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Evaluation method of marine spaces for the planning and exploitation of offshore wind farms in isolated territories. A two-island case study

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ABSTRACT

The interest in offshore wind energy is fundamentally based in most cases on the exploitation of the high levels of wind power found in offshore areas. The evaluation of marine spaces for planning and exploitation of this type of energy source is even more important in territories with isolated and/or weak electrical systems and limited available territory. In the study developed in this paper, GIS-based techniques are applied to identify priority zones for the exploitation of offshore wind farms in the islands of Gran Canaria and Tenerife, the two largest of the eight islands that make up the Canary Archipelago (Spain). The zones identified are prioritized and differentiated by the most viable type of wind turbine substructure technology (bottom-fixed or floating), capacity factor (in MWh/MW), and specific cost (€/MWh). The results are expressed in map form, which can form part of future energy planning processes for the islands. The resulting identified offshore priority zones comprise 375.9 and 68.2 km^2, with bottom-fixed:floating surface area ratios of 1:6 and 1:21, for Gran Canaria and Tenerife, respectively. The method developed in this paper is vital for detailed energy planning, an important aspect in the optimization process of offshore wind energy integration in isolated and/or weak electrical systems.

1. Introduction

One of the strategic objectives of EU Directive 2018/2001 on the promotion of the use of energy from renewable sources (EU, 2018) is to increase the contribution of renewable energies to satisfy energy demand in general and electrical energy demand in particular. In this regard, it sets as a general goal for the time horizon of 2030 a renewable contribution to electrical energy demand of 32%. This overall goal is individualized for each of the EU's member countries through specific targets (see Article 3 of (EU, 2018)).

The case study in this present paper considers Gran Canaria and Tenerife, the two largest islands of the Canary Archipelago (Spain). The archipelago, situated some 1100 km southwest of mainland Spain, had a total population of 2,172,944 inhabitants at the end of 2021. The two islands correspond to 81.9% of the total population of the archipelago (Canary Institute of Statistics (ISTAC), 2021), and 79.7% of its electrical energy demand (Spanish Electricity System Operator (REE), 2022). The singular nature of these islands can be seen in the following characteristics:

→ They have isolated electrical systems, with no connection to any other island or continental territory (Canary Government, 2020). As a result, they are considered weak systems, with electrical energy generation needing to be adapted precisely to the demand of each island in order to avoid electrical system instability.
→ Territorial fragility. The available surface area for renewable energy exploitation is limited. The total surface area of Gran Canaria is 1508 km^2 and that of Tenerife 2030 km^2. Of this area, 48.6% and 43%, respectively, are subject to environmental protection status as part of the EU's Natura 2000 network and in accordance with the Law on Natural Spaces of the Canary Islands (Canary Government, 2022a).
→ As they are islands of volcanic origin, their bathymetry varies considerably. Depths greater than 50 m are found at relatively short distances from the coast.

With respect to marine wind energy exploitation and planning, precise knowledge of the bathymetry of an area is a key characteristic when it comes to selecting between bottom-fixed or floating substructure technologies as the method used to maintain the wind turbines in place.

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With the aim of maximizing the integration of renewable energies in electrical energy demand, the Canary Government has established the exploitation of marine wind energy as one of its strategic objectives, including a specific goal of 330 MW by 2030 (Canary Government, 2022b). At the end of 2021, the total installed offshore wind power in the islands was just 5.2 MW (Canary Government, 2022b).

Given the singular nature of the islands under study, not to mention the considerable distance between the currently installed offshore wind power and the strategic target that has been set, precise research studies need to be undertaken to help in the planning and optimization of the large-scale integration of this renewable energy source. Given that a good design should be governed by multiple dimensions, most offshore wind energy studies are carried out using multi-criteria decision analysis (MCDA). This technique allows the decision maker to pay special attention to the criteria that they deem necessary (economic, technical, social and environmental) and make appropriate priority-based decisions. In this regard, an extensive review of the MCDA method and its multiple applications on the field of renewable energies can be found in (Kumar et al., 2017). In addition, a broad-ranging analysis of site selection criteria and procedures for the development of onshore and offshore wind energy can be found in (Spyridonidou and Vagiona, 2020). For their part, geographic information systems (GIS) are a contributory support tool in the decision-making process, using a large amount of spatial data related to the abovementioned diverse criteria. In this regard, the same authors report in (Spyridonidou and Vagiona, 2020) that GIS-MCDA is the most widely used technique in the scientific literature for the purposes of the evaluation of the most suitable locations for both onshore and offshore wind farms.

However, very few studies have been carried out on small-sized regions or regions of a singular nature. Most of the studies found in the literature were developed for broad territorial contexts, focused fundamentally on determination of the offshore wind resource potential where the basic variables are wind speed and water depth. For example, in (Schwartz et al., 2010) a report was presented on the offshore wind resource potential in the U.S. for various scenarios combining state administrative areas, while in (Dvorak et al., 2010) a study was undertaken in California determining the degree of energy coverage according to water depth range and the available substructure technology in each case. Another approach is related to production costs. In this regard, in (Martinez and Iglesias, 2022) potential areas for exploitation were identified in Ireland considering the levelized cost of energy, while in (Hong and Möller, 2011) an investigation was undertaken into the available offshore wind energy resources in China, providing information about the available power at or below a given cost and its corresponding geographical locations. Fewer works have been developed for regions with small available areas and/or weak and/or isolated electrical systems. In (Majidi Nezhad et al., 2022), an examination was undertaken of the offshore wind energy potential in Iranian islands in the Persian Gulf based on a longitudinal study. In (Christoforaki and Tsoutsos, 2017), a method was presented for the siting of offshore wind farms in a partial zone of the island of Crete which included examination of environmental and legislative restrictions. Subsequently, a method was developed in (Gkeka-Serpetsidaki and Tsoutsos, 2022) using GIS-MCDA for the study of Crete as a whole. In (Schallenberg-Rodríguez and García Montesdeoca, 2018), a study was carried out on the possible exploitation of the offshore wind resource in the Canary Archipelago. However, no differentiation was made of the energy potential of each delimited zone, no information was given that could be used to obtain a geographic reference of the delimited zones, and a spatial distribution of wind turbines was only provided for the island of La Gomera. In the same archipelago, a study was undertaken in (Abramic et al., 2021) which considered diverse variables such as wind speed, environmental sensitivity and existing costal economic activities. The zoning result of (Abramic et al., 2021) is used in the present paper as input data.

