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Evaluation of maritime spatial planning for offshore wind energy in the Canary Islands: A comparative analysis

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ABSTRACT

Following a European Union directive, European countries with territorial waters have developed their maritime spatial planning (MSP). One of the objectives of MSP is to identify areas with high potential for the development of offshore wind energy (OWE). In one of Spain's maritime regions, the official planning of suitable areas for OWE generation differs significantly from the results of previous scientific studies. The region is the Canary Islands, an archipelago of small islands with a high population density and land scarcity. The aim of this study is to identify suitable marine areas for OWE in this region and to compare them with the suitable sites identified in the official MSP and with previous academic studies. This work adopts the framework proposed by the US National Renewable Energy Laboratory for OWE assessment. The results show that less than 1% of the marine area can be used for OWE generation. One conclusion of this study is that the official MSP of the Canary Islands territory includes marine areas that are not suitable for OWE generation. Another conclusion is that deciding on suitable sites for OWE should involve negotiation between stakeholders and allow for some flexibility in marine use.

1. Introduction

1.1. Maritime spatial planning as a framework for offshore energy development

The European Union (EU) has established the so-called Integrated Maritime Policy Blue, one of the objectives of which is to contribute to climate neutrality by 2050 [15]. Offshore Renewable Energy (ORE) can be an important means of achieving this goal. However, the orderly development of ORE is a complex process given the diversity of shared interests and stakeholders involved. The development of ORE depends heavily on three aspects [30]: (i) the establishment of an appropriate regulatory framework and the capacity of states to manage their maritime space; (ii) the overcoming of technical barriers due to technologies that have not yet reached maturity; and (iii) the breaking down of economic barriers that will allow marine renewables to compete in cost with other energy sources.

The EU has promoted, as a part of its marine policy, the application of maritime spatial planning (MSP) principles to the management of human activities performed offshore [14]. The Directive 2014/89/EU on the establishment of a common framework for MSP has been developed for this purpose. This Directive proposes the use of MSP as a tool for the spatial and temporal distribution of activities and uses at sea. It recognizes the ability of MSP to contribute to the accomplishment of renewable energy targets of the EU by creating a stable regulatory framework and reducing administrative costs and responsibilities [29, 30]. The outcome of an MSP process is not only the identification of spatial uses, but also the time distribution of human activities [11]. The goal is to achieve an effective balance to ensure that social and economic objectives are met, whilst at the same time ensuring the long-term sustainable management of the marine resources. The growing concern about the cumulative effects of human activities on marine ecosystems, in particular the progressive use of ORE, has intensified the importance of correctly developing MSP activities [22,62]. The complexity of MSP is evident when the simultaneous confluence of barriers to ORE is

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Nomenclature

EEZ	Exclusive Economic Zone.
EU	European Union.
GIS	Geographic Information Systems.
MSP	Maritime Spatial Planning.
NREL	National Renewable Energy Laboratory (US Department of Energy).
ORE	Offshore Renewable Energy.
OWE	Offshore Wind Energy.
ZEC	Spanish initials for Special Area of Conservation.

considered. These barriers include [4,18,32,59]:

- Environmental impact on marine ecosystems, given the diversity of energy devices and the lack of historical data on the environmental impact of offshore installations.
- Competition for the use of marine waters, which is often complicated by the simultaneous involvement of different actors and economic interests when deciding what use/s to adopt in a certain extension of marine waters (e.g. aquaculture, fishing, navigation, maritime tourism, maritime sports, mineral drilling, etc.). In the case of the marine renewables industry, there is extra pressure resulting from the vast oceanic extensions required by offshore energy devices (e.g. wind turbines can each require as much as 1 km^2) and the need for often lengthy underwater cable connections with the onshore electricity network.
- Land-sea infrastructure planning coordination, which affects mainly the area of energy management. The consumption of energy takes place onshore, where an established network of transformation and distribution stations allows the arrival of energy to final consumers. However, current networks have been designed for land generation facilities, resulting in a lack of power evacuation facilities for marine-based energy.
- Lack of institutional experience and integrated management models of marine spaces. Usually, each sector involved in the human use of marine waters has its own management authority. This dispersion results in, among other problems, a spatial overlapping of human activities, a lack of coordination between institutions, difficulties for nature protection and insecurity for investors. There is a general lack of experience on the part of national institutions with respect to the integrated management of marine resources.

Currently, offshore wind energy (OWE) occupies the leading position among marine renewable technologies for electricity production [30]. The worldwide offshore wind cumulative capacity is expected to increase from the 27 GW registered in 2019 to 120 GW in 2025 [14,25]. As a subset of ORE, the development of OWE is subject to MSP issues. Other issues faced by OWE decision-making are the state of maturity of offshore wind technology and the economic barriers to widespread development of OWE [25]. As far as technological developments are concerned, a number of offshore wind foundations for commercial projects have been developed, with the most popular to date being monopiles, jackets, tripods or gravity-based systems [28]. All are seabed-based structures, thus making them especially suitable for shallow waters. Offshore wind sites situated further from land and in deeper waters constitute a major challenge for this sector. This new scenario will require improved and more advanced structures [7]. Consequently, the current research focus is to provide economically and technical feasible solutions for deep water wind energy devices. The technological developments in this field point towards the massive use of semi-submersible platforms or spar buoys that can support wind turbines with an electricity generation capacity of more than 10 MW [25].

1.2. Problem statement

According to Directive 2014/89/EU on the establishment of a common framework for MSP, all EU countries with territorial marine waters are required to develop their own MSP. The complexity of this task is such that, in the case of Spain, the process of developing its MSP has taken several years. This MSP proposal has been developed by public institutions of the Spanish government and regional authorities. A first version of the MSP proposal for the entire Spanish maritime territory was published in 2021. Economic and social stakeholders made remarks and suggested changes; many of them were included in the final planning. The official Spanish MSP was approved and published in 2023 [35]. In one of the five Spanish maritime regions, the Canary Islands, changes in suitable sites for OWE were particularly significant between the first and the final version of the MSP. The Canary Islands are a Spanish archipelago consisting of seven islands with a high population density and several small isolated electricity systems. In this region, the suitable areas for OWE development were reduced from around 673 km^2 in the first version of the MSP to 562 km^2 in the final version. The final size of the areas allocated for OWE development may be reduced further. This is because each wind farm project will have to be assessed according to its impact on the landscape and other uses of the area not included in the MSP. The difference in available areas for OWE between the two documents reflects the multiple limitations on marine use of this territory, a complexity that exists in similar areas around the world.

