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Sensitivity analysis of cost parameters for floating offshore wind farms: an application to Italian waters

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Abstract. Floating offshore wind farms represent the next frontier in wind power industry. However, the development of this technology is strongly dependent on its economic feasibility. There follows that the development of economic analyses is crucial to highlight the possible greater potential of floating offshore wind farms and to support their sustainability and technical value.

In this context, the purpose of this paper is to present a sensitivity analysis of the main cost parameters for floating offshore wind farms, namely the distance from the coast, the distance from the closest port and the sea depth. It can give specific information on which parameters are more important, and how much they affect the total cost.

To this aim, a comprehensive life cycle cost assessment of floating offshore wind farms has been developed. In this study the cost model has been applied to the Italian waters.

The results shown should provide guidance on how to preliminary assess the quality of a given site for floating offshore wind farm installation, and should be helpful for future development of decision-making procedures in the offshore wind sector.

1. Introduction

Over the past few decades, a renewed progress in the offshore wind sector has taken place. In particular, floating wind turbines represent the next frontier in the wind power industry.

The global installed offshore wind capacity is to be close to 34 GW by 2020, and in 2030 it might exceed 200 GW [1]. These figures also reflect the decrease in the costs of offshore wind farms, and the expected shortage of suitable onshore areas for wind energy generation, in particular for densely populated countries or areas characterized by high environmental risks [2,3].

Floating wind generation has the advantage of an almost unlimited resource, combined with a larger producibility due to higher winds with lower turbulence; the latter is also beneficial to fatigue life of wind turbines [4]. Floating wind farms being placed in the open sea, have fewer physical constraints than onshore and shallow water ones, such as operating noise and visual amenity. Moreover, floating foundations offer environmental benefits compared to fixed base ones due to less-invasive activity on the seabed during installation [5]. These aspects allow floating wind farms to be installed relatively quickly at GW scale [6].

On the other hand, floating wind farms have higher installation, maintenance and decommissioning costs compared to fixed base ones; this is due to the higher cost of supporting structures, to expensive installation procedures and to restricted site access because of possible harsh weather conditions.

Nowadays, only research prototypes of this new technology exist. The main floating foundation concepts are the Spar Buoy (SB), the Semi-Submersible Platform (SSP) and the Tension Leg Platform (TLP). In particular, prototypes of SB are the Hywind Pilot and the Hywind Scotland Pilot Park. The former is the first single 2.3 MW full-scale floating wind turbine concept ever built (in September 2009) and it was assembled offshore the city of Stavanger, in Norway [7]. On the other hand, the latter is the first prototype wind farm, which began production in October 2017. It is located in the North Sea, off the Scottish coast, featuring five turbines with a total installed power of 30 MW [8]. Prototypes using SSPs are Trifloater and WindFloat. The former is a single 5 MW turbine realized in Netherlands [9]; the latter is a single 2 MW turbine, located in the Atlantic Ocean off the Portuguese coast [10]. Finally, prototypes of TLP are Gicon and PelaStar. The former is a single 2 MW turbine to be installed in the Baltic Sea [11]; the latter is a single 6 MW turbine, which has not yet been installed [12]. Other prototypes, are still going through a feasibility study.

The future development of these technologies will be based on their economic feasibility. In this context, an accurate economic analysis is crucial in order to highlight the possible greater potential of floating offshore wind farm, and to support their sustainability and technical values.

Currently, only a few studies are available on their possible investment costs. Therefore, a cost assessment for floating offshore wind farms is mainly necessary to assess whether this new technology is economically sustainable. The main objective of this work is to develop a sensitivity analysis of the main cost parameters for floating offshore wind farms. This derives from a proposed general cost model which takes into account all the cost parameters [13]. In this study, the model is applied to the Italian national waters.

The proposed study should be helpful for future decision-making processes. Results should provide guidance on how to preliminary assess the quality of a site for floating offshore wind farm installation.

The paper is organized as follows. In Section 2, the methodology is presented and the sensitivity analysis is applied to a TLP offshore floating wind farm project. In Section 3, the results obtained from the sensitivity analysis are presented and finally, in Section 4 some conclusions are drawn.

