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Feasibility analysis for floating offshore wind energy

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Abstract

Purpose The assessment of the economic feasibility of floating offshore wind farms (FOWFs) plays an important role in the future possible spreading of this challenging technology in the wind power industry. The use of specific economic analyses is fundamental to point out the potential of FOWFs and to sustain their technical value. Within this topic, the implementation of the FOWF life cycle cost model and producibility analysis in a geographic information system is developed, with the aim of carrying out a feasibility analysis at the territorial scale, for different types of floater. Moreover, a simplified model for a quick life cycle cost assessment is proposed and calibrated.

Methods The available cost model is first validated comparing the costs of FOWFs based on different floaters (Semi-Submersible Platform—SSP, Spar Buoy—SB and Tension Leg Platform—TLP) with corresponding results available in the literature. Then, it is implemented in QGIS to be used for territorial-scale analyses and sensitivity analyses of the cost parameters. A feasibility analysis is developed through the main financial parameters. Finally, the results are then used to calibrate a simplified version of the cost model that depends on three main parameters, namely distance to shore, distance from the port of operation and bathymetry.

Results and discussion The FOWF cost values are found to be in good agreement with those coming from analytical methods similar to the one from the authors. However, some discrepancies with those based on average costs are observed. Then, the results of the sensitivity analysis are presented as life cycle cost maps, giving an overall picture of the variation of the total cost of FOWF installations on a reference domain. The results show that among the three types of floaters considered here, the SSP proved to be the most promising one, giving lower costs than the SB and the TLP. Moreover, a good agreement between the results in terms of total cost of FOWFs calculated with the analytical and simplified models for SSPs, SBs and TLPs is observed. Finally, the feasibility analysis showed that the financial parameters are more influenced by the wind speed than by the cost of the farm.

Conclusions The paper aims to provide guidance on how to carry out feasibility analyses of a specific site for FOWF installation, thus supporting decision-making procedures. The approach and the results presented here are meant for use in the early stage of the decision-making process, as a tool for the assessment of the economic feasibility of FOWFs installation.

Keywords Wind energy · Floating offshore wind farms · Life cycle cost models · Quantum geographic information system · Sensitivity analysis · Feasibility analysis

1 Introduction

Renewable energy plays a central role within the low carbon transition, and it is nowadays facing the challenge associated with moving from a niche to the broader market. Indeed, there are barriers hindering its diffusion on a large scale, the effects of which bring a position of disadvantage from the economic, regulatory and institutional points of view when compared with conventional energy sources. Although such barriers are not to be understood as universal, as strictly dependent on the reference context, they come grouped into

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four main categories, namely (*i*) costs and pricing, (*ii*) legal and regulatory aspects, (*iii*) market performance and (iv) environmental and social aspects (Seetharaman et al. 2019; International Renewable Energy Agency 2019a). The first barrier refers to the fact that still young a technology, the costs of renewable energies are significantly higher than those of conventional energy; the latter, in fact, often do not pay economical externalities and can benefit from subsidies. The second barrier refers to the lack of framework provisions for independent producers, to the existence of restrictions on the choice of installation sites and to the existence of possible unfavourable conditions of access to network. The third barrier concerns the difficulty of access to credit for investors and to the presence of risk and uncertainty on the performance of younger renewable energy technologies. Finally, the fourth barrier refers to the lack of public awareness on renewable energy projects, based on insufficient knowledge regarding both environmental and economic benefits, uncertainties about the economic viability and public opposition due to a number of reasons including land- and seascape impacts and environmental damage.

Despite these barriers, future scenarios forecast a significant fall in prices for key renewable technologies, especially for wind energy. Indeed, among renewable energy sources, wind is recognized to be secure, reliable and cost-effective (Ahmed and Cameron 2014; Richards et al. 2012). This fall is reflected not just in a decline in the price of components, but more important in a decline in the generation cost. This is also due to technology developments that will dramatically increase the productivity and efficiency of equipment. For example, simulations carried out within the *Corewind project* for two different floating offshore wind sites demostrated that cost reductions of 55% and 60% respectively in the mooring systems can be achieved (International Renewable Energy Agency 2021). Moreover, project siting and operational efficiency lead to producibility increase, generally measured in terms of capacity factor. The global weighted average capacity factor for newly commissioned projects increased from an average of 27% in 2010 to 34% in 2020. Ongoing improvements in wind turbine technologies, higher turbine dimensions and the deployment of the latest technologies in markets such as China and India (among others) would further improve the average capacity factor, expected to reach 58% by 2030 and 60% by 2050 (International Renewable Energy Agency 2021).

Recent years have seen a significant development of offshore wind generation technology, in particular with the introduction of the new concept of floating offshore wind turbines (FOWTs). These are currently in a prototyping stage and stand as the frontier of the wind power industry. Main floating foundations are the Semi-Submersible Platform (SSP), the Spar Buoy (SB) and the Tension Leg Platform (TLP). Floating wind turbines represent a revolutionary technology to take effectively advantage of the large wind potential in deeper waters; therefore, in the future it can lead to a greater growth in the offshore wind power market (Ricciardelli et al. 2021).

At the end of 2020, only a few experimental FOWTs existed: four in Japan (*Mitsui Zosen* in Suzuki et al. (2011), *Fukushima Offshore Wind* in Fukushima Offshore Wind Consortium (2016), *Hitachi Zosen* in Heger (2016) and *Kabashima Island in* Association (2017)) and five in Europe (*Trifloater in* Musial et al. (2004)*, Windfloat in* George (2014)*, Hywind Scotland Pilot Park* in Statoil. (2015), *Gicon* in Kausche et al. (2018), *Floatgen* in Jestin et al. (2018)), summing up to about 50 MW of total installed capacity. Further installations have been announced in Europe, in Asia and in the USA (GlobalData 2019). By 2030, it is estimated that between 5 and 30 GW of floating offshore wind capacity could be installed worldwide, as part of the expected global 200 GW of offshore wind power (Kumar et al. 2019). Moreover, based on the current development rate FOWFs should cover by 2050 5% to 15% of the total installed offshore wind capacity, which is estimated in approximately 1,000 GW (International Renewable Energy Agency 2019a).

In the early 2000s, the total installed costs for offshore wind farms were evaluated from those of existing shallow water, close to shore farms and then extrapolated to deeper waters and further offshore farms; this was done by increasing the costs of foundations, grid connection and installation. The new farms so designed had the effect of increasing the average cost of offshore wind installations from 2,300 €/kW in 2000 to a peak of 5,000 €/kW in the period 2011 to 2014. Then, from 2015 the total costs of FOWFs started to decrease, falling down to 4,000 €/kW in 2018 (International Renewable Energy Agency 2019a, b). It is also estimated that the total installed costs for offshore wind projects would drop to around 2,300 €/kW by 2030 (Shouman 2020). These figures would make offshore wind an attractive option, able to compete with traditional energy sources even without incentives.

Current research also predicts a reduction of the expected cost for FOWFs, mainly driven by technology improvements. These allow capacity factors to increase and total installed costs and maintenance costs to be reduced. Furthermore, the rise in competitiveness of this technology is also supported by: (i) the increase in designers' experience, which reduces project development costs and risks, (ii) the increase in the industry maturity, bringing lower capital cost and, finally, (iii) the presence of economies of scale across the value chain.

Indeed, the future development of floating wind technology will benefit from accurate financial analyses sustaining the economic and technical value of FOWTs. Nowadays, limited literature is available on methods and procedures of use for the assessent of possible investment costs of FOWFs. The life cycle cost assessment of the *Telwind* concrete floating offshore wind platform was presented by Cartelle-Barros and co-workers (Cartelle-Barros et al. 2019) and by Baita and co-workers (Baita-Saavedra et al. 2019); more in general, these studies aim at calculating the main economic parameters affecting economic feasibility of FOWFs. A parametric study on the material and manufacturing costs of SSP, SB and TLP was developed by Ioannou and co-workers (Ioannou et al. 2020). The assessment of the economic feasibility of FOWFs in Galicia was presented by Castro-Santos and co-workers (Castro-Santos et al. 2018a, 2020a); the former paper contains a procedure to be used in the analysis of the economic incidence of size of FOWFs; in the latter paper the economic aspects of FOWFs are analysed through financial parameters, namely the internal rate of return (IRR), the net present value (NPV) and the levelized cost of energy (LCOE). Moreover, in some studies geographic information systems (GISs) are used to assess possible sites for offshore wind farm installation based on wind potential and LCOE assessment (Cavazzi and Dutton 2016; Gadad and Deka 2016; Amirinia et al. 2017; Elsner 2019). In particular, in these papers GIS implementations are used to investigate the economic feasibility of offshore wind resource exploitation in the UK, India, Persian Gulf and Africa. Finally, only few studies can be found on site analysis and selection of offshore wind farms using GIS combined with Multi Criteria Decision Making (MCDM) integration (Vasileiou et al. 2017; Mahdy and Bahaj 2018; Gavériaux et al. 2019; Stefanakou et al. 2019; Castro-Santos et al. 2020b; Tercan et al. 2020). Among these, Vasileiou et al. (2017) presents a GIS implementation of the analytical hierarchy process (AHP) to detect potential sites for wave and wind energy generation in the Aegean Sea; Castro-Santos et al. (2020b) proposed a software tool to calculate the relevant parameters for the economic feasibility of FOWFs in a given location; Tercan et al. (2020) present and used a systematic GIS-MCDM-based integrated approach to find optimal locations for offshore wind energy installations, including also legal, political and socio/economic aspects. Generally, it is concluded that a cost assessment for FOWFs is largely required to evaluate whether this technology is economically sustainable. Moreover, its implementation in a GIS platform is very useful to extend cost analyses to a territorial scale.