The method applied in the present paper makes use of GIS techniques to identify priority zones for offshore wind energy exploitation. In this case, all map digitalization, conversion and analysis processes were performed using ESRI ArcGis 10.8.1 software.

The original contribution and novelty of this study include the application of the method to territories of a singular nature, with the results obtained from the application of the method expressed in map form. Differentiation is made in these maps of specific areas within each priority zone on the basis of parameters that include the most viable substructure technology to maintain the wind turbines in position (bottom-fixed or floating), the capacity factor (CF) in MWh/MW, the specific cost (€/MWh) of offshore wind energy exploitations and the installable offshore wind power. The precise geographic identification of zones with a higher CF minimizes the area required for the attainment of the energy objectives set out in planning documents. This is key in the case of regions with a low availability of area for offshore wind exploitation and/or with weak electrical systems. In addition, the identification of zones with lower offshore wind energy generation specific costs optimizes the economic saving of the electrical systems of isolated and/or remote regions where the costs of conventional electrical energy generations are very high.

2. Materials and methods

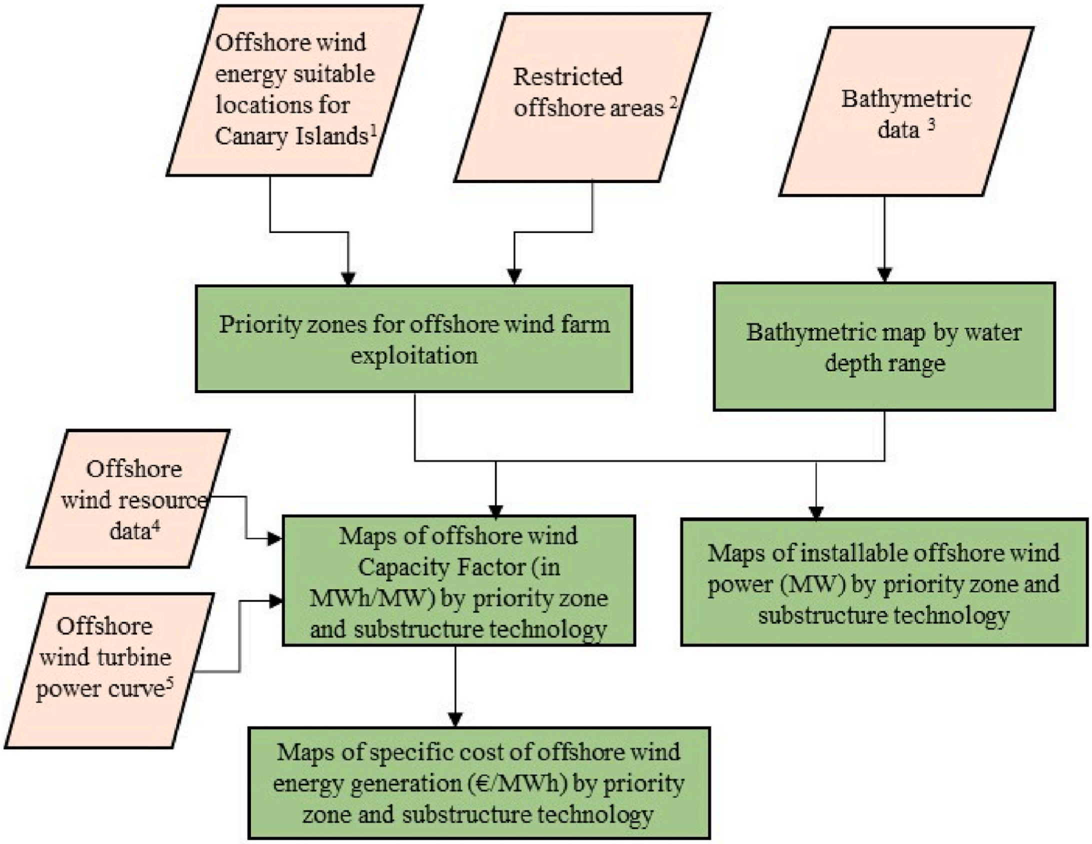
Fig. 1 shows the method developed to obtain the results that are the research object set out in the present paper.

3. Suitable offshore wind energy locations

The starting point for the process used to identify suitable locations is the work undertaken in (Abramic et al., 2021), where an analysis was made of the maritime space of the Canary Islands considering five factors: oceanographic potential, environmental sensitivity, restrictions related to marine conservation, land-sea interactions, and the avoidance of possible conflicts with maritime and coastal activities. On the basis of these five factors, the authors of the aforementioned study identified, using the web tool and decision support system INDIMAR, a set of marine areas with significant wind and depth potential, minimum impact on the marine environment, and compatibility with marine conservation and the prevention of conflicts with maritime economic sectors and coastal operations (such as coastal tourism, fishing, fish farming, etc.). The result of the aforementioned study shows three maps which reflect three different suitability profiles for the Canary Islands according to the different criteria defined by: project experts, external experts and maritime spatial planning (MSP) stakeholders. In the present study, the zoning corresponding to the MSP stakeholders profile was taken as the reference framework as it best corresponds to the objective of this study and, in addition, includes a less restrictive approach (see Fig. 5 in (Abramic et al., 2021)).

One of the major difficulties when considering the offshore installation of a wind turbine is how it is attached to the seafloor. According to the available data, the investment required for the necessary substructures can represent up to 20% of the cost of a wind farm (European Wind Energy Association, 2010). The cost of installation rises with water depth, which is the most important factor to consider. In consequence, it is essential to have bathymetric data of the areas that are under study. For the work developed in the present paper, the necessary data was obtained using the European Marine Observation and Data Network (EMODnet) website (European Marine Observation and Data, 2022) through an ASCII file that was transformed into a digital elevation model (DEM). The DEM was subsequently classified into different depth ranges to serve as a reference for determination of substructure type according to depth (Fig. 2).