The Canary Islands have been the subject of several studies to analyze their potential for the installation of offshore wind farms [2,8,9,33], as well as on the socio-economic impact of such wind farms [34]. However, the results of the studies on the marine areas that could be used for offshore wind farms vary considerably. The results of these studies also differ from the suitable sites for OWE in the official MSP approved by the Spanish government. The MSP for the Canary Islands establishes the uses of the marine area for 10 years, the maximum period in which the obligation to carry out a review of the MSP is established by law [35]. This official planning reflects the fact that part of the marine area that can be used for OWE generation is located in areas protected by the EU's Natura 2000 network. In addition, part of the designated area is located less than 3 km from the coast, which is likely to cause some public opposition due to the proximity of the facilities to the coast.

The following is a summary of some of the results obtained in previous studies in this territory. The study by Schallenberg-Rodríguez and García Montesdeoca [33] identified a marine area suitable for OWE with values seven times higher than those set in the official MSP. Their study considered a maximum depth of 500 m, which is lower than the depth adopted for the identification of suitable OWE sites in the official MSP, and it established a minimum distance of 1 km from the coast for offshore wind farms. However, this distance is incompatible with other uses such as fishing or recreational tourism, in addition to the foreseeable social response against the proximity of wind farms to coastal residential and tourist areas. The study by Díaz and Soares [9] provides results for marine areas suitable for OWE development that accounts for 25.6% of the OWE area established in the official MSP. It is a study that considers a wide range of constraints, but taking these constraints into account should result in a larger area than the one finally obtained. However, it is not possible to identify the reasons for the discrepancy as only one figure of sea areas affected by restrictions is shown in their paper. With this information it is not possible to trace the excluded marine areas. Finally, the study by Abramic et al. [2] uses a three-pronged approach to identify suitable offshore areas for OWE, based on a 10-point suitability scale. The study leaves it open to planning developers to choose a minimum suitability value and then derives the area suitable for offshore wind farms from this value. The existence of up to thirty different values of suitable offshore area resulting from this study makes decision making in this area difficult.

The existence of divergent results in the research studies among themselves, and between the research studies and the suitable sites for OWE set in the official MSP, points to the need to analyze the reasons for the differences. The interest of this analysis lies in the fact that MSP is a key instrument of marine policy and therefore its guidelines imply long-term economic and social consequences. The aim of this study was to identify suitable marine areas for OWE in the Canary Islands and to compare them with the areas allocated for OWE in the official MSP and with OWE areas identified in previous academic studies. For this purpose, a contrasted methodological framework was adopted. Using the indicators proposed in the framework, the main causes of discrepancies with other scientific studies and with the official MSP were identified. Implications for the energy policy of the analyzed territory were derived from the results. Due to the adoption and further adaptation of a contrasted methodological framework, the conclusions of this work may be useful for other island and coastal territories with similar characteristics.

2. Methodology and data

This study adopted the framework of the US National Renewable Energy Laboratory (NREL) for offshore wind energy resource assessment, developed by Musial et al. [26]. The choice of this framework was based on the wide international prestige of the US National Renewable Energy Laboratory in the field of energy. The document is available at www.nrel.gov/publications and it has been widely referenced in articles related to offshore wind energy assessment. Another reason for choosing this framework was its organized way of arriving at the identification of suitable sites for OWE through a structure consisting of two blocks with nine steps that can serve as result indicators. The steps of the framework are shown in Fig. 1. The reference values proposed by the NREL framework focus on extensions that cover the entire Exclusive Economic Zone (EEZ) (200 nm) when it does not exceed a certain depth (1000 m), and consider installed power densities per square kilometer (3 MW/km^2) and minimum wind speeds (7 m/s) calculated for large marine areas adjacent to continental electrical systems. This study analyzed and justified the adoption of reference values different from those considered in the NREL framework in the case of small islands with multiple limitations on marine use.

The information related to physical constraints was obtained from reliable cartographic databases developed by Spanish and European public entities and institutions. Annex A shows the list of entities with databases used in this study. A decisive factor in marine planning is the laws and international agreements that establish limitations on territorial use. Legislation affecting the use of marine waters is highly varied. It can establish the location of maritime routes, port and airport facilities, exclusion zones for military activities and environmental protection areas, among others. A specific law [48] is currently in force that regulates offshore electricity generation and establishes the administrative procedure for authorization of electricity generation facilities in the Spanish territorial sea. This law sets out the limitations and criteria for the concession of marine territory for the installation and operation of offshore electrical installations, and the division of the maritime-terrestrial public domain into offshore wind power areas. The offshore wind power area is defined as the surface extension comprised between two parallels and two meridians, whose separation is one degree, which must coincide with whole degrees and minutes. As part of the approach adopted, all the maps generated include the representation of marine areas in the form of grids using this measurement unit. The laws that establish conditions for the use of maritime waters are shown in Table 1.

The proposed approach is based on the use of a GIS-based model, which has been described as an efficient tool for the selection of offshore

