is equivalent to 300 €/MWh. This value is a quantity representing the computed costs related to particular geo-physical parameters over one year of energy produced by a hypothetic farm. It shouldn’t be confused with the actual LCoE of a location.

This methodology may be applied for floating offshore wind and wave energy site selection, at a pre-feasibility study stage, allowing to compare the suitability of different locations in a given geographic region, and to prevent competition for marine space. It would as well be useful to restrict the number of suitable locations to study in more detail, such as shown for offshore continental Portugal in annexes figures Figure 4 - Floating Offshore Wind Suitability – Portugal and Figure 5 - Wave Energy Array Suitability – Portugal.

This methodology may be improved by adding the following components, amongst many others:

- Seabed slope in cable related costs computations,
- Vessel costs related to waiting time to get access to appropriate weather windows,
- Improved cost functions; as most of the costs information is not publicly available, we can just rely on order of magnitude,
- Incentives in the studied region.

Moreover, as offshore wind turbines failure statistics are starting to be available, such as in [28], it may be interesting as well to derive costs related to vessels used to fix the failures. By associating appropriate vessels to failure types, part of the maintenance costs over time related to the time taken to go back and forth from port to the offshore location could be computed. They would be derived from the combination of selected vessels, speed, daily rates, failure rates, plant size and project lifetime, then included in the suitability index computations.

6. CONCLUSION

This paper presented a methodology to perform offshore site selection using economic decision factors. Cost functions derived from geo-physical properties such as depth, distance to shore, distance to suitable ports and seabed substrates have been presented. The methodology of offshore site selection based on these cost functions and available energy has been described and implemented in a GIS software in the North Sea region for bottom-fixed and floating offshore wind technologies. For bottom-fixed technology, results show that the further offshore the location is doesn’t necessarily imply a decrease in suitability. Moreover, there is a clear match between the model and actual wind farm locations in the region. Resulting figures and values may even be used as a
For floating wind and wave energy technologies, this methodology helps to compare the suitability of locations over a wide area and provide some insights into the relatively “best” locations without overlapping existing activities, before studying candidate locations into more detail.

Finally, ideas of improvement have been suggested, in order to obtain a methodology with a higher level of accuracy.

7. ACKNOWLEDGEMENTS

I’d like to thank, Mr Didier Mayer, responsible of the EnR post-master at Mines ParisTech, to have given me the chance of a new start in the challenging, interesting and sustainable world of renewable energies. Furthermore, I’d like to thank all the academic team of the EnR post-master, in Mines-Paristech and of the Instituto Superior Técnico in Lisbon, it has been a genuine pleasure to learn from them. And finally, thanks to WavEC Offshore Renewables team to have allowed me to make my first steps, surrounded by many different expertise, in the offshore renewable energies development.

REFERENCES

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ANNEXES

<table>
<thead>
<tr>
<th>Type</th>
<th>Functions [9, 10]</th>
<th>Cost (MBL) = 0.0718 · MBL^0.4332 [€/m]</th>
<th>Cost (MBL) = 0.0773 · MBL^0.4445 [€/m]</th>
<th>Cost (MBL) = 0.1457 · MBL^0.4092 [€/m]</th>
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<tbody>
<tr>
<td>Parallel strand polyester</td>
<td>d(MBL) = 3.3962 · MBL^0.4332 [mm]</td>
<td>3.3962 · MBL^0.4332</td>
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<td>Parallel strand Nylon</td>
<td>d(MBL) = 3.2699 · MBL^0.4445 [mm]</td>
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<tr>
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<td>d(MBL) = 2.6224 · MBL^0.4092 [mm]</td>
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<tr>
<td>Spiral Strand Steel Wire</td>
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<td>0.9 · d^2</td>
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<td>Stud link Chain Grade R4</td>
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Cost function for Anchor type:

- Suction Pile Anchor, SPA
  Cost (VBL) = 22500 + 135 · VBL

- Drag Embedment Anchor, DEA
  Cost (VBL) = 45000 + 225 · VBL

<table>
<thead>
<tr>
<th>Foundation type</th>
<th>Cost functions (d: depth in meters) [€/M/MW]</th>
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<tbody>
<tr>
<td>Monopile</td>
<td>Cost (d) = 0.00132d^2 + 0.00276d + 1.47036</td>
</tr>
<tr>
<td>Jacket</td>
<td>Cost (d) = 0.00096d^2 − 0.01848d + 1.90164</td>
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<table>
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<th>Rated voltage (kV)</th>
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<th>c2</th>
<th>c3</th>
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<td>7.2</td>
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<table>
<thead>
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<th>Max. Trenching speed in ideal conditions (m/min)</th>
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<td>18</td>
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<td>Dredging</td>
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4 HMPE : High Modulus PolyEthylene
Figure 5 - Wave Energy Array Suitability - Portugal