In general, a greater depth corresponds to a greater distance from the coast and, therefore, higher installation and maintenance costs (Ribeiro et al., 2020). The technologies required to ensure an offshore wind turbine remains in position can be divided into two different types; bottom-fixed and floating (Subbulakshmi et al., 2022). With respect to



[1] See in [17]
[2] Marine areas restricted by:
  - Natura 2000 network (Special Conservation Areas, Special Bird Protection Areas, and Sites of Community Importance) [18]
  - Maritime Transport, Atlantic and Mediterranean Port Networks [19]
  - Sensitive areas for air navigation [20]
  - Distance from the coast [21]
[3] Bathymetric data [22]
[4] Offshore wind resource data [23]
[5] Offshore wind turbines power curve [24]

Fig. 1. Method developed.

the former, most wind farms in depths less than 30 m use monopile-type foundations (Musial and Butterfield, 2004), as they are relatively simple to manufacture, relatively easy to install and relatively cheap. For depths between 30 and 50 m, jacket-type or tripod support structures are used, which entail higher design, manufacturing and maintenance costs (Plodpradit et al., 2019). For areas of greater depth (more than 50 m), floating technologies are more common (spar, tensioned-leg platform, etc.) (Oh et al., 2018) given a series of benefits that include greater flexibility in the construction and installation procedures, the ability to transfer bending loads onto water instead the rigid seafloor, and easier removal when the site is decommissioned (European Wind Energy Association, 2010). In view of the above, the criterion was assumed in the present paper of considering the use of bottom-fixed technologies in zones with depths $\leq$50 m and floating technologies when the depth is $>$ 50 m.

3.1. Capacity factor (CF)

To assess the energy potential of the considered wind zones (suitable wind locations), the CF parameter was used, defined as annual energy production per wind power unit (MWh/MW) (Canary Government, 2020).

The Canary Islands Wind Resource tool, developed by the Canary Islands Technological Institute (ITC for its initials in Spanish), a public-owned company of the Canary Government (Canary Government, 2022c), contains the information required to assess the wind resource of the archipelago. This tool provides the wind speed and direction data, as well as the Weibull distribution parameters, at 40, 60 and 80 m height for the different points of a geographic mesh of the entire archipelago with a cell size of 100 × 100 m.

The aforementioned tool also has a software application that can be used to calculate the electrical energy generated by a wind turbine at a specific geographic point. For this, it uses the wind resource data at that point and the power curve of the turbine. To obtain the CF (in MWh/MW) at different points of the suitable locations, the power curve of a Siemens-Gamesa SG 8.0 turbine (The Windpower, 1558), with 8 MW rated power and 80 m hub height, was used in the calculations.

4. Results and discussion

4.1. Capacity factor maps in suitable locations

Using as starting point the maps of suitable locations (Fig. 2) and following the procedure described in section 2.2 for CF calculation, the

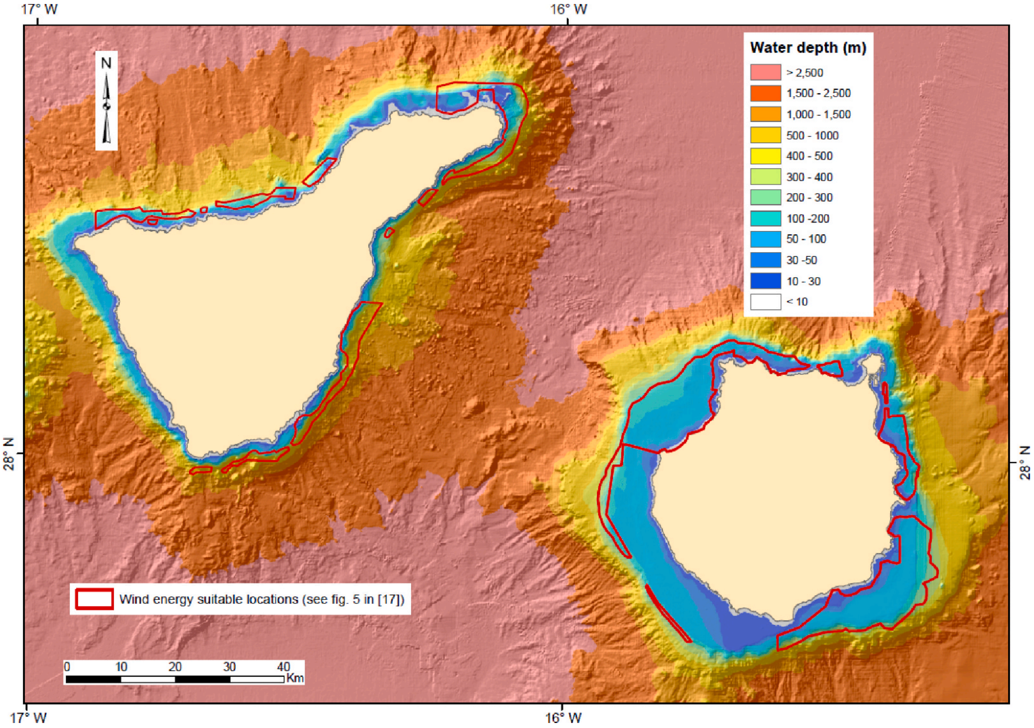


Fig. 2. Bathymetric map with the suitable locations for offshore wind farms.

suitable locations CF maps were generated (Fig. 3). Areas can be observed in suitable locations in both islands with CF below 3,500, though they are more predominant in Tenerife. Additionally, a higher energy potential can be observed in Gran Canaria, with areas above 5000.