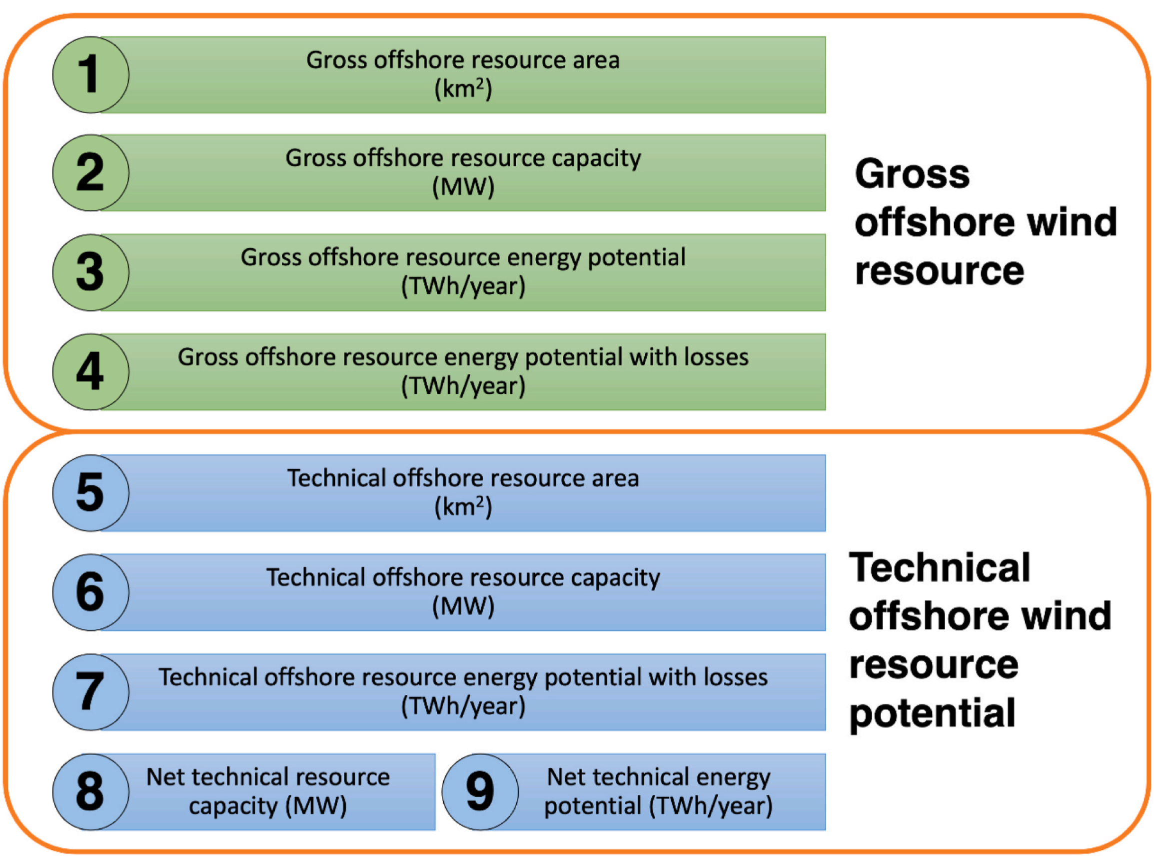

Fig. 1. Schematic representation of the adopted offshore wind energy resource assessment framework, showing its division into two blocks and nine steps. (adapted from [26]).

Table 1
Types of restrictions on the technical offshore resource area and the laws defining its scope.

Type of restriction	Law/decree
Military areas	[56]
Fish farms	[37,44,50–52,54,55]
Marine protected areas	[13]
Airports	[36,38,41,42,45,46,49,57]
Ports	[42]
Maritime routes	[48]

wind farm sites [8]. The reliability of the results depends on the accuracy of the data used and hence the quality of the sources. The reference coordinate frame adopted is EPSG:4083, compatible with the WGS84. The basic information (graphic and alphanumeric layers) used in this study was generated by public institutions and is available in the public domain. Based on the basic information layers, further layers were developed for their application in different steps of the framework adopted. To enable their visualization with any GIS software, the layers were developed in an internationally compatible format (SHP). Three different software applications were used to handle the graphic and alphanumeric data, two GIS packages, QGIS 3.12 and ArcGIS 10.8, and a PostGIS 2.0 spatial database. QGIS was used to import spatial data in open format, such as KML. Most of the intermediate processing and analysis was performed with ArcGIS, and the final analysis of all layers was completed with PostGIS. All the layers were processed in vector format, adopting as reference the official cartography of the Canary Islands, independently of the format and reference system of the other original additional layers.

In accordance with the framework proposed by Musial et al. [26] in their wind energy resource assessment for the United States, two blocks are considered. Each block includes a set of steps that can be adopted as intermediate indicators. The first block includes the steps that need to be taken to obtain a value for the gross offshore wind resource. Factors such as available wind power generation technology, conflicts in the use of offshore waters, environmental restrictions or physical environment parameters do not intervene in this calculation, but it does take into consideration the experience and future trends of the offshore wind industry in order to establish a parameter related to the array power density. This parameter constitutes a reference of the maximum energy production that can be obtained per unit of sea surface, although it can be modified as technology evolves.

The second block consists of five steps to calculate the technical offshore wind resource potential. The technical offshore wind resource potential is a subset of the gross offshore wind resource that identifies what energy can actually be recovered based on the available technology and reasonable limits that are set based on various factors. The energy recovered will be a dynamic variable as technology evolves and the limits imposed on offshore wind exploitation areas change over time. The development of the different steps of the framework makes it possible to obtain indicators that can be used both to compare results in different marine areas and to compare different studies on a given marine area.

2.1. Gross offshore resource area

The determination of the gross offshore resource area is the starting point on which the subsequent steps of the framework depend. Its determination can be complicated by geopolitical factors that add uncertainty to the calculation. The delimitation of marine waters for exploitation by coastal states is based on the United Nations Convention on the Law of the Sea [61]. This agreement establishes five categories of marine areas for which different sovereignty conditions are set. However, despite the existence of international legislation, the immense casuistry of possible situations has given rise to disputes between countries in their claim to territorial waters. In the case of archipelagos, the Convention on the Law of the Sea establishes a distinction between archipelago-states and non-state archipelagos. This distinction implies restrictions on the delimitation of archipelagic territorial waters in those cases where they are located in areas bordering or within 200 nautical miles (nm) of waters belonging to the EEZ of other coastal states. In the case of the Canary Islands, which is a non-state archipelago, according to international law the 200 nm of EEZ cannot be extended beyond the perimeter of the islands of the archipelago. International law recognizes only 12 nm of territorial waters, with the possibility of extending another 12 nm of the contiguous zone where the sovereign state (Spain) has surveillance powers, up to 24 nm from the coast in total. Consequently, for this research, the framework adopts the 24 nm from the coastlines of the islands of the archipelago as the study area.

2.2. Gross offshore resource capacity

Following the framework developed by Musial et al. [26], the gross offshore resource capacity is the result of multiplying the gross offshore resource area by the nominal array power density. The framework establishes a power density of 3 MW/km^2 [26]. Their authors argue that this value is lower than most current offshore wind farms, as the larger rotors (and hence lower specific power) of today's turbines compared to those used in the past mean that wider spacing between devices is required [26]. According to Musial et al. [26], a 3 MW/km^2 power density ensures reasonable wake replenishment for turbines in large arrays. Nonetheless, based on actual data from licensed and/or operating offshore wind farms, it was found that the trend is to set nominal array power densities higher than the value proposed by Musial et al. [26]. Using the database of the offshore energy consultancy firm 4 C Offshore [1], an analysis was undertaken of all world offshore wind installations with a power equal to or greater than 200 MW and that were licensed or started operations during the period 2017–2020 (see Annex B), and it was found that the average power density in the use of marine territory is close to 6.5 MW/km^2 (with a standard deviation of 3.1 MW/km^2). Consequently, 6.5 MW/km^2 was adopted in this study as an alternative, more realistic, value of the average power density. This value is close to that proposed by Enevoldsen and Jacobson [12], based on actual European offshore wind farm data and estimated at ~7.2 MW/km^2.