2. Methodology

2.1. Economic aspects

The sensitivity analysis of a floating offshore wind farm is the outcome of a parametric economic analysis. Hence, the method proposed is based on a model for the life cycle cost assessment of floating offshore wind farms [13]. This includes calculation of Capital cost (CAPEX), C_{Capex}, Operation and Maintenance cost (OPEX), C_{Opex} and Decommissioning cost (DECEX), C_{Decex} [14]. CAPEX is the most significant contributor to the life cycle cost of wind farms and includes all investment costs covered before the commercial operation date. These can be as large as 80% of the total cost of the wind farm project [15]. OPEX includes all costs incurred after the commercial operation date, but prior to decommissioning, necessary to operate the project and guarantee turbine efficiency [16]. It sums up to around 20 to 30% of the total costs of a wind farm project [17]. Finally, DECEX covers costs of the last stage of wind farm lifespan and in particular, the costs for cleaning or repowering the area of the wind farm. It sums up to around 1-3% of the total costs of a wind farm project [18].

Therefore, the life cycle cost C_{LC} of a floating wind farm is given by Equation 1:

$$C_{LC} = C_{Capex} + C_{Opex} + C_{Decex} \tag{1}$$

where,

$$C_{Capex} = C_T + C_P + C_{TS} + C_M + C_A + C_{IT} + C_{IP} + C_{ITS} + C_{IMA} \tag{2}$$

$$C_{Opex} = C_O + C_{MD} + C_{MI} \tag{3}$$

Regarding CAPEX in Equation 2, C_T is the cost of wind turbine, C_P is the cost of floating platform, C_{TS} is the cost of transmission system, C_M is the cost of mooring system and C_A is the cost of anchoring system. Moreover, C_{IT}, C_{IP}, C_{ITS} and C_{IMA} represent the costs of the installation procedures of wind turbine, floating platform, transmission system, mooring and anchoring systems, respectively. In the cost model, CAPEX is mainly calculated analytically and/or as a function of the installed power of the wind farm. In particular, C_T and some components of C_{TS}, that are offshore and onshore substations, are calculated as a function of the installed power of the wind farm. On the other hand, C_P, other components of C_{TS}, that are array cables, offshore export cable and onshore cable, C_M, C_A, C_{IT}, C_{IP}, C_{ITS} and C_{IMA} are calculated analytically.

Component and installation costs are considered separately, mainly because the former is only moderately dependent on site location, whereas the latter strongly depends on it. Moreover, each installation procedure involves costs depending on a number of variables, such as the number of lifts, the crane capacity, the installation time, the type of vessel and number of travels, the storage area of shipyard, and the type of assembly, whether it is realized totally in the port or partly at sea [16].

Referring to OPEX in Equation 3, C_O, C_{MD}, and C_{MI} represent the costs of operation and of direct and indirect maintenance, respectively. In the cost model, OPEX is calculated analytically and/or as a function of the installed power of wind farm. C_O includes the cost of seabed rental, insurance, and grid access fee. Seabed rental is calculated analytically, while insurance and grid access fee are calculated as a function of the installed power of the wind farm. On the other hand, C_{MD} is given as the sum of preventive maintenance, i.e. all actions aimed at avoiding failure of a component and its downtime, and corrective maintenance, i.e. all actions taken after a breakdown has happened [19]. Both are calculated analytically. Finally, C_{MI} includes costs faced to guarantee repair services, such as port fees, vessel hiring fixed costs and maintenance planning and managing costs; they are calculated analytically.

Regarding DECEX, it includes the decommissioning cost of the floating offshore wind farm. It is calculated as a percentage of installation procedures costs, and in particular corresponds to 70%, 10%, 90% and 90% of the complete floating system, cables, substations and mooring and anchoring system installation procedures costs, respectively [7]. Moreover, to these percentages the site clearance cost is added, which involves the removal of all assets of the offshore wind farm from the site area.

2.2. Sensitivity aspects and QGIS implementation

The model for the cost assessment of floating offshore wind farms was implemented for the sensitivity study. A farm made of 12 wind turbines with a nominal power of 5 MW, supported by a TLP floater and located at a distance of seven rotor diameters from each other, is considered (Figure 1). The rotor diameter is 126 m. Moreover, farms are arranged in three rows of 4 turbines, respectively, and each wind farm covers a total area of around 8 km^2.