Within this topic, a life cycle cost model for FOWFs, based on the explicit and analytical assessment of capital costs (CAPEX), operation and maintenance costs (OPEX) and decommissioning costs (DECEX), was previously developed by the authors (Maienza et al. 2020a) and applied to the assessment of the LCOE of a FOWF located in the Italian national waters. Then, an implementation of the cost model in QGIS was developed in Maienza et al. (2020b), to be used in a territorial-scale analysis for the assessment of the life cycle cost of FOWFs limited to TLP floaters. Furthermore, an overview of the complete feasibility analysis was presented in a recent review paper on technical and financial aspects of TLP floating wind farms (Ricciardelli et al. 2021).

In this framework, the main purpose of this work is to present a comprehensive application of the FOWF life cycle cost model proposed in Maienza et al. (2020a), combined with producibility analysis, so to extend the feasibility analysis at the territorial scale to different types of floater also with the aim of a comparative analysis of their economic performance. In doing this, a simplified model for a quick life cycle cost assessment was developed and calibrated, which is also presented in the paper.

First, the analytical cost model is validated through comparison with corresponding data from the literature. Then, the implementation of the cost model and of producibility analysis in QGIS is developed, to be used for a complete feasibility analysis at the territorial scale in the Italian national waters. Finally, a simplified version of the original cost model depending on five parameters, namely distance to shore, distance from port of operation, bathymetry, number of turbine and turbine power, is developed and calibrated for a preliminary and quicker life cycle cost assessment.

The main aim and novelty of the analyses developed here are to shed light on the assessment of the economic feasibility of FOWFs based on financial parameters, namely the payback period (PP), the internal rate of return (IRR), the net present value (NPV) and the levelized cost of energy (LCOE), also comparing different technologies for the floating foundation (TLP, SB and SSP) and different energy sources. A second main purpose of the paper is that of providing practical results for the specific domain investigated; these would serve as a reference for future studies.

2 Methodology

2.1 Feasibility analysis

The economic feasibility analysis for FOWFs is developed starting from the evaluation of its life cycle total cost and of its producibility. In order to highlight the role of the main input parameters, in Fig. 1 the workflow for the analyses is summarized. In particular, the life cycle cost is affected by three main site-dependent parameters, namely distance to shore, distance from port of operation and bathymetry, as well as by the characteristics of the FOWF. On the other hand, the producibility, which is expressed in terms of annual energy production (*AEP*), is affected by the site-dependent mean wind climate and by the turbine specifications. As an output, the economic feasibility of FOWFs is assessed from different financial parameters, namely the LCOE, the IRR, the PP and the NPV.

The life cycle cost assessment of the FOWFs is carried out using the model of Maienza et al. (2020a). Three shares contribute to the total costs: CAPEX, which is the largest

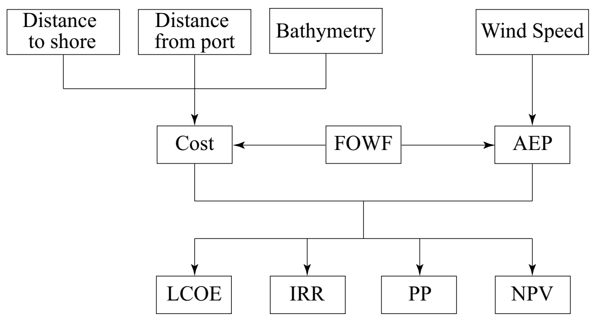


Fig. 1 Flow chart of the feasibility analysis

share including all investment costs to be faced before the commercial operation date; OPEX, including all the costs required to manage the project and to guarantee the turbines efficiency over lifetime; DECEX, which refers to the costs associated with the last stage of the FOWF lifespan, including the costs for re-powering the farm or for its dismantling and the cleaning of the site. The advantage provided by this life cycle cost model lies in its analytical approach that lend itself to direct application to FOWFs with different floaters (SSP, SB and TLP). Moreover, the cost model can be easily implemented in a spreadsheet and the different cost components can be modified to meet alternative criteria, in case more accurate evaluation methods become available.

The efficiency of the farm is measured by the *AEP*, reflecting the way the wind turbine exploits the wind resource and estimating the power generation in a year. It is related to the mean wind climate and to the power curve, $P(v)$, of the turbine as:

$$AEP = 8760 \cdot \int_0^\infty P(v) \cdot f_V(v)\,\mathrm{d}v \tag{1}$$

where $f_V(v)$ is the probability density function of the 1-*hr* averaged wind speed, usually assumed of a Weibull form, which parameters are available from Wind Atlases.

A reliable measure of the wind energy production potential is the capacity factor (*CF*), i.e. the ratio of the actual energy produced by a wind turbine versus the energy that would be produced by the turbine always operating at the rated conditions (Wang et al. 2010):

$$CF = \frac{AEP}{8760 \cdot p_W} \tag{2}$$

The feasibilty analysis is based on the comparison between the life cycle total cost and the expected value of the energy produced. Four methods of financial evaluation are generally used to screen through the investment proposal of wind farms. To compare the cost of energy coming from different sources (e.g. wind, solar, natural gas, etc) and to optimize the design of wind farms, the *LCOE* is used as a summary parameter. It is expressed as the ratio between the total cost of the project and the *AEP* (Ebenhoch et al. 2015):

$$LCOE = \frac{CAPEX \cdot FCR + OPEX + DECEX}{AEP} \tag{3}$$

where *FCR* is the fixed charge rate, representing the annual return that is needed to meet investor requirements. *FCR* is derived from the capital recovery factor (*CFR*) used to determine the amount of each future pay (Manwell et al. 2010), expressed as

$$CFR = \begin{cases} \left[\frac{i}{1-(1+i)^{-N}}\right] & \text{for } i \neq 0 \\ \frac{1}{N} & \text{for } i = 0 \end{cases} \tag{4}$$

where i is the discount rate and N represents the lifetime of the farm.

The *PP* is defined as the time required for the positive cash flows of the project to recover the initial investment. It is an indicator of the project risk: the higher the return time, the larger the risk for investors. The *PP* can be estimated as (de Oliveira and Fernandes 2013):

$$PP = \frac{ICC}{AAR} \tag{5}$$

where *ICC* is the initial capital cost and *AAR* represents the average annual revenue based on hourly production. Generally, *PP* values lower than half the lifetime indicate a good investment.

The *PP* has the limitation of constant revenue stream, not accounting for the discount rate and the lifespan of the project. Instead, the *NPV* considers all the costs and benefits of the project, also taking into account the capital value over time (Kealy 2014). For renewable energy projects, the *NPV* is defined at the present value of benefits less the present value of costs. It is evaluated through the following equation (de Oliveira and Fernandes 2013):

$$NPV = AAR \cdot \left[\frac{(1+i)^N - 1}{i \cdot (1+i)^N}\right] - ICC \tag{6}$$

For both *PP* and *NPV*, the actual capital cost of the project is needed, representing a limit to use of the two financial indicator for renewable energy projects.

The *IRR* is a measure of the expected future returns for an investment, permitting to accept or reject a project. By equating Eq. (6) to zero, it is possible to define the *IRR* as the discount rate i that makes zero the *NPV* (de Oliveira and Fernandes 2013); it follows that:

$$\frac{ICC}{ARR} = PP = \left[\frac{(1 + IRR)^N - 1}{IRR \cdot (1 + IRR)^N} \right] \tag{7}$$

Equation (7) shows that increasing *IRR*, *PP* decreases for any *N* value. Since the higher the *IRR*, the larger the profitability (Baita-Saavedra et al. 2019), then maximizing the *IRR* has the same effect of minimizing the *PP*.