2.3. Gross offshore resource energy potential

Step 3 of the adopted framework consists of obtaining the gross offshore wind resource energy potential. The unit of measurement for this indicator is TWh/year. For this purpose, the values obtained in step 2 of the framework were multiplied by the potential hours of operation (8760 h/year) and by a capacity factor. The capacity factor is defined as the actual output divided by the nameplate capacity of a wind farm (Aldersey-Williams et al., 2020). It is influenced by the wind speed conditions, the turbine power curve, wind farm effects, the availability of the turbines and other losses. This study adopted the value proposed by the National Renewable Energy Laboratory [27] as the reference value for the capacity factor (average capacity factor of 50.02% with 15 MW turbines at 150 m hub height, in 2030, in a moderate wind speed scenario).

2.4. Gross offshore resource energy potential with losses

Step 4 of the framework aims to make a realistic approximation of the available gross offshore wind energy. Negative operational effects, which are incorporated into the operation of real-world energy facilities, reduce the amount of available energy. This is a general approximation, not specific to a particular geographical location on the sea surface. The values proposed in the framework [26] were based on previous studies which establish likely minimum and maximum values for losses of 10.6% and 21.3% respectively, corresponding to marine geographic locations at the most and least advantageous extremes for energy recovery. The losses contemplated were as follows: (a) wake losses arising from effects on wind flow due to interactions between turbines (4%–12%) [26]; (b) Joule losses in the electrical wires discharging energy into the onshore grid (1%–5%) [3]; (c) downtime losses that may be due to adverse weather conditions, technical service problems or the unavailability of land-based infrastructure (4%) [24]; (d) other losses that may be due to unforeseeable factors, such as facility accidents and underperformance, among others (2%) [3].

2.5. Technical offshore resource area

In the proposed framework, the term technical is used to refer to the subset of the gross offshore wind resource from which energy can be recovered by available technology. The two technological exclusions proposed in the framework consist of the maximum depth at which the current floating wind turbine technology can operate, and the minimum annual average wind speed required to ensure the economic feasibility of offshore wind farms [26]. In relation to the first technological constraint, depth, the framework exclude from the technical potential assessment depths greater than 1000 m. In line with the state of the art in offshore floating wind technology, this depth exceeds by far the maximum depths of floating wind energy platforms currently in operation and development. In the case of this study, this value was maintained as the maximum operating depth.

In relation to the average annual wind speed, the framework proposes that its lower limit be set at 7 m/s on the basis that there is little likelihood of an economic return below this value [26]. However, their authors leave open the possibility that lower average speeds may be adopted as a technological limit when high energy prices make it possible to offset the costs at less energetic sites, with island communities cited as an example of this situation [26]. This is precisely the case of the Canary Islands, where the average annual cost of electricity was three times higher than the national average in 2019[1] (152.45 €/MWh [21] vs. 53.4 €/MWh [31]). This high cost of electricity in the Canary Islands justifies the possibility of taking advantage of less energetic sites in the marine area. Other similar studies for archipelagos have set a minimum annual wind speed of 4 m/s [9]. In this study, a minimum of 5 m/s at a height of 150 m was adopted as the acceptable average annual wind speed. The average annual wind speed data was extracted from the Global Wind Atlas database [10] with a resolution of 9''.

Although the reference framework of this study only considers depth and wind speed as technological constraints, there are other geological variables that may also hinder the use of offshore wind technology. More specifically, these are the materials the seabed is made of and its slope [64,65]. In this study, both variables were included as part of the geological factor limiting the capacity of current offshore technology. Rocky bottoms or those formed by gravel sediments are unsuitable for anchoring floating wind platforms, either because of the high costs incurred or because of the unreliability of the anchoring [64]. Seabed areas consisting of rocky soils or gravel sediments were excluded. Slopes greater than 8 degrees (15%) can pose a risk in anchoring operations [65]. For the purpose of this study, zones in the technical offshore resource area with slopes greater than 15% were discarded.

2.6. Technical offshore resource capacity

The technical offshore resource capacity was obtained as the result of multiplying the technical offshore resource area by the nominal array power density. Two values were adopted for the nominal array power density (3 and 6.5 MW/km^2).

[1] The 2019 values are adopted as a baseline because electricity demand during 2020, 2021 and 2022 were significantly distorted by the effects of the Covid-19 pandemic.

2.7. Technical offshore resource energy potential with losses

In order to obtain the technical offshore resource energy potential, the values obtained in step 6 of the framework were multiplied by the potential hours of operation (8760 h/year) and by the average capacity factor adopted in this study (50.02%). The unit of measurement for this indicator is TWh/year.

2.8. Net technical resource capacity

In this section of the framework, the technical offshore resource energy potential is further reduced in terms of the capacity of the total resource. This reduction is due to limitations of suitable space for the location of wind farms as a consequence of environmental restrictions, restrictions on the shared use of marine space and other factors. The framework establishes examples of applicable restrictions, such as the existence of national marine sanctuaries, marine protection areas, shipping and towing lanes, etc. [26]. However, each territory will have its own specific restrictions, and it is at this stage of the framework that the particular exclusions considered necessary were applied.

In the case of the territory under study, the installation of marine power generation facilities is subject to the provisions of Spanish law. In 2007, a law [48] was published establishing the administrative procedures for processing applications for this type of facility. One of the sections specifies that wind farms may only be installed in suitable areas as set out in the Strategic Study of the Spanish Coastline [47]. In that document, in order to protect the landscape and ensure offshore wind farms are not visible from the coast, it is recommended that wind farms should not be located within a band of 8 km parallel to the coast. Although not mandatory, this constraint has been taken into account in this study. There are numerous economic and social activities that take place in the coastal strips near the coast, including recreational tourism, whale watching, aquatic tourism, aquaculture and fisheries, etc. Such activities share marine surface that may be in conflict with the location of offshore wind farms. Most of these types of activities are carried out within the marine strip located 8 km from the coast. Conflicts of use and visibility of offshore wind facilities have been studied in the literature. However, there is no general agreement on a recommended minimum distance between offshore wind farms and the coast. Authors such as Gkeka-Serpetsidaki and Tsoutsos [17], in a study on the optimal siting of offshore wind farms on the coast of Crete, underline from a qualitative logic that the siting of offshore wind farms should reduce the likelihood of complaints about visible wind farms from observers. Other authors, in their studies, advocate the indication of recommended distances between offshore wind farms and the coast. This is the case of Spyridonidou and Vagiona [58], who in their study of the Brazilian coast recommend that sites less than 8 km away from the coast should be prohibited due to visual impact. Cranmer et al. [6] advocate longer distances, arguing that emphasis should be placed on minimizing visual impacts by siting projects at least 10 nm (∼18.5 km) from shore, as is the case for all currently proposed projects along the US East Coast.