4.2. Offshore wind maps in priority zones

To obtain the priority zones from the suitable locations obtained in (Schallenberg-Rodríguez and García Montesdeoca, 2018) (represented by a red line in Fig. 2), the following additional restrictions were taken into consideration:

- Elimination of zones subject to different legislative restrictions. Firstly, it was verified whether the zoning established in (Abramic et al., 2021) took into account the restrictions established in Natura (2000) in the Marine Environment (European Commission, 2000). This verification was considered necessary to ensure the maintenance or, when applicable, reestablishment of a habitat conservation status favourable for species in their area of natural distribution in the marine environment.
- The existence of aerodromes close to suitable locations. In this regard, an area needs to be established that delimits the air space that must be kept free of obstacles in order to minimize the danger that a group of wind turbines situated close to an aerodrome could pose for

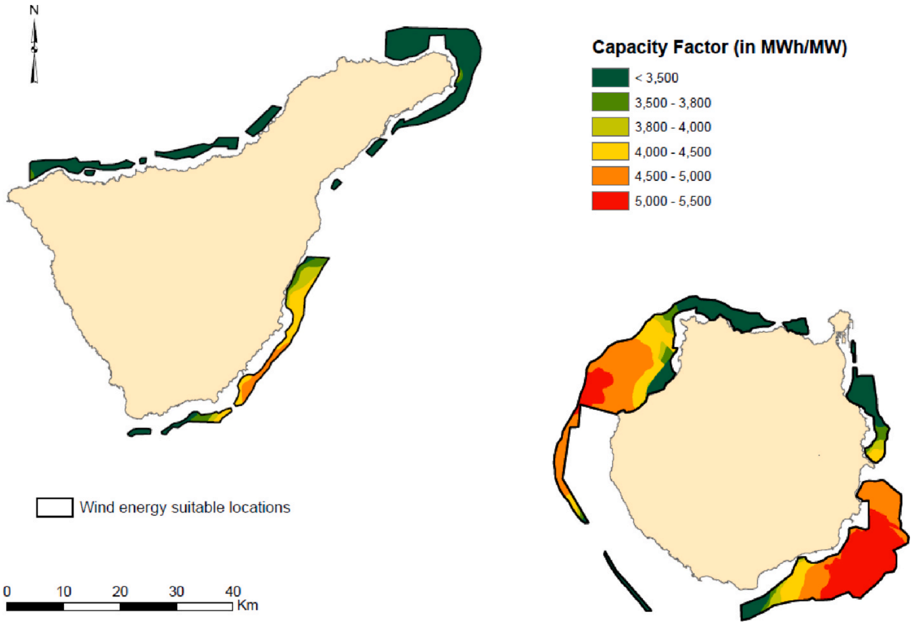


Fig. 3. Capacity factor maps in offshore suitable locations.

aircraft. For this study, the recommendations of the International Civil Aviation Organization (ICAO) (International Civil Aviation Organization ICAO, 2018) were followed in relation to the restriction and elimination of obstacles that need to be taken into account in the design of aerodromes. Of the different recommendations on surface area limitations considered by the ICAO, only the approach and take-off areas were taken into consideration, as this is the space that must be maintained free of obstacles in order to ensure the safety of the aircraft during these manoeuvres.

– The most important maritime routes of the islands (Delgado-Aguiar and LuisJÁ, 2019) were taken into account to ensure safe vessel passage. For this, a vessel right of way was established with a safety width margin of 2672 m, equivalent to 16 times the rotor diameter of the reference wind turbine.
– Bearing in mind the additional costs involved in the installation of an offshore wind farm, consideration was given to whether all the zones established in (Abramic et al., 2021) were viable in terms of economic investment. For this, a selection of priority zones was made that would guarantee project feasibility. This selection was made on the basis of three parameters: the CF of the potential wind zones, distance to the coast, and the presence of nearby port facilities. For the particular case of CF, it was determined that the priority zones must have wind characteristics and energy potential greater than can be found on land. According to (Canary Government, 2020), in 2020, the mean CF of onshore wind farms reached values of up to 3403 MWh/MW for Gran Canaria and 3109 MWh/MW for the archipelago as a whole. On the basis of these data, it was decided to select as priority zones only those with a CF higher than 3500.

As for the logistics required for the installation of offshore wind farms (Barlow et al., 2018), it is essential that there be relatively nearby ports, serving as a support for the storage and loading of the different wind turbine elements (Baudino Bessone et al., 2022), and that these ports have sufficient space for the handling and management of such large-sized structures (Crowle and Thies, 2022) and for the subsequent installation and maintenance processes of the wind farm (Trueba et al., 2021). Other decisive factors include the planning of the installation process (Irawan et al., 2017), optimization of the supply chain (Irawan et al., 2018) and the distance between the coast and the wind farm site (Tekle Muhabie et al., 2018) as a longer distance increases the installation and maintenance costs (Vis and Ursavas, 2016).

- With respect to the distance of these infrastructures from the coast, a restricted area is established in (General Secretary of Energy, 2009) comprising the first 10 m of depth closest to the coast. This is the only restriction taken from the aforementioned reference that cannot be violated in the installation of offshore wind farms.

Table 1 shows a summary of the most relevant additional criteria/restrictions considered in the present study.

After considering the additional restrictions listed above and using as starting point the suitable locations shown in Fig. 2, the priority zones for the two islands under study were obtained and are shown in Fig. 4. More specifically, two priority zones were identified for Gran Canaria (GC-Z1 and GC- Z2) and one for Tenerife (TF-Z1).

Figs. 5 and 6 show the CF maps for the priority zones. Areas can be observed in both islands with CF values above 4500 MWh/MW. The total available area in the priority zones is 375.9 and 68.2 km^2 for Gran Canaria and Tenerife, respectively.

In the maps, areas are differentiated by the type of substructure technology used to install the turbines (bottom-fixed or floating). The ratio of available area by technology type (bottom-fixed:floating) is 1:6 and 1:21 for Gran Canaria and Tenerife, respectively.

4.2.1. *Installable wind power in the priority zones*

The regulations for the installation and exploitation of wind farms in the Canary Archipelago are set out in Decree 6/2015 (Canary Government, 2015). These regulations include the minimum distance required between turbines to ensure minimization of possible interference between the two in the capture of wind energy. Measured with respect to the prevailing wind direction and perpendicular to it, the respective minimum distances must be 8 and 2 times the rotor diameter, respectively.

To assess the installable offshore wind power in each of the different priority areas, a spatial distribution of the reference wind turbine (The Windpower, 1558) was undertaken in lines perpendicular to the prevailing wind direction. The prevailing wind direction data was obtained from (Canary Government, 2022c). Given the significant concentration of wind turbines in each area, it was considered opportune to adopt as the distance between wind turbines along a same line the equivalent of 4 times the rotor diameter. In this way, any potential interference between turbines is minimized even further as too, in consequence, are any differences that might exist between the CF of the individual wind turbine and that of the group of turbines.