Sensitivity analysis has been developed in QGIS (Quantum Geographic Information Systems). It is an open-source geographic information system that supports viewing, editing, and analysis of geospatial data [20]. Through QGIS, a cost map has been produced. The procedures for obtaining the cost map are described below.

First, a map of Italy and of its national water limit has been downloaded from the Open Street Map package. This package accesses high-resolution raster maps using the Open Street Map protocol and allows using road, satellite, and topographic maps.

Subsequently, the mapping has been defined by choosing the reference system for Italy, namely the WGS84 (World Geodetic System 1984). It is a geodetic, worldwide geographic coordinate system based on a reference ellipsoid developed in 1984.

Italy lays between about 36° and 46° of Latitude North and between 7° and 20° of Longitude East. A grid of sites spaced by 0.1° (around 11 km) has been defined, both in Longitude and in Latitude. The geographic reference domain for the definition of input and output maps has been defined using point, linear and polygonal vectors. Furthermore, it has been defined using tools of geoprocessing (subtraction, intersection), geometry (extract vertices, from lines to polygons or vice versa), data management (merge

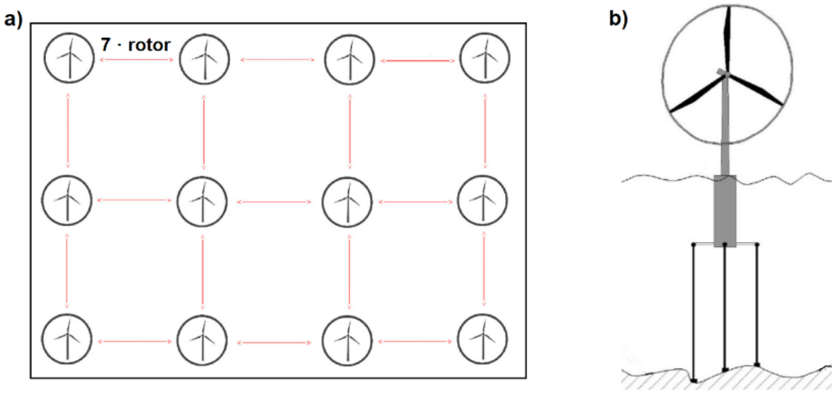

Figure 1: a) Layout of wind farm and b) illustration of TLP. Edited from: Baita-Saveedra (2019) and Manikandan (2019).

attributes by position), research (create lattice, regular sites) and processing (distance from the nearest node, add X/Y fields to layer) present in QGIS.
The calculation domain has been defined, corresponding to the space between coastline and the national water limit. In this domain, 1621 sites have been generated corresponding to possible farms positions. Each point has been georeferenced, entering the coordinates using EPSG codes (European Petroleum Survey Group), used for classification of the reference system WGS84. They are a set of coordinate reference systems and coordinate transformations which may be global, regional, national or local.
Again, the distance to shore, the distance from the ports and the bathymetry maps has been defined and implemented assigning the corresponding values to single point of the reference domain. To this aim, Web Map Service (WMS) defined by the Italian National Geoportal have been used by hand interpolating the reference raster data. WMS defines maps as a representation of geographical information by returning a digital image suitable for display on a web browser. These maps are rendered in an image format, and only occasionally as vector elements.
Finally, using the QGIS field calculator and implementing calculation tools based on the cost model for the assessment of the life cycle of floating offshore wind turbines, the software calculated the total cost for all sites in the reference domain, based on the actual value of the input variables.