With regard to conflicts of use between OWE and fishing areas, Genç et al. [16] recommend a minimum distance of 3 km between OWE sites and commercial fishing areas for Turkish waters. The studies by Tercan et al. [60] in the Aegean Sea and Vinhoza and Schaeffer [63] in Brazilian waters do not establish separation buffers between OWE and commercial fishing activities, but completely restrict OWE use in fishing areas. Likewise, in relation to conflicts of use between OWE and protected wildlife areas, Spyridonidou and Vagiona [58], in a study on the Greek coast and based on previous work, recommend that the distance between OWE and protected wildlife areas should be greater than 2 km. In the studies by Gkeka-Serpetsidaki and Tsoutsos [17] in Crete waters and Vinhoza and Schaeffer [63] in Brazilian waters, OWE activities are completely restricted in protected wildlife areas, although no separation buffers are established.

Table 1 shows different types of restrictions on the technical offshore resource area and the laws defining its scope. There are naval and air military units stationed in the Canary Islands that carry out training activities in strips of marine territory. In the Canary Islands, fishing has been a traditional economic activity for many years and is conducted over large extensions of the marine space. Some of these areas have been declared fishing reserves. The EU's Natura 2000 network [13] covers more than 35% of the archipelago's territorial waters with the aim of protecting different marine species. The Canary Islands, as both an important tourist destination and an international cargo shipping route, are home to some of the airports and ports with the highest volume of traffic in Spain. Most of the airports are located on coastal strips of land. In order to guarantee the safety of air and sea traffic, zones have been established in which no activity that could affect air or sea navigation is allowed. The international maritime route that connects Europe and North Africa with the western and southern coast of the African continent passes through the waters of the Canary Islands. Two international corridors of circulation in a north-south direction are recognized in its jurisdictional waters [48].

The reduction in the area available for OWE due to existing constraints results in the net technical resource area. Following the adopted framework [26], the net technical resource capacity is the result of multiplying the net technical resource area by the nominal array power density (3 and 6.5 MW/km^2).

2.9. Net technical energy potential

In order to obtain the net technical energy potential, the values of net technical resource capacity were multiplied by the potential hours of operation (8760 h/year) and by the average capacity factor adopted in this study (50.02%). The unit of measurement for this indicator is TWh/year.

3. Results

3.1. Gross offshore wind resource

Table 2 shows the gross calculations considering the NREL criteria [26] and data from the 4 C offshore database. Higher values are observed with the latter as the power density considered is higher in 4 C Offshore than NREL. An estimate of gross offshore resource energy is not calculated in this section because the gross offshore resource area includes sea areas whose low average wind speed values make them unsuitable for offshore wind farm deployment.

3.2. Technical offshore wind resource

The geological characteristics of the Canary Islands are due to eruptions of volcanoes located on the seabed that have shaped its geography for millions of years [23]. As a result, there is hardly any marine platform, with significant depths reached relatively close to the coast. Fig. 2 shows the limits established by the 1000 m depth restriction in relation to the 24 nm considered as jurisdictional waters of the archipelago. As can be seen, this technological restriction is more limiting than the one due to the extension of the jurisdictional waters (black line in Fig. 2). The resulting technical offshore resource area, after applying the technological restriction of depth limit of 1000 m, is 12,356 km^2. This corresponds to a reduction of 83.5% with respect to the 74,855 km^2 of the gross offshore resource area.

Table 2
Gross calculations considering the NREL criteria [26] and 4 C Offshore data.

	NREL (average power density: 3 MW/km^2)	4 C Offshore database (average power density: 6.5 MW/km^2)
Gross offshore resource area (km^2)	74,855	74,855
Gross offshore resource capacity (MW)	224,565	486,558

Fig. 3 shows the remaining available area once another geological exclusion is incorporated in addition to previous constraints. The area available when excluding the seabed areas consisting of rocky soils or gravel sediments from the technical offshore resource area is 10,733 km^2. This exclusion means a reduction of 13.1% with respect to the previously established technical offshore resource area of 12,356 km^2.

The seabed in the technical offshore resource area includes 6920 km^2 in areas with a slope of less than 15% and 3813 km^2 in areas with a slope of more than 15%. Those zones of the technical offshore resource area with slopes greater than 15% were discarded, entailing a reduction of 35.5% with respect to the available area (10,733 km^2) after applying previous exclusion criteria. Fig. 4 shows the remaining available area when the average seabed slope exclusion of more than 15% is added to the previous constraints.

In this study, a minimum of 5 m/s was adopted as the minimum acceptable average annual wind speed. Fig. 5 shows the zones available when excluding areas with less than 5 m/s minimum average annual wind speed from the technical offshore resource area in addition to previous exclusions. The resulting technical offshore resource area is reduced by 7.5% from 6920 km^2 to 6400 km^2.

Table 3 shows the technical offshore resource calculations considering the NREL criteria and data from the 4 C Offshore database. As in the gross calculations (Table 2), higher values can be seen when using the latter as the power density value considered is higher for 4 C Offshore than NREL. The results in Table 3 show a reduction, in terms of resource area, of 91.45% compared to those obtained in Table 2. For the calculation of the technical offshore resource energy potential, the technical offshore resource capacity is multiplied by the potential operating hours (8760 h/year) and by the average capacity factor adopted in this study (50.02%).

3.3. Net technical offshore wind resource

The following subsections address other types of limitation to the location of offshore wind farms which can result in further reductions of the technical offshore resource area, and hence the net technical resource capacity and the net technical energy potential.

3.3.1. Legal issues

The available area after excluding the 8 km band of marine space parallel to the coast from the technical offshore resource area is 2091 km^2. This exclusion entails a reduction of 67.3% with respect to the 6400 km^2 technical offshore resource area. Fig. 6 shows the limits established by the exclusion of the marine band of 8 km parallel to the coast in relation to the 24 nm considered as jurisdictional waters of the archipelago.