Figs. 7 and 8 show the installable wind powers for each of the study islands and priority zones, again with differentiation according to the substructure technology employed. The corresponding installable offshore wind power for Gran Canaria and Tenerife is 3632 and 688 MW, respectively. Bearing in mind the available area for each priority zone (Figs. 5 and 6), the resulting mean weighted power density for each island is 9.7 and 10.1 MW/km^2, respectively.

Considering the geographical location (x,y) of each wind turbine (Figs. 5 and 6), it was possible to associate to each turbine a CF value (in MWh/MW) using the CF map (Figs. 5 and 6). In this way, a mean capacity factor value could be obtained for the global distribution of wind turbines in each of the priority zones. Finally, the annual wind energy was estimated though Eq. (1). The results are shown in Table 2.

$$\text{Wind Annual Energy}(\text{MWh}) = \text{Offshore Wind Power }(\text{MW}) \times \text{CF}\left(\frac{\text{MWh}}{\text{MW}}\right) \tag{1}$$

The extractable annual offshore wind energy in Gran Canaria and Tenerife is equivalent to 5.4 and 0.9 times their respective electrical energy demand (Spanish Electricity System Operator (REE), 2022).

Table 1
Summary of relevant criteria/restrictions.

Criterion	Range-limits	Source/Website
Wind energy suitable locations	See Fig. 5 in (Abramic et al., 2021)	Abramic A et al. (Abramic et al., 2021)
Capacity factor (in MWh/MW)	>3500	Hypothesis based on data from Canary Islands Government document (Canary Government, 2020)
Natura 2000 network	The perimeter of protected areas	European Commission. Natura 2000 (European Commission, 2000)
Maritime transport	A vessel right of way was established, equivalent to 16 times the rotor diameter of the reference wind turbine	Delgado-Aguiar G and Hernández Luis JÁ (Delgado-Aguiar and LuisJÁ, 2019)
Distance from the coast	The first 10 m of depth closest to the coast	General Secretary of Energy and General Secretary of the Sea (Spanish Government) (General Secretary of Energy, 2009)
Ports	Presence of nearby port facilities	Delgado-Aguiar G and Hernández Luis JÁ (Delgado-Aguiar and LuisJÁ, 2019)
Sensitive areas for air navigation	The approach and take-off areas	International Civil Aviation Organization (International Civil Aviation Organization ICAO, 2018)

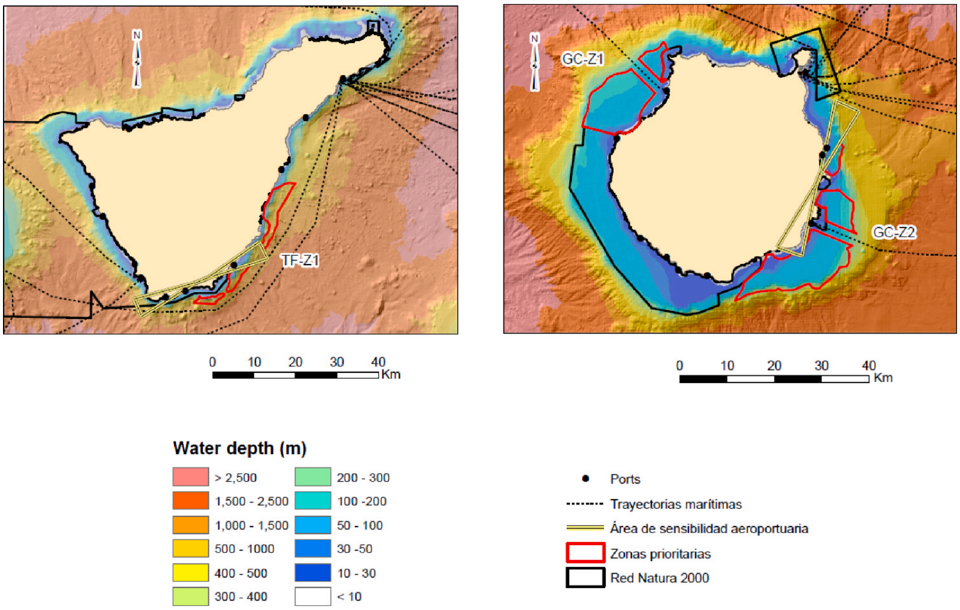


Fig. 4. Priority zones maps.

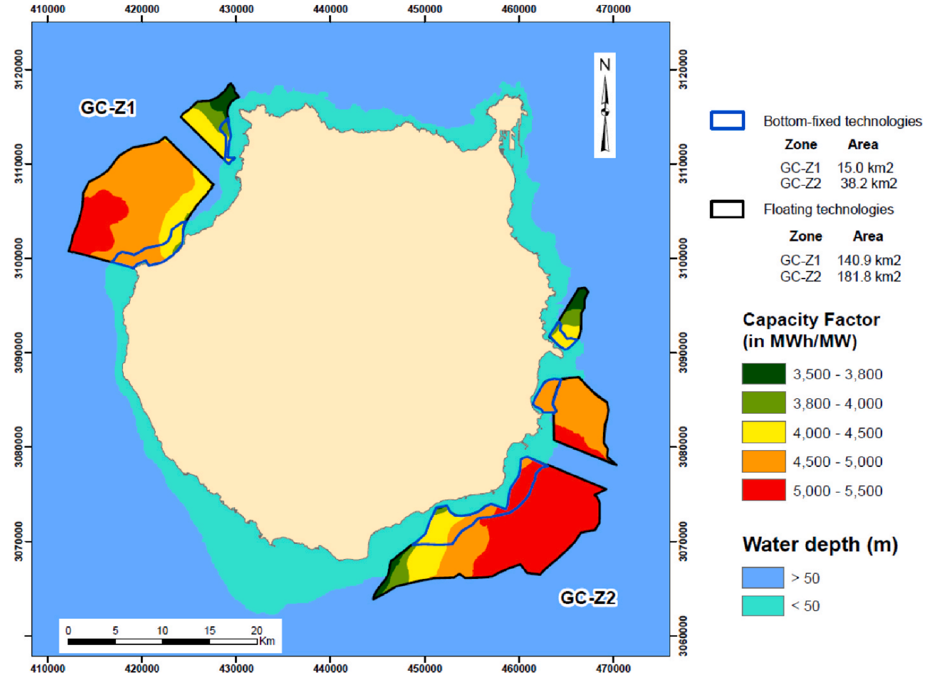


Fig. 5. Capacity factor map and substructure technology differentiation in offshore priority zones for Gran Canaria.