2.3. *Input variables*

The main input variables considered in this work are the distance to shore, the distance from port of operation and bathymetry. These parameters vary depending on where the site is located.
Italy features a total of about 7500 km of coast and overlook the Mediterranean Sea [21]. The latter includes the main Italian seas: Tyrrhenian Sea, Adriatic Sea and Ionian Sea (Figure 2).
National waters extend 22 km (12 NM) from the baselines. These are lines that follow each other continuously along the coast. There are two types of baselines, namely normal baselines and straight baselines. The normal baseline represents the coastline in low tide conditions, indicated on large-scale nautical charts. In locations where the coastline is very hollow and jagged, or where there are islands along the coast in its immediate vicinity, it is possible to use the method of straight baselines that connect sites, usually headlands, to trace the baseline from which the width of the national sea is measured. Furthermore, these baselines are drawn following a specific methodology. Considering the curved surface of the Earth, two methods can be applied: the geodetic line (or orthodromy), that considers the minimum path that joins the two sites, or the rhumb line, that considers the line that cuts the meridians under constant angles.
According to the conformation of the Italian coasts, the predominantly jagged locations are present at the Bay of Venice, the Tuscan Archipelago, the Pontine Islands, the Campanian Archipelago, the Bay of Naples and Salerno, the Aeolian Islands, the Egadi Islands, the Tremiti Islands and the Bay of Manfredonia. On the other hand, the most hollowed out places are present in the Bay of Taranto (Figure

2). Sometimes, the national water limit of 22 km may increase in the presence of historic bays, such as the Bay of Taranto. In particular, the historic bays can be closed with a straight baseline even greater than 44 km (24 NM), maximum continuous extension of the territorial sea in case of opposite stretches of coast [22].

All these criteria have been considered in the definition of the reference domain.

In this work, the distance to shore ranges between 0.6 to 93.5 km. The distance to shore of the Italian peninsula and of the major islands of Sardinia and Sicily has been taken into account, without considering the distance smaller islands. Italy has 30 smaller islands, which sum up 0.3% of the national territory [23]. Most of these smaller islands are not connected to the peninsula or to the major islands by power lines. Only the Venice Lagoon, the Island of Elba and the Campanian Archipelago are connected to the national electricity network.

As shown in the Figure 3a, the shortest distances are located along the Italian coastline. While, longer distances are found in the Tuscan Archipelago, in the Pontine Islands, in the Campanian Archipelago, in the Egadi, Aeolian and Ustica Islands, of the Ionian sea, in particular in the Bay of Taranto and of the Adriatic sea, corresponding to the Tremiti Islands.

The distance to shore affects the costs of different components of the wind farm or of elements that support the installation procedures. In particular, the distance to shore affected the length of the offshore export cable and its installation.

With reference to the distance from port of operation, first of all an analysis of Italian ports has been carried out, choosing those providing storage and assembling facilities. Italy has a total of 534 ports excluding private or emergency moorings, most of which are located on the Tyrrhenian coast [24]. In this work, the ports considered suitable for operation are 28, which are listed in Table 1 and shown in Figure 3b. In particular, 64.2% of the ports are located in the Tyrrhenian Sea, 25% in the Adriatic Sea and 10.8% in the Ionian Sea.

The range of distance between the floating offshore wind farms and the nearest ports is between 5.9 and 321 km. The shorter distances are found along the Tyrrhenian coast, excluding the South West coast of Sicily where in some sites it is even more than 200 km. Similar distances are found in the Southern portion of the Ionian coast. The longest distances on the other hand, are found along the Adriatic coast, where in some cases they exceed 300 km (distance to nearest ports of Trieste or Manfredonia).

Figure 2: Illustration of the Italian Islands, Bays, Archipelagos and of the main seas.

Table 1: Italian ports.

Sea	**Ports**
Tyrrhenian	Genova (44.403°N, 8.887°E), Savona (44.311°M, 8.488°E), La Spezia (44.109°N, 9.844°E), Carrara (44.033°N, 10.040°E), Livorno (43.552°N, 10.300°E), Viareggio (43.863°N, 10.241°E), Piombino (42.930°N, 10.542°E), Civitavecchia (42.100°N, 11.782°E), Napoli (40.833°N, 14.266°E), Castellammare di Stabia (40.695°N, 14.479°E), Palermo (38.131°N, 13.370°E), Vibo Valentia (38.717°N, 15.122°E), Gioia Tauro (38.456°N, 15.908°E), Arbatax (39.937°N, 9.704°E), Cagliari (39.210°N, 9.108°E), Capitana (39.207°N, 9.303°E), Portoscuso (39.201°N, 8.380°E), Porto Torres (40.838°N, 8.391°E)
Ionian	Augusta (37.237°N, 15.198°E), Siracusa (37.080°N, 15.269°E), Taranto (40.478°N, 17.219°E)
Adriatic	Brindisi (40.647°N, 17.962°E), Margherita di Savoia (41.378°N, 16.115°E), Manfredonia (41.630°N, 15.921°E), Barletta (41.325°N, 16.284°E), Bari (41.132°N, 16.866°E), Trieste (45.646°N, 13.761°E), Monfalcone (45.790°N, 13.560°E)