2.2 Simplified cost model

In Table 1, the installation costs of a farm are listed showing their connection with the main input parameters to the cost model. In detail, offshore export cable and its installation are influenced only by the distance to shore; wind turbine, floating platform and offshore substation installation as well as direct maintenance are affected only by the distance from port of operation; finally, the array cables and their installation, and the mooring lines are influenced by bathymetry.

Instead of the model of Maienza et al. (2020a), it is possible to define a simplified model expressing the life cycle total cost of the wind farm as the sum of five terms:

$$C_{LC} = C_0 + n_T \cdot p_W \cdot \left(C_1 + C_2 + C_3 + C_4 \right) \tag{8}$$

In Eq. (8), C_0 represents fixed costs, i.e. costs that do not depend on any variable (in a reasonable range of the farm size up to 500 MW); n_T is the number of turbines and p_W is the power of turbines; C_1, C_2 and C_3 are the variable cost shares depending on the distance to shore, on the distance from port of operation and on bathymetry, respectively; and C_4 represents the cost share depending only on the number and the power of the turbines. To calibrate these coefficients, a regression analysis is performed based on the results of the territorial-scale implementation of the analytical cost model.

Table 1 Influence of the main input parameters on component and installation costs

	Distance to shore	Distance from port	Bathymetry
Array cables	×	×	✓
Offshore export cable	✓	×	×
Mooring lines	×	×	✓
Wind turbine installation	×	✓	×
Floating platform installation	×	✓	×
Array cables installation	×	×	✓
Offshore export cable installation	✓	×	×
Offshore substation installation	×	✓	×
Direct maintenance	×	✓	×
Decommissioning	✓	✓	✓

2.3 Territorial-scale implementation

As an example, farms featuring 12, 5 MW turbines are considered in the analyses, with a rotor diameter of 126 m. The turbines are located seven rotor diameters apart and are arranged in a three by four pattern. The floating foundation includes a floater, its mooring lines and the anchoring system. In particular, the draft of the floater is 10 m, 120 m and 45 m for the SSP, for the SB and for the TLP, respectively (Castro-Santos et al. 2018b); the mooring lines are six steel chains for the SSP, three steel chains for the SB and eight synthetic fibre ropes for the TLP; finally, each mooring line is equipped with a plate anchor (Maienza et al. 2020a).

The feasibility analysis is site-related. In order to show how the main input parameters of the cost model affect the life cycle total cost of FOWTs and how these costs meet the potential energy production of a specific site, a sensitive analysis is performed at territorial scale. The application is carried out with specific reference to the Italian national waters, and analyses were developed in QGIS, an open-source software allowing to analyse and manage geo-referenced spatial data. The geographic domain of interest falls between 36° N and 46° N and between 7° E and 20° E, and is discretized with a rectangular grid spaced by 0.1° (6 NM or around 11 km). Each of this points represent a possible offshore site for FOWF installation. Adopting the WGS84 coordinate system (International Civil Aviation Organization 2002), the following procedure is applied:

1. the map of Italy is loaded from Open Street Map, together with the WMS maps defined by the Italian National Geoportal, containing bathymetry, ports and protected areas;
2. a grid of equally spaced points is generated on the whole map, corresponding to possible sites;
3. the Italian national waters are delimited, defining the domain of possible offshore wind farm sites, i.e. of the associated geo-referenced points;
4. the above wind farm sites are filtered by excluding those falling into protected areas;
5. distance to shore and distance to the nearest port as well as water depth are associated with each geo-referenced point starting from knowledge of the coastline, of the location of ports and of bathymetry;
6. based on the life cycle cost model (Maienza et al. 2020a), the life cycle cost is evaluated for each wind farm site;
7. starting from the parameters of Weibull distribution at each site, the *AEP* is numerically evaluated by using MATLAB; then, the values are imported into QGIS;
8. the four financial parameters described in Sect. 2.1 are evaluated for each of the geo-referenced points, and the corresponding maps are produced.

Table 2 Comparison of FOWF costs between literature data and the results of current work (CW)

	Turbine Power	N. of Turbines	Distance to shore	Distance from port	Bathymetry	Total Cost [M€/MW]		
	[MW]	[−]	[km]	[km]	[m]	SSP	SB	TLP
Castro-Santos and Diaz-Casas (2014)	5.08	21	19.84	53.58	188.1	3.27	3.47	4.16
CW						3.22	3.41	3.57
Nilsson and Westin (2014)	6.00	48	22	22	267	4.76	3.84	3.50
CW						3.44	3.66	3.97
Heidari (2017)	7.00	70	40	50	100	4.08	3.60	3.85
CW						2.96	2.83	3.46

The above procedure is repeated for each of the three floater types.

3 Results and discussion

3.1 Validation of the analytical cost model

With the aim validation, the analytical cost model of (Maienza et al. 2020a) was first applied to literature cases, and the results are shown in Table 2. In particular, the works of Castro-Santos and Diaz-Casas (2014), Nilsson and Westin (2014) and Heidari (2017) are considered as reference.

The first considers a farm of 21, 5 MW turbines, the second considers a farm of 48, 6 MW turbines, and the third considers a farm of 70, 7 MW turbines. For the purpose of comparison, in the calculations, the same values of the input parameters of distance to shore, l_2, distance from port of operation, d_p, and bathymetry, w_δ, used in the literature cases were used. It was found that the cost values calculated with the proposed approach are in good agreement with Castro-Santos and Diaz-Casas (2014), except for the case of TLP farms, for which there results a lower value of C_{LC} of 3.57 M€/MW, as opposed to 4.16 M€/MW derived in the original study. On the other hand, the proposed model seems to underevaluate the costs calculated in Nilsson and Westin (2014) and Heidari (2017), especially in the case of SSP farms (3.44 M€/MW and 2.96 M€/MW, as opposed to 4.76 M€/MW and 4.08 M€/MW found in the original studies). The differences can be ascribed to the different evaluation approachs used in Mediterranean European countries and in Scandinavian countries. In particular, in Castro-Santos and Diaz-Casas (2014) and Maienza et al. (2020a) the costs are calculated analytically, whereas in Nilsson and Westin (2014) and Heidari (2017) they are calculated based on average values available in the literature, mainly derived from data available for Northern Europe. Furthermore, in the reference results a large scatter in the costs of SSP and TLP farms is observed. This is explained by the fact that in the work of Castro-Santos and Diaz-Casas (2014), as well as in the current work, the final cost of TLPs is mainly influenced by the expensive installation process, whereas in the works of Nilsson and Westin (2014) and Heidari (2017), the floater of SSPs has a higher cost and this largely influences the final cost of the farm.

In Table 3, a comparison between the costs of shallow water wind farms and FOWFs is shown, using literature data from Shafiee et al. (2016) and Ioannou et al. (2018) for the formers and the current approach for the latters. In Shafiee et al. (2016), a one-hundred turbine farm at a water depth of 45 m was analysed, to be considered towards the upper limit for fixed base offshore farms. In Ioannou et al. (2018), 140-turbine farm at a water depth of 25 m was analysed, to be considered an average value for this type of shallow water farms. Both works consider the same value for the distance to shore and for the distance from port of operation, equal to 40 km in Shafiee et al. (2016) and to 36 km in Ioannou et al. (2018). This is clearly a simplification, as this condition is

Table 3 Comparison of shallow water and FOWF costs between literature data and the results of Current Work (CW)

	Turbine Power	N. of Turbines	Distance to shore	Distance from port	Bathymetry	Total Cost
	[MW]	[−]	[km]	[km]	[m]	[M€/MW]
Shafiee et al. (2016)	5.00	100	40	40	45	3.50
CW					70	2.97
Ioannou et al. (2018)	3.60	140	36	36	25	3.43
CW					70	3.03

very seldom met. The total cost of the shallow water farm calculated in Shafiee et al. (2016) is 3.50 M€/MW, while the total cost calculated in Ioannou et al. (2018) is 3.43 M€/MW. The same input parameters of distance to shore and distance from port of operation were considered when the total cost of FOWFs with SSP floaters were calculated with the current approach. Only bathymetry was modified to 70 m, corresponding to the minimum values suitable for SSPs. Choice of the SSP floater, as opposed to a SB or to a TLP derived from the former being cheaper than the latters. The costs obtained with the current model for SSP FOWFs are 2.97 M€/MW and 3.03 M€/MW, respectively, lower than those of fixed base structures.