4.2.2. *LCOE maps in priority zones*

To estimate the specific cost of the offshore wind energy at a point of geographic coordinates “x” and “y”, the levelized cost of energy (LCOE) parameter was used Eq. (2). This parameter has been widely used in the literature, in both general energy planning studies (Yu et al., 2022) and in specific renewable energy installations (Mensah et al., 2022).

$$LCOE_{(x,y)}\left(\frac{\text{€}}{MWh}\right)=\frac{Specific\ investment\left(\frac{\text{€}}{MW}\right)\times CRF+CO\&M\left(\frac{\text{€}}{MW}\right)}{Capacity\ Factor_{(x,y)}\left(\frac{MWh}{MW}\right)} \qquad (2)$$

where $CO\&M$ is the annual operating and maintenance cost and CRF is the capital recovery factor . $CRF=\frac{d(1+d)^n}{(1+d)^n-1}$, with d being the annual discount rate and n the wind turbine lifetime. For the calculations developed in this paper, an n value of 20 years was chosen and a d value of 0.03. This latter parameter was estimated on the basis of the annual inflation rate in Spain over the 2010–2019 period (World data.info, 2022). The years 2020–2021 were ignored as they were economically atypical years due to COVID-19. The resulting CRF value is 0.067.

The values for specific investment and operating and maintenance costs depend fundamentally on the distance from the coast, the substructure technology employed and the total installed wind farm power. The International Renewable Energy Agency (IRENA) in its study “Renewable power generation cost in 2021” (International Renewable Energy Agency (IRENA), 2021) gives the mean data for these values obtained on the basis of already installed offshore wind farms throughout the world. The mean values used for the calculations made

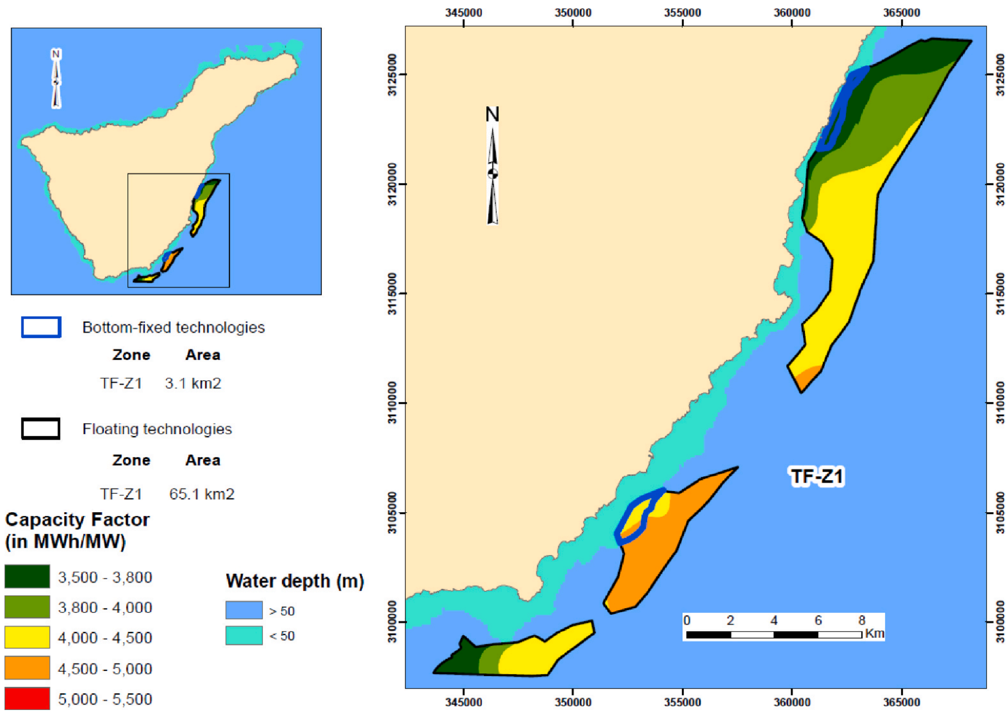


Fig. 6. Capacity factor map and substructure technology differentiation in offshore priority zones for Tenerife.

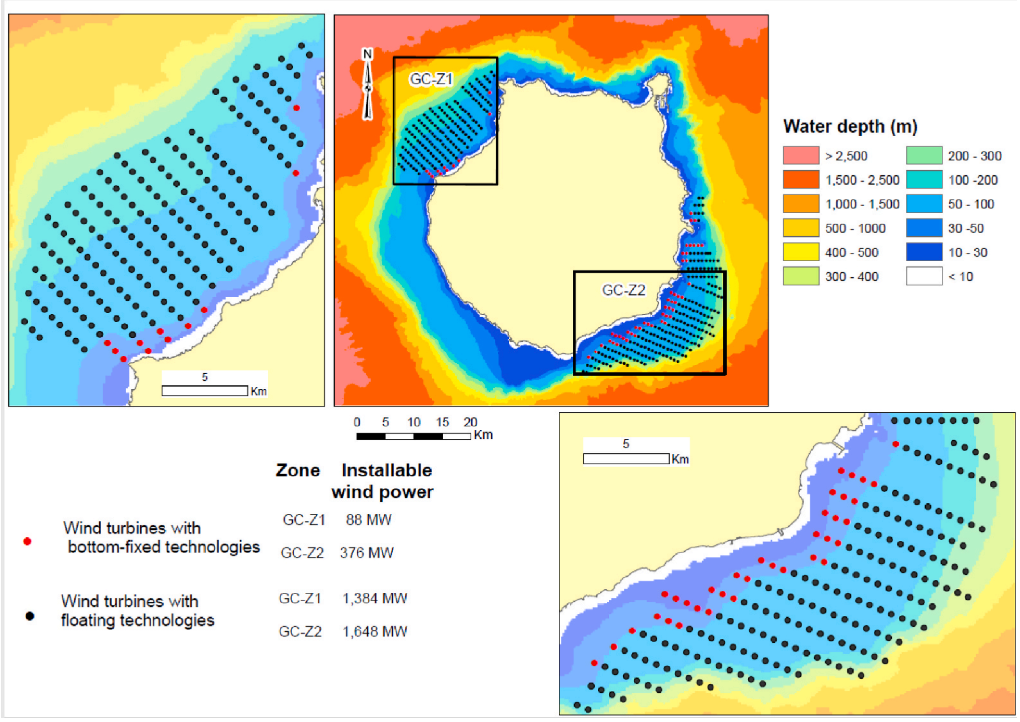


Fig. 7. Maps with installable offshore wind power by priority zone and substructure technology in Gran Canaria.