3.3.2. Military exclusions

Although the exclusions due to military use of marine space include mostly the area whose depth is greater than 1000 m, there is a small fraction of waters affected by this kind of constraint (9 km^2). For this reason, the exclusion of military zones results only in a small further reduction of 0.4%, thus giving a remaining net technical offshore resource area of 2082 km^2.

3.3.3. Fisheries

According to government regulations, fishing occupies up to 156 km^2 of the remaining net technical offshore resource area. When fisheries exclusion is applied the area is reduced by 7.5% from 2082 km^2 to 1926 km^2. Fig. 7 shows the remaining available area after the exclusion of fisheries in addition to the previous constraints.

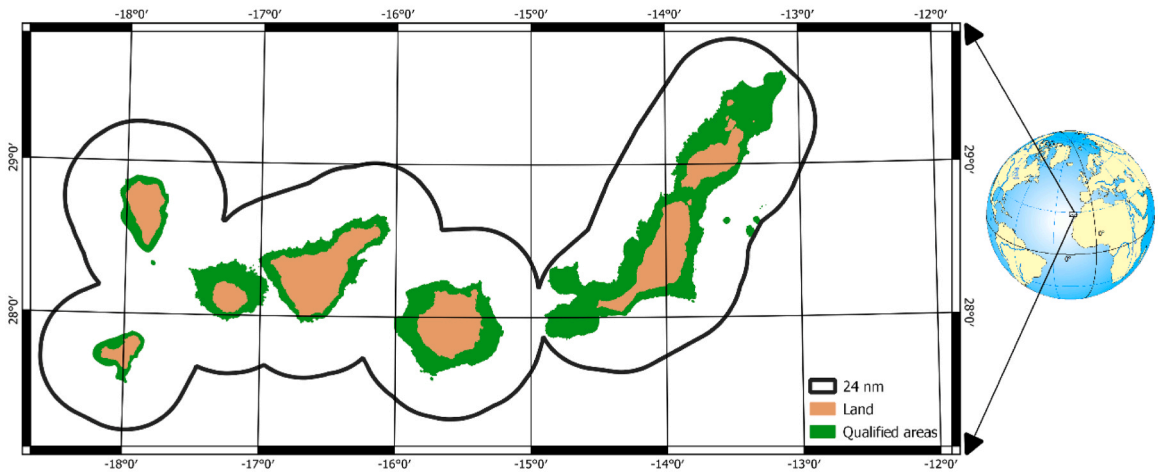

Fig. 2. Limits established by the 1000 m depth restriction (qualified areas) within the 24 nm jurisdictional waters (black line) of the Canary Islands.

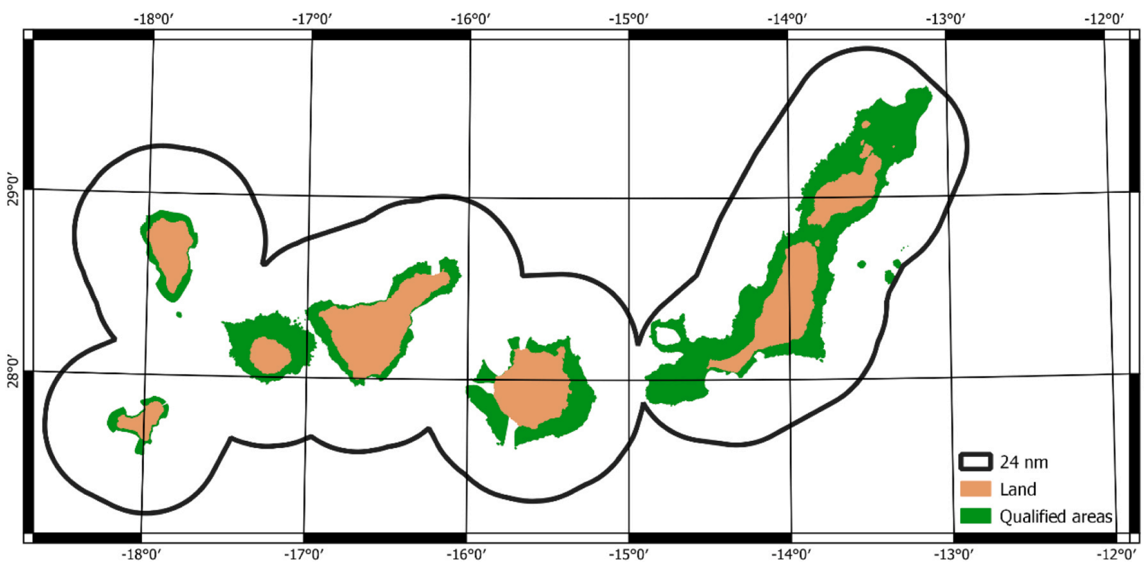

Fig. 3. Technical offshore resource area (qualified areas) after the exclusion of areas with rocky soils or gravel sediments on the seabed is added to previous technical exclusions.

3.3.4. Environmental protection areas: special protection areas for birds

When special protection areas for birds are incorporated in the calculation, the available area is reduced by 21.4% from 1926 km^2 to 1514 km^2. Fig. 8 shows the remaining available area after applying the exclusion of special protection areas for birds in addition to the previous constraints.

3.3.5. Airport and port exclusions

Safety restrictions affect the remaining net technical offshore resource area in the case of airports but not in the case of ports. The total amount excluded is 13 km^2, which corresponds to a 0.9% reduction from 1514 km^2 to 1501 km^2.

3.3.6. Maritime route exclusions

Exclusion of maritime routes entails a reduction of 9% from the remaining net technical offshore resource area of 1501 km^2 to 1366 km^2. Fig. 9 shows the available area after incorporating airport and maritime route exclusions in addition to previous constraints.

3.3.7. Environmental protection areas: special areas of conservation

The exclusion of special areas of conservation results in a technical resource area reduction of 64.9% from 1366 km^2 to 479 km^2. Fig. 10 shows the remaining available area after applying environmental exclusion constraints in addition to previous limitations.

Table 4 shows the percentage reduction in the marine area that each exclusion represents with respect to the initially available marine area (74,855 km^2). As can be seen, exclusion due to the constraint of a maximum depth of 1000 m was the highest (83.5%), followed by the geological nature of the seabed (22.9%) and maximum acceptable seabed slope (21.7%). Consequently, it is the technological factors that are associated with greater exclusion areas with respect to the initially available offshore resource area. If the available technology develops sufficiently to overcome these types of physical obstacle, the usable sea area could rise considerably. Each restriction is considered separately for the evaluation of the percentage of the total area, although between them there are overlapping areas.