3.2 Input variables

Italy is surrounded by the Adriatic Sea, the Ionian Sea, the Tyrrhenian Sea and the Lygurian sea, and has 7,418 km of shore. Italian Law No. 689/1994 (Italian Ministry of Environment 1994), in agreement with the principles defined by the United Nations Convention on the Law of the Sea of 1982 (United Nations 1982), established that the sovereignty of the coastal State extends to a strip of sea adjacent to the coast, termed national waters, to the airspace above the national waters and to its relevant seabed and its subsoil (Italian Ministry of Economic Development 2013).

According to these provisions, Italian National waters extend up to 12 NM (22.2 km) from the baselines. In particular, two types of baseline exist: normal baselines and straight baselines. The formers coincide with the coastline in low tide conditions, coming large-scale nautical charts. The latters are used when the coastline is hollow or indented, or in the presence of islands; in that case, straight baselines are used connecting points, mainly headlands (Maienza et al. 2020a).

With Decree of the President of Republic No. 816 (1977), Italy adopted a system of baselines divided into 38 total segments, which led a simplification of the external limit of national waters, with an extension of less than 5000 km. Moreover, the Italian internal waters, which separate straight baselines from the coastline, have an area of about 47,000 km^2. National waters have a total extension of approximately 109,000 km^2 (Pizzighello 2018).

As many indented areas exist, locations can be detected with a much larger distance from shore than 12 NM. The largest one, identified with a straigth baseline, is the historic Bay of Taranto, in which case the national water limit reaches 24 NM (44 km). Considering also the presence of islands, and in particular those of the Tuscan Archipelago, the range of distance to mainland shore for the sites considered is between 0.6 and 93.5 km (Fig. 2a).

For the evaluation of the distance to shore, only the coast of the Italian mainland and of Sardinia and Sicily were considered. The shores of other 30 smaller islands were neglected as some of them are self-sufficient in terms of energy management, therefore not connected to the national electricity network; others, namely the Venice Lagoon islands, the Campanian Archipelago and the Elba Island are either connected to the national electricity network though a low capacity connection, or the areas are unsuitable for offshore energy production. Distance to shore affects the cost of different components of the wind farm and of installation procedures. In particular, the length of the offshore export cable and of its installation mainly depend on distance to shore.

With the purpose of evaluating the distance from port of operation, a screening of Italian ports was done, bringing to include in the analyses only those equipped with storage and assembling facilities. In this paper, 28 ports out of a total of existing 543 (Informest 2013) are considered properly equipped to support FOWF installations (Fig. 2b). These are industrial ports or shipyards. In particular, 21% of the ports considered are located in the Lygurian ses, 43% in the Tyrrhenian Sea, 25% in the Adriatic Sea and 11% in the Ionian Sea. The distance between the possible sites of FOWF installations and the closest port ranges between 5.9 and 321 km. The shortest distances are found along the Lygurian shore, especially in the northern coast of Tuscany and in the western cost of Calabria, as well as in the southern Adriatic. The largest distances are detected along the nothern and central Adriatic shore, including sites located at a distance in excess of 300 km from the nearest ports of Manfredonia or Trieste. The costs associated with sea transport of components during installation and maintenance are mainly affected by the distance from port.

Bathymetry of Italian seas is rather heterogeneous (Fig. 2c). Tyrrhenian Sea, extending between the western coast of Sardinia and the Italian peninsula is characterized by sudden and steep steps, numerous pits and ridges, with many active volcanoes in its southernmost portion, north of Sicily. Bathymetry reaches a maximum depth of around 3,500 m south-west of the Pontine islands. Ionian Sea stretches between the western coast of Sicily and Puglia. It is particularly rugged, with long deep slopes up to 3,000 m. Finally, the Adriatic Sea extends south of the Gulf of Venice down to the south of Puglia; it features the most shallow waters, with an average depth of less than 250 m, and in its northern part, only in a few points the depth exceeds 100 m. For the sites considered in this paper, bathymetry is between 0 and 3500 m. In the building of FOWFs, the lowest value of this input parameter to be considered is 70 m for SSPs, 150 m for SBs and 55 m for TLPs. These values derive from an average of minimum bathymetry considered in Energy Technology Institute (2015) and Castro-Santos et al. (2020a), based on the respective draft. For the maximum bathymetry, technological limits shall be taken into account. Reference values can be gathered from Oil & Gas industry, from which

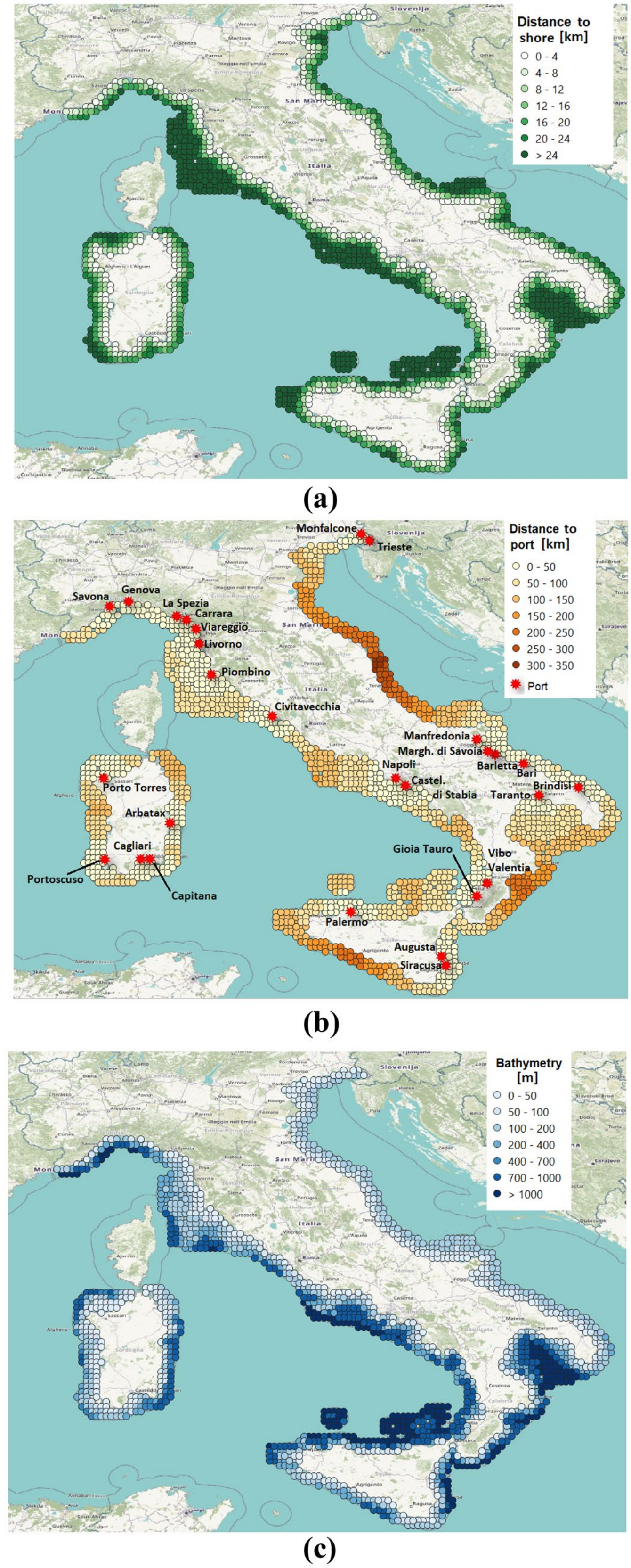


Fig. 2 Maps of the input parameters for the sites considered in the analyses: **a** distance to shore; **b** distance to nearest port of operation; **c** bathymetry

the FOWT technology derives. Nowadays, *CNOOC981* is the deepest Oil & Gas SSP, at 3,000 m (CNOOC 2016). *Perdido* is the deepest Oil & Gas SB platform at 2,438 m of depth (Perrons 2010). Finally, *Big Foot* is the deepest Oil & Gas TLP platform, at a depth of 1580 m (SAIPEM 2010). Array cables and mooring line lengths are influenced by bathymetry, and it will be shown that very deep sea installations, like those of Oil & Gas platforms, are not sustainable for the wind energy industry due to economic reasons.