in the present paper, based on (International Renewable Energy Agency (IRENA), 2021), are shown in Table 3. It should be noted that these are mean values and that the actual final cost may vary depending on key aspects such as the slope of the seafloor and the cost of transmission infrastructure both as collectors and for onshore distribution.

On the basis of the data shown in Table 2 and using Eq. (2), the offshore wind energy specific costs maps were obtained (Figs. 9 and 10). It can be observed that the specific costs range between 55 and 120€/MWh for Gran Canaria and between 60 and 120€/MWh for Tenerife.

The electrical systems of the islands, given their condition of isolated systems, have far higher conventional electrical energy generation costs than continental-based systems. This surplus cost compared to mainland Spain is defrayed by Spain's system operator. According to the official energy data of the Canary Government for 2020 (Canary Government, 2020), the last year for which official data is available, the mean weighted cost of conventional electrical energy generation in Gran

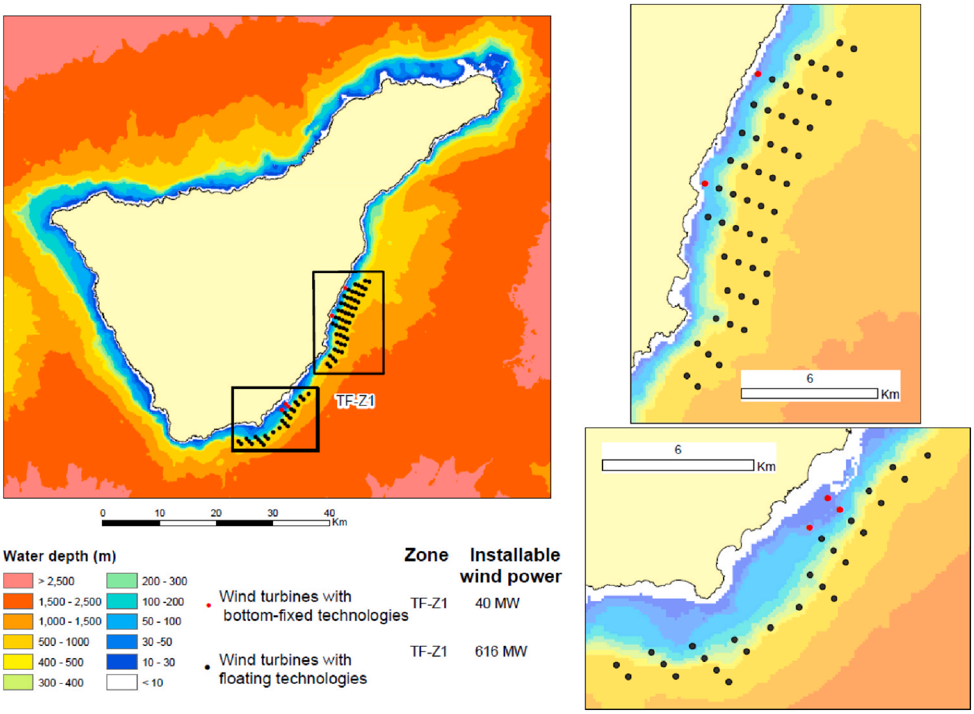


Fig. 8. Maps with installable offshore wind power by priority zone and substructure technology in Tenerife.

Table 2
Total installable wind power and annual energy production by priority zone.

Priority zone	Installable wind power (MW)	Mean capacity factor (in MWh/MW)	Annual energy production (GWh)
GC-Z1	1472.0	4658.7	6857.6
GC-Z2	2024.0	4882.0	9881.2
TF-Z1	656.0	4159.1	2728.4

Table 3
Mean values established for specific investment and CO&M.

Type of substructure technology	Specific investment (€/MW)	CO&M (€/MW_Year)
Bottom-fixed	3200	95,000
Floating	4200	125,000

Canaria and Tenerife, calculated on the basis of mean monthly costs and energy demand (Canary Government, 2020) was 125.91€/MWh and 128.99€/MWh, respectively. These costs are higher than the maximum offshore wind generation cost in both islands. In this regard, the specific economic saving that could be obtained with offshore wind energy generation as opposed to conventional generation ranges between 5.91€/MWh and 70.91€/MWh for Gran Canaria, and 8.99€/MWh and 58.99€/MWh for Tenerife.

As a general discussion of the results obtained and on the basis of the partial discussions made in the different subsections above, it should be highlighted that, in the case study, it has been possible to identify priority zones for the exploitation of offshore wind energy. In these zones, areas have been differentiated according to their CF with the aim of optimizing exploitation of the offshore wind resource and obtaining a higher energy production per unit area. This aspect is key in regions of limited territorial availability. In addition, an optimal distribution of wind technology has been made in such a way that the installable offshore wind power is maximized. The criteria that were adopted included the availability of nearby ports to minimize logistics costs in the installation processes, maintenance costs and connection costs to the islands' respective electrical systems. Exploitation of the resource in zones with high CF entails the minimization of offshore wind generation costs. This is a key aspect in isolated or remote regions where the costs of conventional electrical energy generation are much higher than in continental systems.

5. Conclusions

The study conducted in this paper aimed to geographically identify priority zones for the exploitation of offshore wind energy. The study concentrated on two territories (Gran Canaria and Tenerife islands) of singular characteristics due to their geographical location, limited available surface area, variable bathymetry and isolated electrical energy systems. For this, through the application of GIS techniques, capacity factor (in MWh/MW) and levelized cost of energy (LCOE) maps were developed for the identified priority zones.