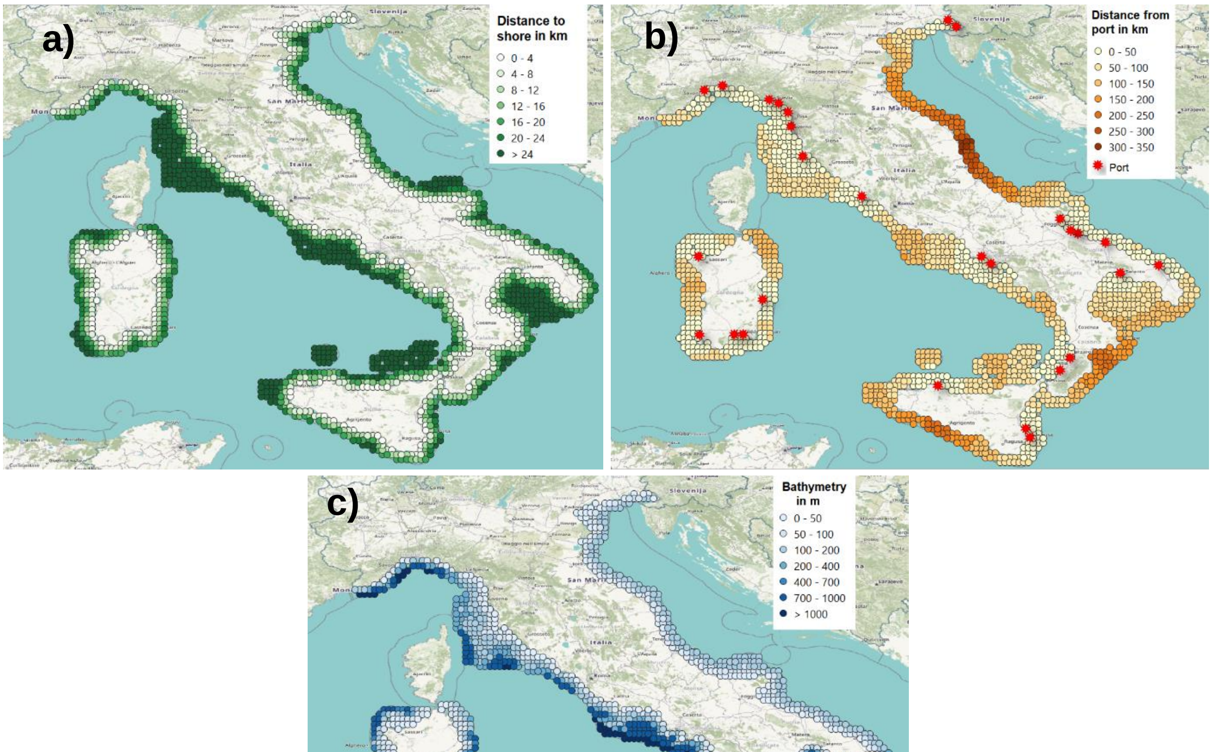

Figure 3: a) Distance to shore, b) distance from closest port and c) bathymetry.

As an input variable, the distance from port influences the sea transportation of components during installation and maintenance activities.

Bathymetry ranges between 0 and 3500 m (Figure 3c). In the construction of TLP floating wind farms, the minimum bathymetry to be considered is 55 m, based on a draft of 45 m. On the other hand, for maximum bathymetry technological limitations must be considered. In this regard, reference can be made to Oil & Gas platforms, which the floating wind turbine technology comes from. Nowadays, Big Foot represents the deepest Oil & Gas with TLP built in a marine area with a depth of 1580 m [25]. Finally, as an input variable, bathymetry affects the length of array cables and of mooring lines.