3.3 Cost analysis

Cost results were derived for farms featuring SSB, SB and TLP floaters. In a first stage, 1621 sites were defined in the Italian national waters, not taking into account specific constraints. Then, considering the technical aspects of the three types of floater, it is necessary to make a selection of the possible bathymetry values. Based on the draft of the SSP, of the SB and of the TLP, firstly the sites where the bathymetry is less than 70 m, 150 m and 55 m, respectively, were removed from the maps. This reduces the number of possible sites to 1,322 in the case of SSP floaters, to 973 in the case of SB floaters and to 1,388 in the case of TLP floaters. The geographic domain consided includes protected areas, i.e. sites where human activities are restricted to protect the natural ecosystem and landscape. These cover some marine areas of Liguria, Sardinia and Tuscany. Considering these protected areas, the number of sites for possible installation of the wind farm decreases to 1,105 for SSPs, to 822 for SBs and to 1157 for TLPs. Finally, it is also required to take into account navigation and mooring limitations, applying to areas where it is forbidden to navigate, moor or unload. Considering these additional limitations, the available sites further decrease to 996, 760 and 1,026 for SSPs, SBs and TLPs, respectively.

The cost maps for SSP, SB and TLP floaters are shown in Fig. 3. It must be noted that most of the sites located in the Lygurian sea are not eligible for FOWF installation. The life cycle cost of the SSP wind farm oscillates between 200 M€ and 670 M€, depending on location. For 34.3% of the sites, the unit life cycle cost is the range of 3.5 to 4.5 M€/MW, and for 31.7% of the sites, it is in the range of 4.5 to 5.5 M€/MW (Fig. 4a). The life cycle cost of the SB wind farm varies between 210 M€ and 520 M€. For 31.1% of the sites, the life cycle cost is in the range of 3.5 to 4.5 M€/MW, and for 38.5% of the sites, it is in the range of 4.5 to 5.5 M€/MW (Fig. 4a). Finally, the life cycle cost of the TLP wind farm varies from 220 M€ to 500 M€. For 34.2% of the sites, it is in the range of 3.5 to 4.5 M€/MW and for 42.6% sites it is in the range of 4.5 to 5.5 M€/MW (Fig. 4a).

In Fig. 4, the cumulative frequency of the life cycle cost of wind farms is shown. It can be noticed that the distribution of costs for the SB and TLP wind farms is roughly the same, whereas it is slightly different for SSP wind farms. In particular, for the most convenient sites (life cycle cost lower than 4.4 M€/MW, almost 40% of sites) SB and TLP wind farms tend to be more expensive compared to SSP wind farms. SB and TLP farms become less expensive than SSP at sites where the life cycle cost is larger.

The lowest values of the wind farm life cycle cost are found in the Tyrrhenian Sea. In particular, the absolute minimum value of the life cycle cost equal to 3.28 M€/MW is that of a SSP wind farm located in the northern coast of Campania, at distance to shore of 5.57 km, a distance from port of 10.89 km and at a bathymetry of 70 m. The minimum life cycle cost for SB wind farms equal to 3.58 M€/MW is found in the south-eastern coast of Sardinia at distance to shore of 3.03 km, a distance from port of 9.04 km and at a bathymetry of 200 m. Finally, the minimum life cycle cost of TLP wind farms equal to 3.73 M€/MW is found in the south-western coast of Puglia at distance to shore of 5.39 km, a distance from port of 6.51 km and at a bathymetry of 100 m.

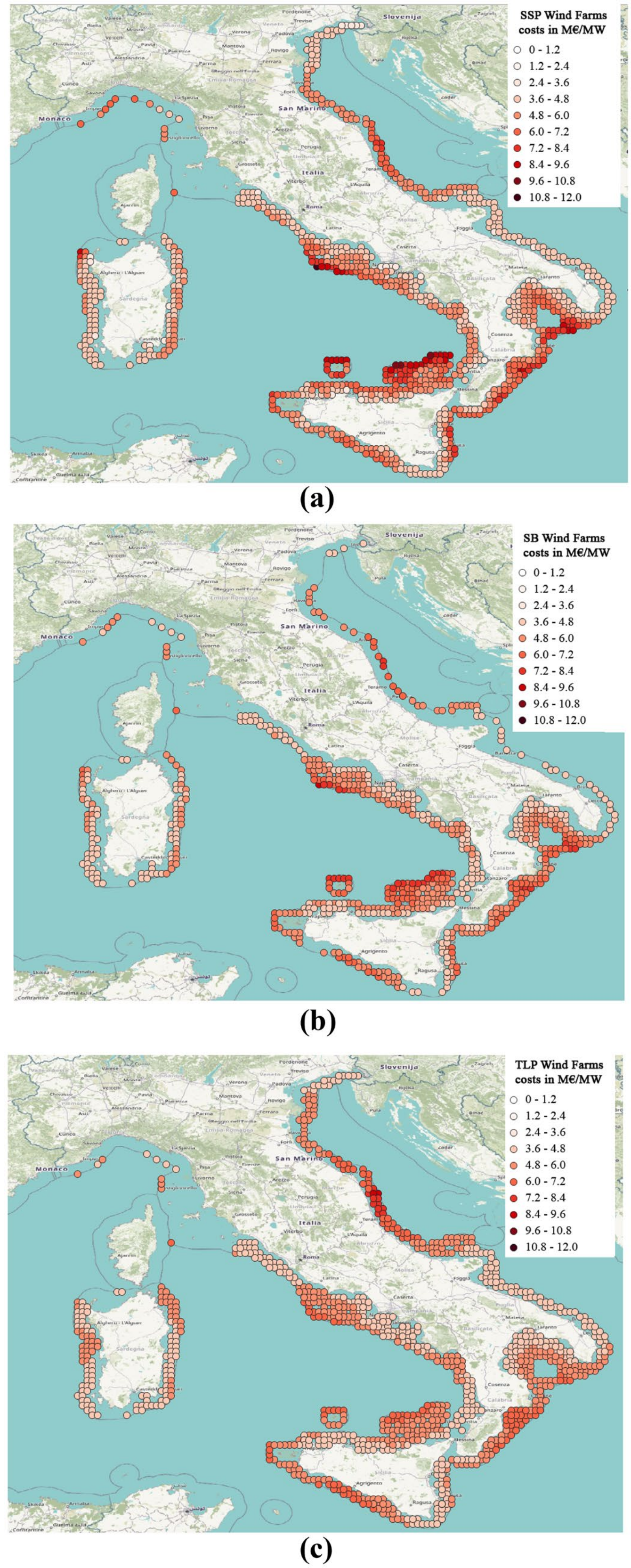
On the other hand, the maximum costs of 11.18 M€/MW and 8.63 M€/MW are found for SSP and SB wind farms respectively, located in the northern coast of Lazio at a distance to shore of 59.85 km, at a distance from port of 128.61 km and at a bathymetry of 3,500 m. The maximum cost for a TLP wind farm equal to 8.25 M€/MW is found in the southern coast of Marche at a distance to shore of 23.17 km, at a distance from port of 312.9 km and to a bathymetry of 200 m.

The life cycle cost of wind farms is found to be mainly influenced by the distance from port of operation and by bathymetry, and to a lesser extent by the distance to shore. In particular, the distance from port of operation mainly affects those areas where the nearest port is at least 200 km away. This is the case of the northern part of the Adriatic Sea, of part of the Ionian Sea, namely the south-western coast of Sicily, and of part of the Tyrrhenian Sea. In these cases, the costs of wind farms exceed 5.5 M€/MW. On the other hand, costs increase for wind farms located in very deep sea areas, exceeding 1,000 m. This applies to sites in the Ionian sea and in the Southern Tyrrhenian Sea, where the life cycle cost of wind farms can exceed 4.3 M€/MW even in the presence of a nearby port.

3.4 Producibility analysis

The analysis of producibility was carried out starting from the climatic data provided by the European Wind Atlas (Troen and Petersen 1989), showing that the mean wind speed in the Italian waters ranges between 6 and 10 m/s. In detail, the scale parameter ranges from 4 to 8.6 m/s, while the shape parameter ranges from 1.36 to 1.64 for the geo-referenced points in the domain of possible offshore wind farm sites.