From the results obtained, offshore areas were identified with capacity factors of between 3500 MWh/MW and 5500 MWh/MW, considerably higher than those of onshore wind farms currently installed on the islands under study. The total electrical energy that can be obtained through exploitation of the offshore wind energy resource is equivalent to 5.4 and 0.9 times the electrical energy demand of Gran Canaria and Tenerife, respectively.

Taking into consideration the current costs of conventional electrical energy generation in the study islands and the offshore wind energy LCOE results obtained, the specific economic saving for Spain's electricity system could be as high as 70.99€/MWh. This saving can vary depending on cost parameters such as type of substructure, distance from the coast, seafloor slope, transmission infrastructure both as collectors and for onshore distribution, etc. A detailed analysis of these economic aspects would be an interesting topic for future research studies.

The method proposed and developed in this paper is vital for detailed energy planning, an important aspect in the optimization process of offshore wind energy integration, particularly in isolated and/or weak electrical systems. The proposed method enables the geographic identification of priority zones for offshore wind energy generation,

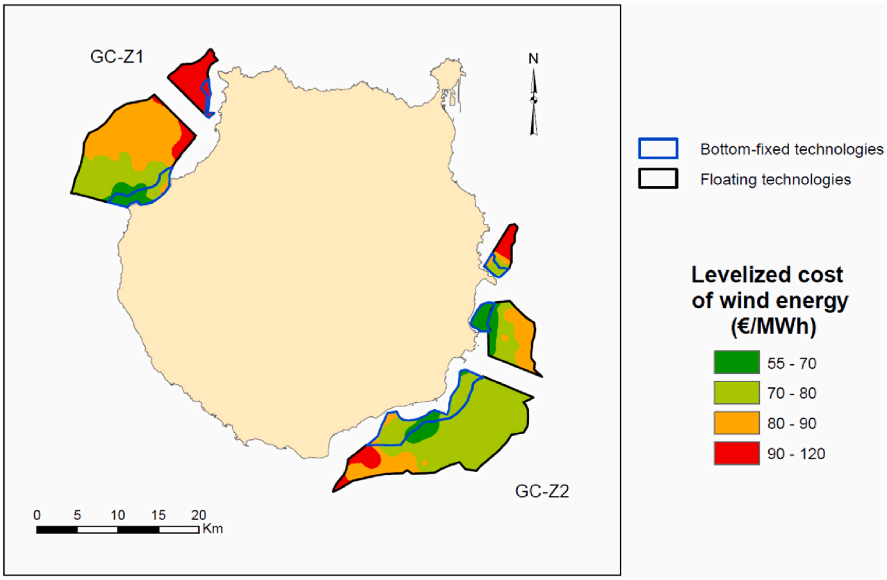


Fig. 9. Levelized cost of offshore wind energy maps by priority zone and substructure technology in Gran Canaria.

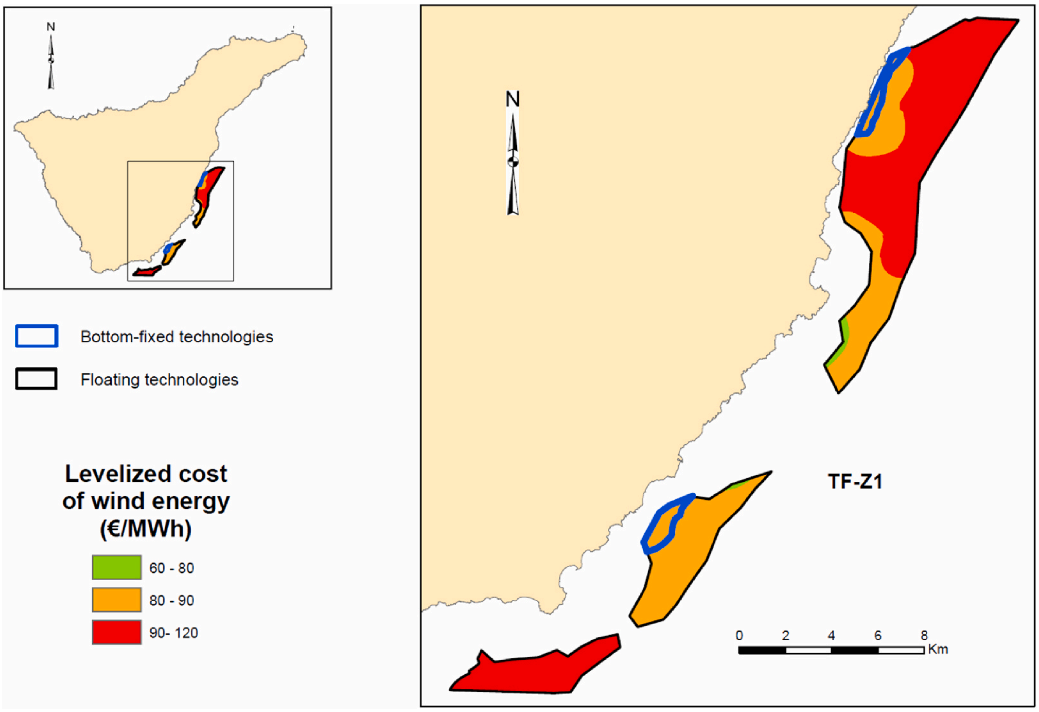


Fig. 10. Levelized cost of offshore wind energy maps by priority zone and substructure technology in Tenerife.

differentiated by the most viable type of wind turbine substructure technology (bottom-fixed or floating), capacity factor and LCOE. In this way, it is possible to maximize the energy generated per surface area unit, as well as the economic savings for the system operator and the potential economic return of the installed offshore wind farm. Maximization of the capacity factor in offshore wind installations minimizes the area required for the attainment of the energy objectives that are established in the planning process for any region. This is especially of fundamental importance in regions with a limited availability of area for offshore wind exploitation.

CRediT authorship contribution statement

Sergio Velázquez-Medina: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – review & editing. **Francisco Santana-Sarmiento:** Conceptualization, Data curation, Investigation, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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