2.4. Output variables

The output variables are the component costs and the installation costs of the farm, which have been calculated using the cost model. Among these variables, some are constant while others are strongly affected by the input variables. The constant output variables are: wind turbine cost C_T; floating platform cost C_P; onshore cable cost C_{TS3}, offshore substation cost C_{TS4}, and onshore substation cost C_{TS5}, that compose the C_{TS} cost; anchoring system cost C_A; onshore cable installation cost C_{ITS3}, onshore substation installation cost C_{ITS5}, that compose the C_{ITS} cost; mooring and anchoring systems installation cost C_{IMA}; operation cost C_O and indirect maintenance cost C_{MI}. On the other hand, the output variables affected by the input variables are: array cables cost C_{TS1}, and offshore export cable cost C_{TS2}, that complete the cost C_{TS}; mooring system cost C_M; wind turbine installation cost C_{IT}; floating platform installation cost C_{IP}; array cables installation cost C_{ITS1}, offshore export cable installation cost C_{ITS2}, offshore substation installation cost C_{ITS4}, that complete the cost C_{ITS}; direct maintenance cost C_{MD} and finally, decommissioning cost C_D.

3. Results

The main result of this work is a cost map for the Italian national waters. Based on the draft length of TLP, the map was limited to the sites were the water depth exceeds 55 m. Consequently, from a total of 1621, only 1388 are considered (Figure 4).

Figures 5a, 5b and 5c show histograms of the distance to shore, distance from port of operation and bathymetry of the sites considered in the analyses. Most sites are located at a distance to shore above 24 km (31.3%) (Figure 5a), at a distance from port of operation ranging from 50 to 100 km (36.3%) (Figure 5b) and at a depth range of 100 to 200 m (32.8%) (Figure 5c).

The costs of TLP wind farms oscillate between 220 M€ and 500 M€, with 49.5% ranging between 210 M€ and 280 M€ and 40.9% ranging between 280 M€ and 350 M€ (Figure 5d). These are located in areas close to shore and to the port of operation, and in relatively shallow waters; the minimum values of the total cost are found in the Southern Adriatic Sea. On the other hand, the most expensive sites are found correspond to large values of the distance to shore and to the port of operation, and to deep waters. They correspond to the cost ranges of 350 to 420 M€ (8.7%), of 420 to 490 M€ (0.7%), and in excess of 500 M€ (0.1%) (Figure 5d).

These costs change as the number of wind turbines changes. In particular, by halving or doubling the number of 12 turbines of the reference wind farm, the cost decreases or increases by approximately 35%, respectively. On the other hand, when the number of turbines is quadrupled or increased eightfold, i.e. the farm has 48 or 96 turbines, the total cost of the farm increases by about 60% or 80%, respectively. This highlights how economies of scale come into play.

The domain defined between the Italian coastline and the national water limit includes also the protected areas; this is another important aspect to be considered for sensitivity analysis.

Protected areas are those places where human activities are partially or totally limited, with the aim of increasing or maintaining their integrity and biodiversity.

In Italy there are 871 protected areas, for a total of over 3 million ha of protected land areas and almost 3 million ha of protected sea areas, including 658 km of coastline.

With reference to protected sea areas, the National Parks cover almost 72000 ha and they include the Tuscan Archipelago and the Archipelago of La Maddalena. On the other hand, marine protected areas are 27, covering an area of about 222,442 ha; to these 2.5 million ha must be added, which include two submerged parks and the International Marine Mammal Sanctuary [26]. The latter extends over a very large surface, including the marine area of Tuscany, Liguria and Sardinia.

In addition to protected areas, it is also necessary to consider navigation and mooring limitations. These may include regulated and precautionary areas, where it is forbidden to anchor, unload or transit. When

protected areas and navigation limitations are considered, the possible sites further decrease, becoming 1026 (Figure 6).
It can be noticed that most of the North Tyrrhenian Sea and part of the seas off the Northern and Southern coasts of Sardinia are not suitable for the installation of offshore wind farms.