Fig. 3 Cost maps of wind farms for different floaters: **a** SSP; **b** SB; **c** TLP



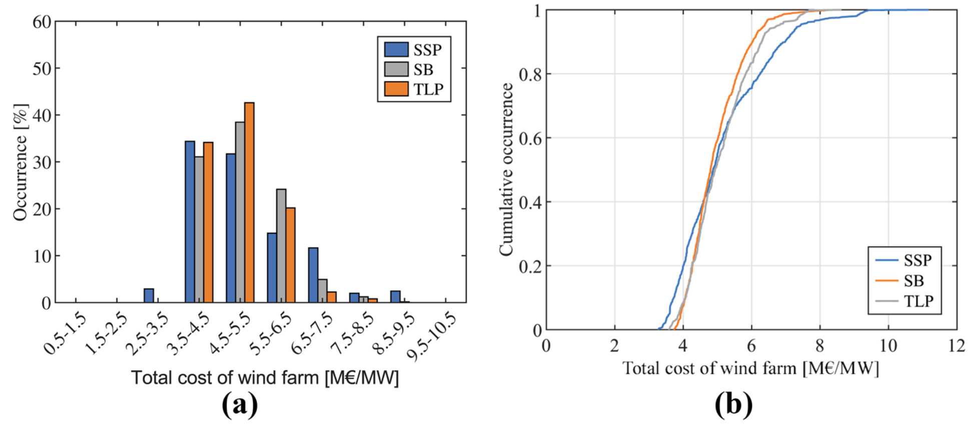


Fig. 4 Total life cycle cost of wind farms: distribution (**a**) and cumulative occurrence (**b**)

The results of the producibility analysis are reported in Fig. 5 in terms of *AEP* and *CF*. It is shown that the *AEP* of a 60 MW FOWF in the Italian national water varies between 62 GWh and 237 GWh. The values are on average larger than the maximum value of 96 GWh obtained for onshore sites in Italy (Maienza 2020). In agreement with the map of the mean *1-hr* averaged wind speed, the lowest values of the *AEP* are located along the north-east coasts of Adriatic sea, with values ranging between 60 GWh and 90 GWh. Instead, the largest values of the *AEP* are found along the southern coasts of Sardinia and along the Western coasts of Sicily, with values ranging between 210 GWh and 240 GWh.

A more direct indicator of the FOWF performance, the *CF* is found to be in the range between 12 % and 46 %. In detail, it reaches values larger than 40 % ($AEP = 210$ GWh) in 4 % of the investigated sites, in particular along the southern coasts of Sardinia and along the Western coasts of Sicily; instead, it is less than 17 % in 5 % of the cases, in particular in the *Adriatic sea*. The largest occurrence is found to be in the range between 23 % and 29 %, corresponding to sites in the Tyrrhenian sea. These CF values are in good agreement with the global average capacity factor expected for the FOWFs project commissioned up to 2018 (International Renewable Energy Agency 2021).

3.5 Feasibility analysis

Maps of the financial parameters illustrate the distribution of the values of *LCOE*, *NPV*, *IRR* and *PP* of FOWFs.

According to the life cycle cost results, highlighting that *SSP* wind farms are generally more convenient, only the financial parameters for the latter type of floater are presented in Fig. 6. The majority of the sites have an *LCOE* that varies between 100 and 150 €/MWh. Almost all sites located in Puglia have a low *LCOE*, with values as low as 68.6 €/MWh; in Sardinia, the lowest *LCOE* of 53.1 €/MWh is found in the south-west of the Island; finally, also in the north-west and in the south-east of Sicily low values are found, with a minimum of 79.7 €/MWh.

The *NPV* maps were prepared considering a discount rate $i = 5\%$, corresponding to the global average discount rate for offshore wind (International Renewable Energy

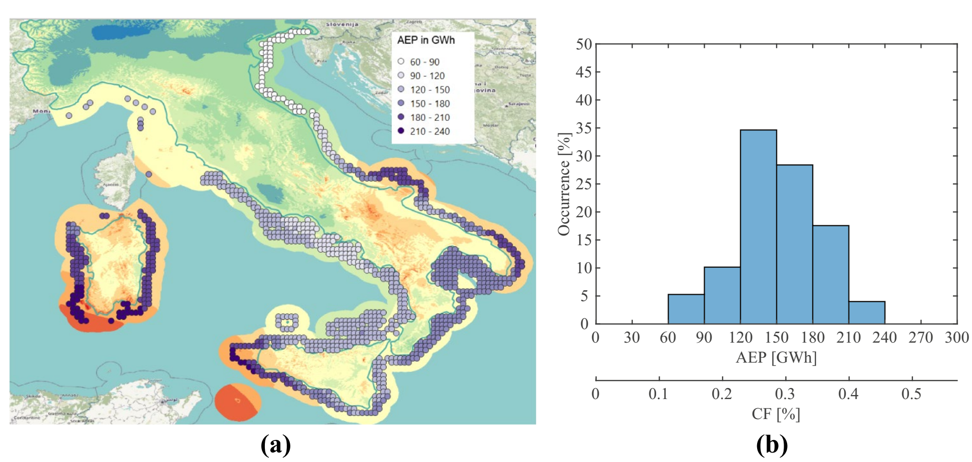


Fig. 5 Producibility of the 60 MW FOWFs for the sites considered in the analyses: **a** *AEP* map; **b** *AEP* and *CF* occurrence diagrams

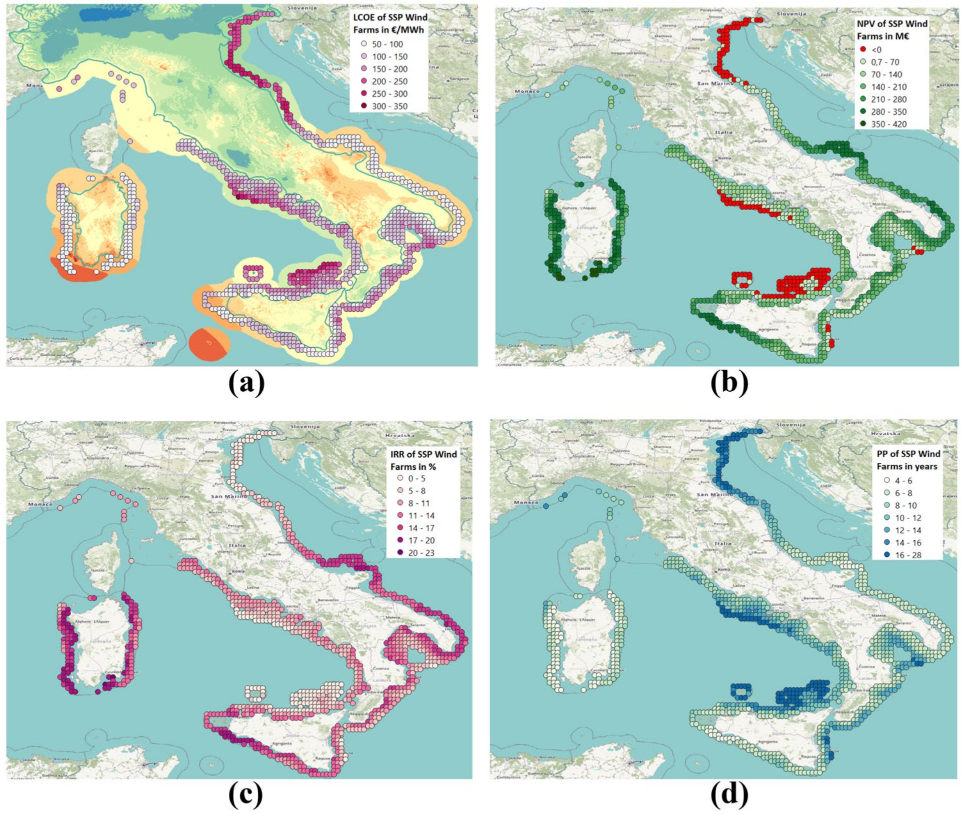


Fig. 6 Financial parameters maps of *SSP* wind farm: **a** *LCOE*; **b** *NPV*; **c** *IRR*; **d** *PP*

Agency 2019b). When the $NPV < 0$, then the investment is not considered acceptable, and large positive values of the *NPV* indicate a good investment. The *NPV* map for SSP floaters (Fig. 6b) indicate as inappropriate the sites located in the north of Adriatic Sea due to the low resource, in the South Tyrrhenian Sea and some in the Ionian Sea because of bathymetry. A similar result was found also for SB wind farms, but in that case all the sites in the Ionian Sea are acceptable. On the other hand, for TLP floaters only the farms located in the North Adriatic sea are not convenient, due to the low wind speed. Based on the *NPV* results, the most convenient SSP, SB and TLP wind farm projects are found along the southern coasts of Sardinia. In these projects, the *NPV* can reaach values between 350 and 420 M€, even though in the majority of the cases the *NPV* ranges between 140 and 210 M€ for SSP and TLP wind farms, and between 70 and 140 M€ for SB wind farms.