Applying the restrictions sequentially, as shown in Table 5, it is possible to observe the evolution of the decrease in the area available for the location of OWE farms. The relevant value is the final one of 479 km^2, after applying all the constraints. As there are territorial overlaps between the different restrictions, the intermediate values obtained depend on the sequence of restrictions applied, and do not

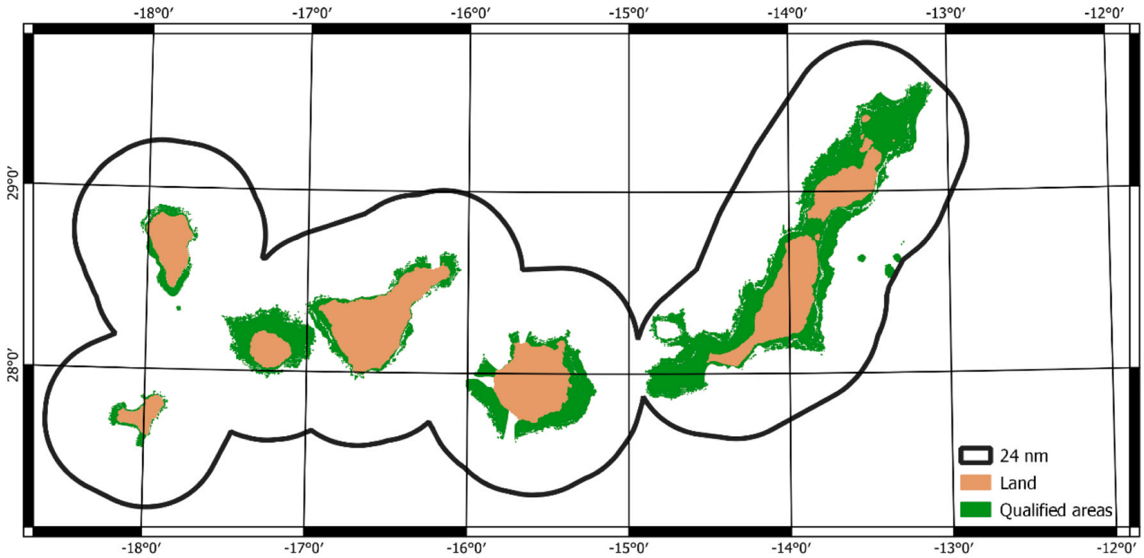

Fig. 4. Technical offshore resource area (qualified areas) after the exclusion of areas with average seabed slopes greater than 15% in addition to previous technical exclusions.

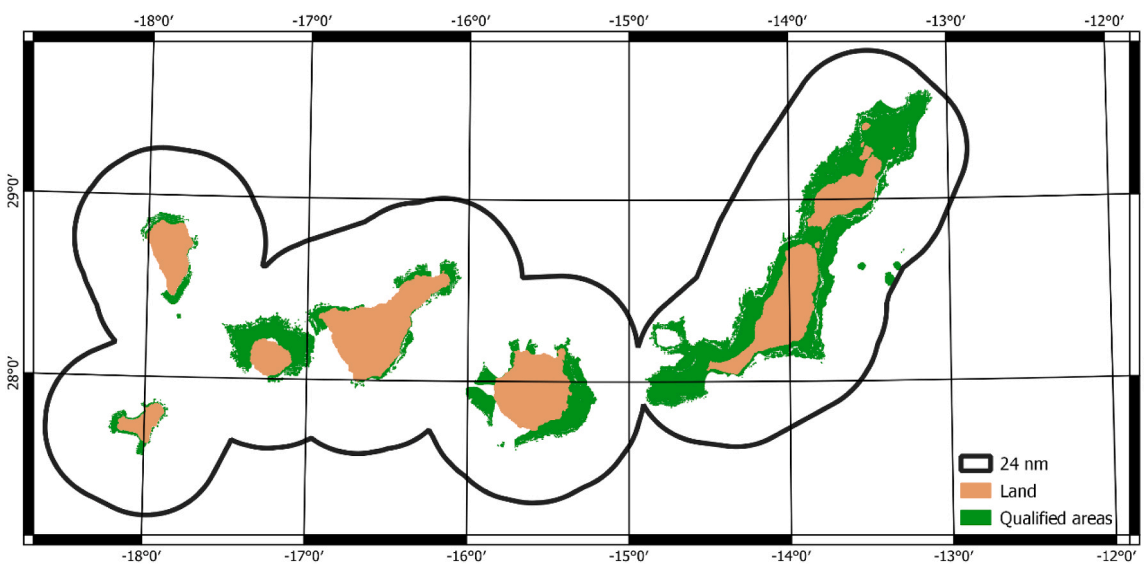

Fig. 5. Technical offshore resource area (qualified areas) after the exclusion of areas with average annual wind speed below 5 m/s in addition to previous technical exclusions.

Table 3
Technical calculations considering NREL criteria [26] and the 4 C Offshore data.

	NREL (average power density: 3 MW/km^2)	4 C Offshore database (average power density: 6.5 MW/km^2)
Technical offshore resource area (km^2)	6400	6400
Technical offshore resource capacity (MW)	19,200	41,600
Technical offshore resource energy potential (TWh/year)	84.1	182.3

provide relevant information.

Annex C provides in greater detail the percentage of overlapping technical resource area and net technical resource area by type of exclusion. Table 6 shows the net technical calculations considering the NREL criteria [26] and data from 4 C offshore database. The results show an important decrease in comparison with the results shown in Table 2, with a reduction in terms of resource area of 99.4%. To calculate the net technical offshore resource energy potential, the net technical offshore resource capacity is multiplied by the potential operating hours (8760 h/year) and by the average capacity factor adopted in this study (50.02%).