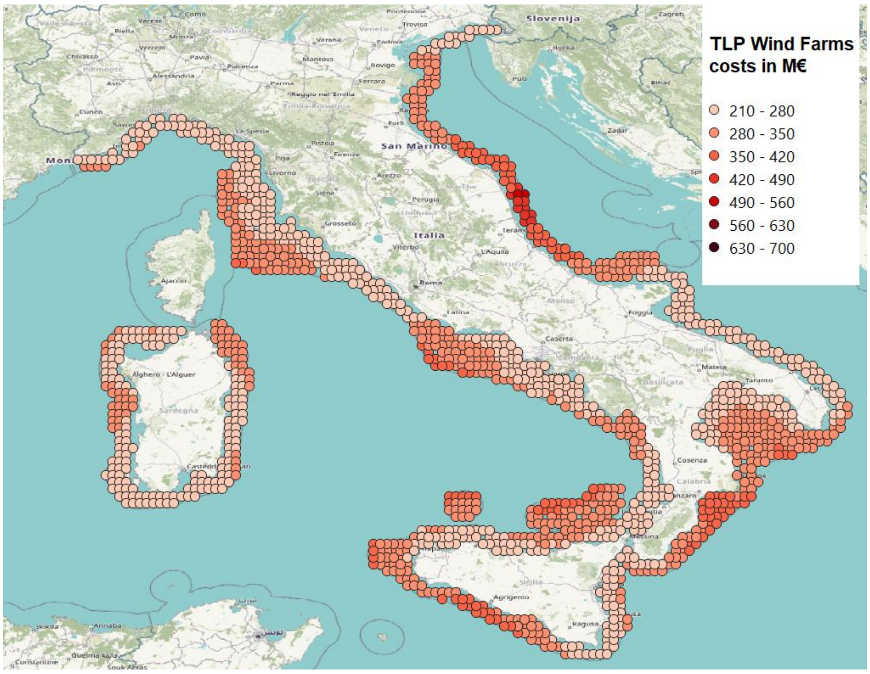

Figure 4: Cost map of TLP wind farm considering bathymetry constraints.

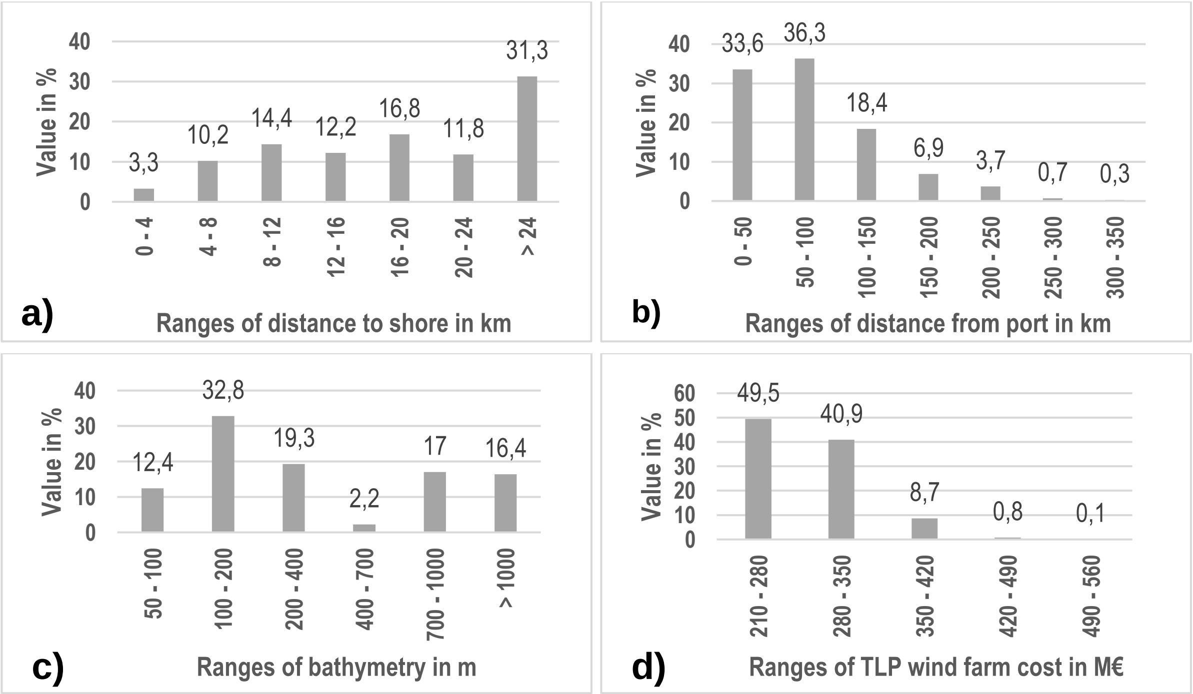

Figure 5: Results in % of the ranges of (a) distance to shore and (b) distance from port (c) bathymetry and (d) TLP wind farm cost.