As to the *IRR* maps, values of $IRR > 5\%$ are considered convenient, corresponding to the reference discount rate. The larger the *IRR*, the better the investment. From the *IRR* map of SSP farms (Fig. 6c) it is seen that the best sites feature an *IRR* ranging between 17% and 23%, and are found along the Eastern coasts of Puglia, the north-western coast of Sicily and around Sardinia. Indeed, most of SSP and SB wind farms have a value of *IRR* ranging between 8% and 11%, while for TLP wind farms this value varies between 11% and 14%.

With reference to *PP* maps, the range of years required for the return on the investment is quite wide; indeed, it varies from 4 to 30 years. In the case of onshore and shallow water offshore wind farms, where the lifetime is generally 20 years, the investment is considered acceptable when the return occurs within 10 years. In the case of FOWFs, where the lifetime is assumed to be 30 years, the investment can be considered acceptable when the return occurs by its mid-lifetime, which is 15 years. From the *PP* map of SSP (Fig. 6d), the most convenient wind farms are located along the northern coast of Puglia, the Western coasts of Sicily and around Sardinia. On the other hand, in the *PP* distribution of SB the most convenient wind farms are found along the coast of Ustica Island, the Western coast of Sicily and the southern coast of Sardinia. Finally, in the *PP* distribution of TLP the most convenient wind farms are located only in the south of Sardinia. Finally, around 30% of SSP and SB projects have a return between 6 and 8 years, and about 35% of TLP projects have a return between 8 and 10 years.

The analyses developed in this paper confirm that most ot the Italian waters is suitable for FOWF installation, and promising from the investment point of view. According to the results obtained, it can be concluded that the best sites are located along the coasts of Sardinia, Puglia and Sicily, corresponding to the largest wind resource. Table 4 shows the financial parameters of some among the most promising

Table 4 Best financial parameters values of SSP, SB and TLP wind farms

	Lat N (º)	Long E (º)	LCOE (€/MWh)	NPV (M€)	IRR (%)	PP (years)
Sardinia						
SSP	39,13681	9,36071	53,1	407	21,2	4,7
SB	38,73681	8,36071	61,4	391	18,4	5,4
TLP	38,93681	8,06071	61,3	372	17,3	5,7
Puglia						
SSP	40,53681	18,26070	68,6	286	17,1	5,8
SB	40,73681	18,26070	75,4	273	14,9	6,6
TLP	40,73681	18,16070	78,5	266	14,8	6,6
Sicily						
SSP	36,93681	15,26070	79,7	209	14,2	6,9
SB	38,13681	12,56070	82,4	266	14,6	6,7
TLP	38,13681	12,66070	85,5	247	14,5	6,6

sites, for all three floater technologies. In all the cases, SSP wind farms are the most convenient compared to SB and TLP solutions.

Comparison of *LCOE* values between different energy sources is shown in Fig. 7. In particular, the comparison highlights the minimum and the maximum value of *LCOE* of FOWFs calculated in this study, with the *LCOE* range of the other renewable sources and fossil fuels considering the European market and disregarding possible incentives (Fraunhofer ISE 2018); Gamboa Palacios and Jansen (2018); International Renewable Energy Agency (2019a, b)). The *LCOE* range of FOWFs is the widest, varying between 53 and 320 €/MWh. The minimum value of 53 €/MWh would be more advantageous than all other energy sources, with the exception of hydro and biomass; indeed, the latter have a minimum value of *LCOE* corresponding to 46 and 37 €/MWh, respectively.

3.6 Calibration of the simplified cost model

The simplified cost model proposed in Sect. 2.2 is calibrated based on the results summarized in Sect. 3.3.

In detail, C_0 includes the costs of the onshore cable and its installation, of the onshore substation and its installation and of indirect maintenance. For the range of wind farms here considered it can be assumed as equal to 9 M€. This value is obtained through regression analysis of the total costs of FOWFs with SSP, SB and TLP floaters considered in Sect. 3.3, calculated using the analytical cost model proposed by Maienza et al. (2020a).

The costs C_1 include the sum of costs of the offshore export cable and of its installation, and they are found to linearly increase with the distance to shore. They do not depend on the type of floater and can be approximately expressed by the following equation:

$$C_1 = 1.51 \cdot 10^{-2} \cdot l_2 \quad (9)$$

where l_2 is the distance to shore in km and C_1 is expressed in M€/MW.

The costs C_2 include the installation of wind turbine, floating platform and substation, direct maintenace and decommissioning. Decommissioning costs are influenced by all three parameters, but for simplicity in this calculation they were

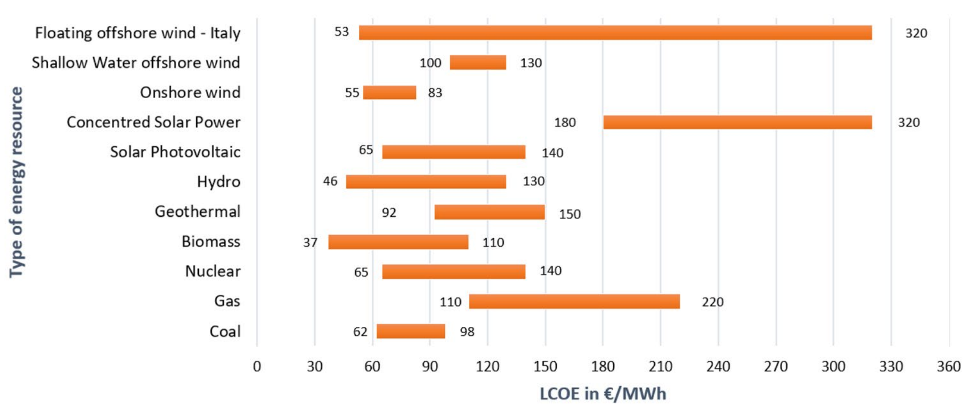


Fig. 7 Comparison of LCOE values between different types of energy sources. Source of data: Fraunhofer ISE 2018; International Renewable Energy Agency 2019a, b