Figure 6 gives an overview of the life cycle costs of the wind farm, to be compared with the benefits coming from producibility. Therefore, a similar map of producibility need to be prepared, which is beyond the scope of this paper, and comparison of then two maps would allow drafting a third map, containing the distribution of the values of the Levelized Cost of Energy (LCOE). This final result is the tool to be used in the planning of possible investments.

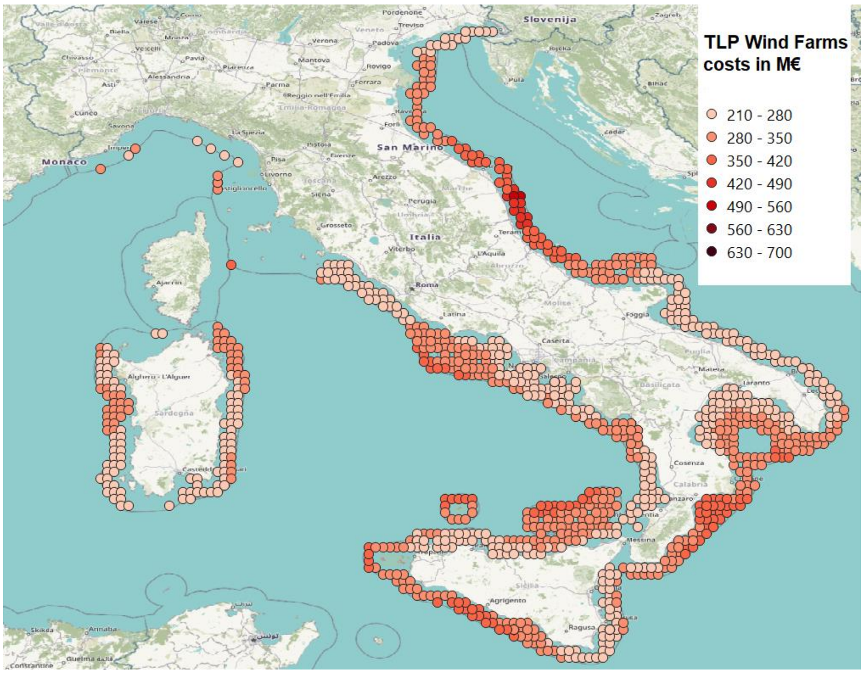

Figure 6: Cost map of TLP wind farms including bathymetry constraints, protected areas and navigation limitations.

4. Conclusions

In this paper an application of sensitivity analysis of the main cost parameters for floating offshore wind farms has been presented; these are the distance to shore, the distance from port and bathymetry. It was applied to a TLP floating offshore wind farm, located in the Italian national waters. The total life cycle costs of the farm were evaluated through a cost model, considering CAPEX, OPEX and DECEX.

In the analysis, bathymetry constrains deriving from the minimum TLP draft, the environmental aspects, i.e. the presence of protected areas, as well as navigation limitations were taken into account. Similar maps can be prepared for different floater solution, which have not been show for brevity.

The final result is in the form of a life cycle cost map, giving a bird's-eye view of the variation of the costs of the farm, to be compared with a similar map describing the variation of producibility. The latter, beyond the scope of this research, should be drafted based on the distribution of the mean wind velocity and power curve of the specific turbines to be installed. Comparison of the two maps allows evaluation of the distribution of the LCOE for a specific project, therefore giving a first idea of its feasibility.

In a second stage, the same tool could be used for refining the analyses. Once a narrower area has been selected, then different solutions can be explored within that area, to find the optimum one. It must be clear that, even after a second refinement, the results obtained must be considered as preliminary, therefore a deeper and more specific analysis must be carried out anyways. Therefore, the approach presented here is to be considered for use in the early stage of the decision-making process, as a tool for the preliminary assessment of feasibility and of political evaluation. Nevertheless, the general framework also lends itself to refinements of the cost model, based on a more detailed knowledge of the particular case under consideration; in that case, a higher level of accuracy can be obtained for the specific case.

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