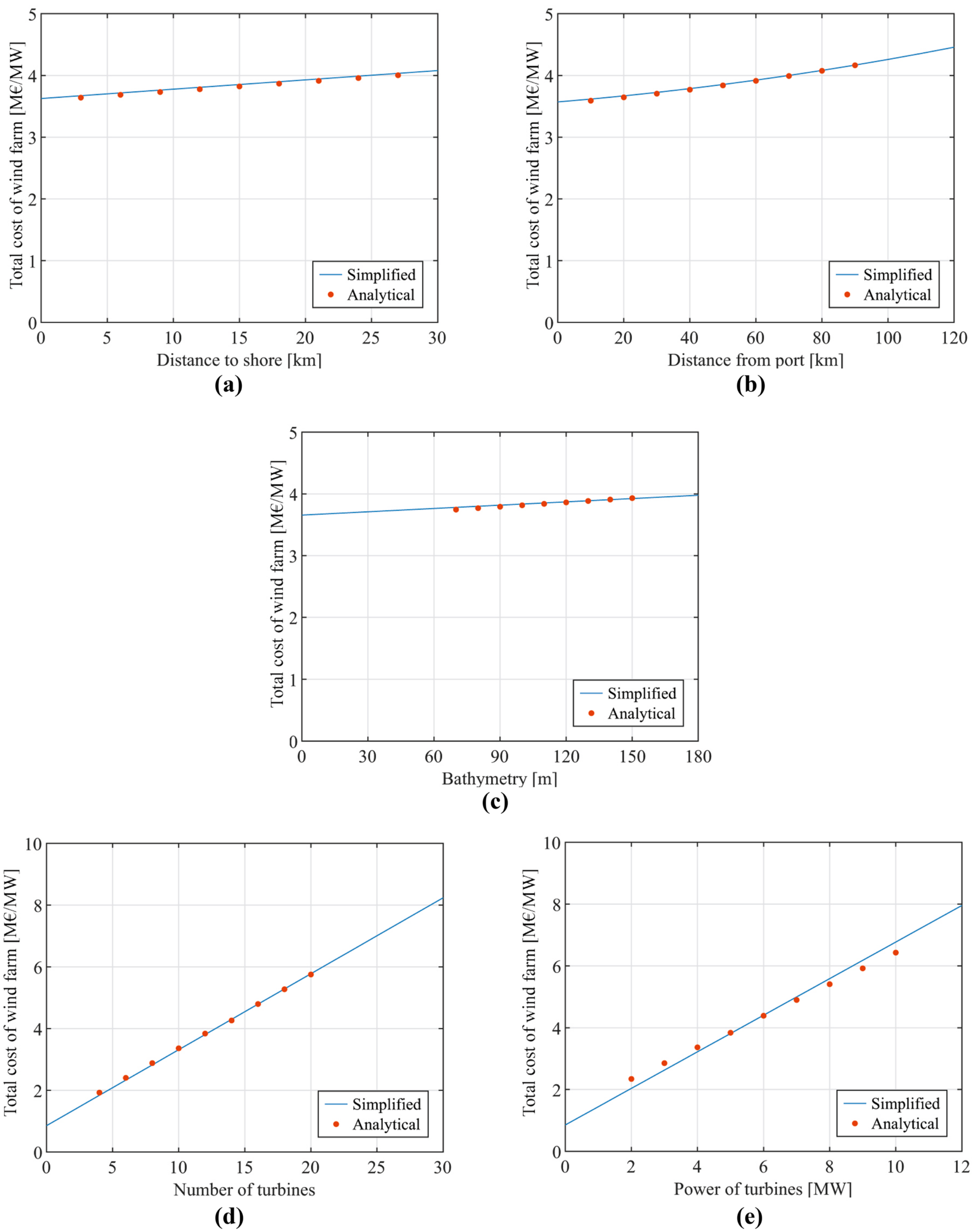


Fig. 8 Variation of the life cycle cost of the FOWFs with distance to shore (**a**), distance from port of operation (**b**), bathymetry (**c**), number of turbines (**d**) and turbines power (**e**)

added to C_2; this is because decomissioning is more influenced by activities whose costs are related to the distance from port. C_2 depends on the type of floater, because of the different installation procedures, and it can be expressed by the following equations, relevant to SSPs, SBs and TLPs, respectively:

$$C_{2,SSP} = 2.45 \cdot 10^{-5} \cdot d_p^2 + 4.40 \cdot 10^{-3} \cdot d_p \quad (10)$$

$$C_{2,SB} = 2.43 \cdot 10^{-5} \cdot d_p^2 + 4.78 \cdot 10^{-3} \cdot d_p \quad (11)$$

$$C_{2,TLP} = 2.34 \cdot 10^{-5} \cdot d_p^2 + 6.10 \cdot 10^{-3} \cdot d_p \quad (12)$$

where d_p is the distance from port of operation in km and C_2 is expressed in M€/MW.

The costs C_3 include the array cables and their installation, and the mooring lines. They are also dependent on the type of floater, because of the different mooring system. The costs C_3 are found to increase linearly with bathimetry, and they can be expressed by the following equations, relevant to SSPs, SBs and TLPs, respectively:

$$C_{3,SSP} = 17.7 \cdot 10^{-4} \cdot w_\delta \quad (13)$$

$$C_{3,SB} = 9.66 \cdot 10^{-4} \cdot w_\delta \quad (14)$$

$$C_{3,TLP} = 2.74 \cdot 10^{-4} \cdot w_\delta \quad (15)$$

where w_δ is the bathymetry in m and C_3 is expressed in M€/MW.

Finally, C_4 includes the costs of the turbines and of their installation, the cost of the floating platforms, the cost of the anchoring system and of its installation, the cost of the offshore substation and, the cost of operation. It is estimated as 2.40 M€/MW for SSPs, 2.65 M€/MW for SBs and 2.65 M€/MW for TLPs.

A comparison between the analytical cost model developed in Maienza et al. (2020a) and the simplified cost model here proposed in Eq. (8) was carried out. Being the simplified cost model calibrated on the analyses presented in Sect. 3.3, its range of validity its strictly related to the cases analysed through the example. In particular, the following ranges are defined for the variables: a) distance to shore between 3 and 27 km; b) distance from port of operation between 10 and 90 km; c) bathymetry between 70 and 150 m; d) number of turbines between 4 and 20; e) turbine power between 2 and 10 MW.

In Fig. 8, the results obtained are shown; in particular, the variation of the life cycle cost of the SSP wind farm according to the variation of the input parameters is obtained using the analytical and the simplified cost models. The results obtained with the two approaches have the same trend. In particular, the curves corresponding to the distance to shore, to the distance from port of operation and to bathymetry have a maximum difference not exceeding 1%, while the curve corresponding to the number of turbines has a maximum difference of about 5%. Finally, the curve corresponding to the variation of total cost of wind farms as function of turbines power shows a maximum error that can be as high as 15% in the low turbine power range (2 MW) and 5% in the high turbine power range (10 MW).

In Fig. 9, the comparison between the life cycle costs of the wind farms calculated with the analytical and the simplified models is shown. A good agreement between the cost results obtained through application of the two models for SSPs, SBs and TLPs is observed; on average the simplified model underestimates the total cost by 1%. The error is larger than 5% only for 10% of the analysed cases. Therefore, the simplified cost model can be very useful to provide a quick estimate of the FOWF life cycle total cost, before any further and more accurate analysis. The advantage presented by this simplified model consists of its derivation from an analytical model.

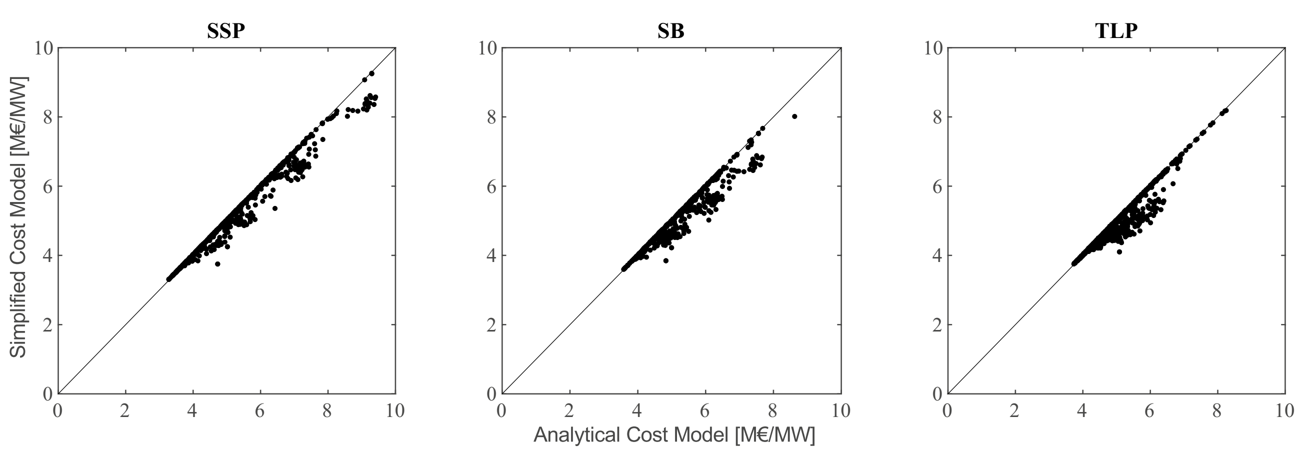


Fig. 9 Scatter plot of the life cycle cost: comparison between analytical and simplified model results for SSPs, SBs, TLPs

4 Conclusions

In this work, a comprehensive application of the life cycle cost model for FOWFs previously developed is presented and complemented with a cost–benefit analysis.

First, the cost model based on the explicit and analytical assessment of Capital cost, Operation and Maintenance costs and Decommissioning cost is validated through comparison with results available from the literature. The cost values calculated with the proposed approach are found to be in good agreement with those coming from similar analytical approaches and show some discrepancies with those based on average costs. Moreover, comparison of the costs of shallow water wind farms taken from the literature, with those of similar floating farms evaluated with the proposed approach, highlights how the latter are quite competitive from the economic point of view.

Then, an implementation is carried out in QGIS of the cost model and of the resource analysis, to be used in evaluations at the territorial scale. Analyses were developed for FOWFs based on SSP, SB and TLP floaters, located in the Italian national waters. In the analyses, the lower limit of the water depth deriving from the minimum draft of each type of floater, as well as environmental constraints (i.e. the presence of protected areas and the navigation limitations) were considered. The final results were presented in terms of life cycle cost maps, giving an overall framework of the variation of the costs of FOWF for each type of floater. Among the three types of floaters considered, the SSP proved to be the most promising one, giving lower costs then the SB and the TLP.

The cost–benefit analysis revealed that the feasibility of a project is mainly driven by the resource availability, but also that floating offshore wind generation is quite competitive with other renewable and fossil sources.

Finally, a simplified cost model was calibrated based on the results of the application of the analytical model. A good agreement between the results in terms of total cost of FOWFs calculated with analytical and simplified models for SSPs, SBs and TLPs is observed.

The approach and the results presented here are meant for use in the early stage of the decision-making process, as a tool for the assessment of the economic feasibility of FOWFs installation.

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