Fig. 11 shows the annual wind speed distribution in the available marine area after application of all the exclusion constraints. The wind speed data were taken from the Global Wind Atlas database [10] at a height of 150 m and a resolution of 9''. Taking into account the average wind speed profiles and the available area, the most suitable area for the installation of offshore wind farms is between longitudes − 16° and − 15° and close to latitude 28° and below. Large areas with lower average wind speeds are situated close to longitudes − 14° and − 13° and above latitude 28°. It should be noted that there are other key factors that may limit the installation of offshore wind farms, such as the onshore electrical infrastructure and intermittence of the wind in terms

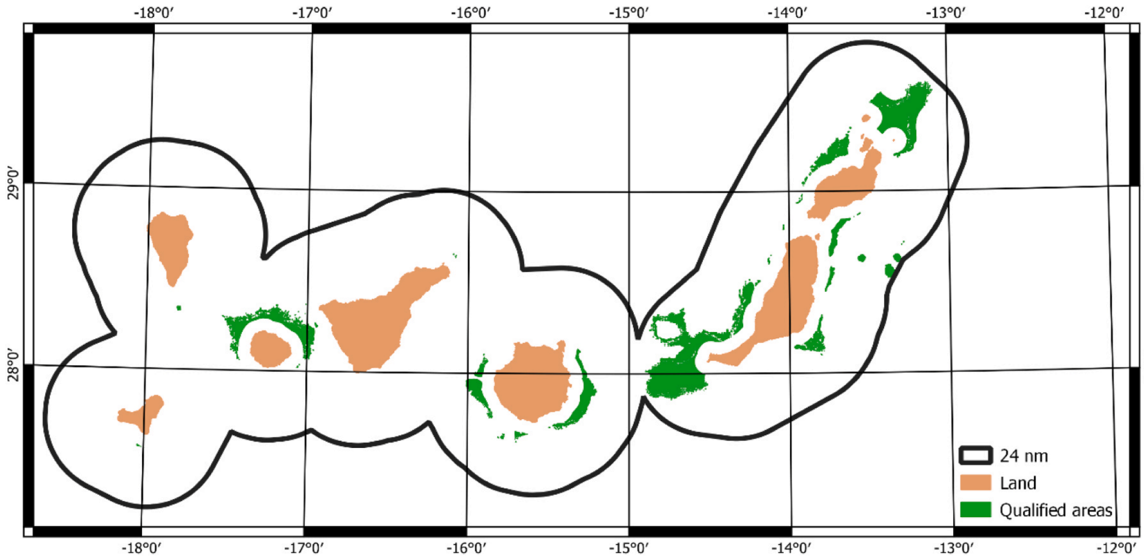

Fig. 6. Net technical offshore resource area (qualified areas) after exclusion of the marine strip of 8 km parallel to the coast from the technical offshore resource area.

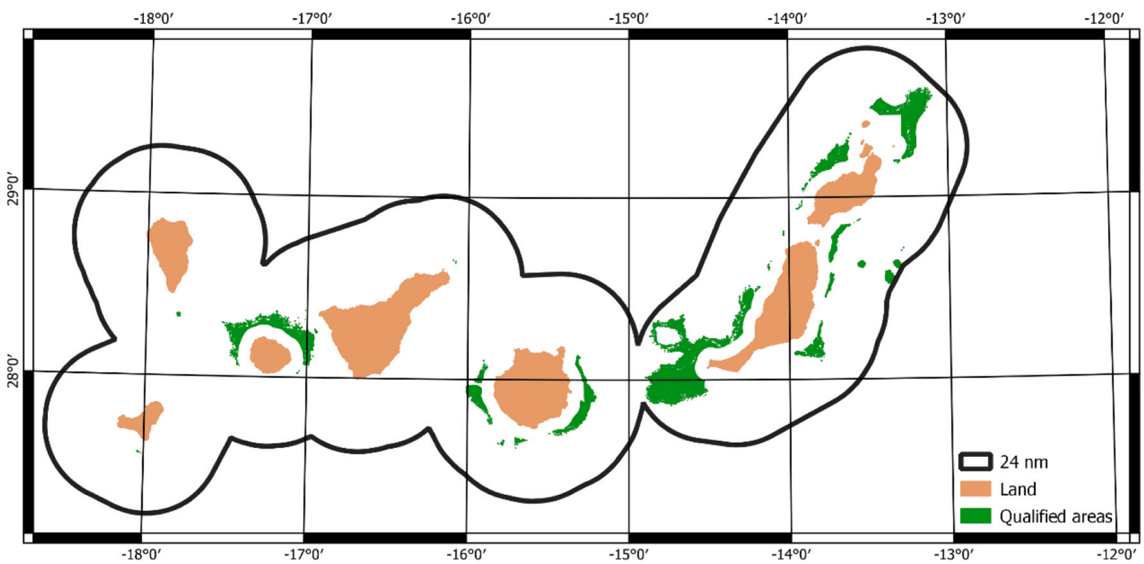

Fig. 7. Net technical offshore resource area (qualified areas) after the exclusion of fisheries in addition to the previous constraints.

of speed and direction, which can affect the performance of offshore wind farms.

Table 7 shows the relationship between average annual wind speed and depth in the net technical offshore area in order to show how the suitable surface area is distributed adopting these two important technological restrictions. Areas of less depth and higher wind speeds would be the ideal candidates for the installation of the offshore wind farms in the territory under consideration. As can be seen, the restriction-free area with depths less than 50 m, considered as shallow waters, barely extends to 1 km^2, which is just 0.2% of the net technical offshore resource area. In contrast, the largest restriction-free area is found in the depth range of 900–1000 m, with its 96 km^2 corresponding to 20.1% of the net technical offshore resource area.

4. Discussion

Several academic studies have recently been published on the potential for OWE generation in the Canary Islands [2,8,9,33]. These studies were based on different methodologies, although they coincide in the use of geographic information systems as a tool for the analysis of the marine territory. Table 8 shows the main results obtained in these studies. The table does not show the results of the study by Abramic et al. [2] since the values obtained in the offshore wind resource area correspond to three suitability scales obtained after using analytical hierarchy process techniques on different groups of stakeholders, with each scale fluctuating between a suitability level of 0–10. Therefore, no specific values of resource area are given. The studies by Schallenberg-Rodríguez and García Montesdeoca [33] and Díaz and Guedes Soares [8] yield unique values for offshore wind resource area and for offshore wind resource capacity and energy potential. The results of this study provide unique values for offshore wind resource area; and values for offshore wind resource capacity potential (MW) and offshore wind resource energy potential (TWh/year) within a range of values. This range of values in this study is due to the adoption of two different average power densities. The offshore wind capacity and energy potential obtained in the study by Schallenberg-Rodríguez and García Montesdeoca [33] are based on the installation of 5 MW turbines, wind speeds measured at 80 m hub height and an average power density of 14.5 MW/km^2. The

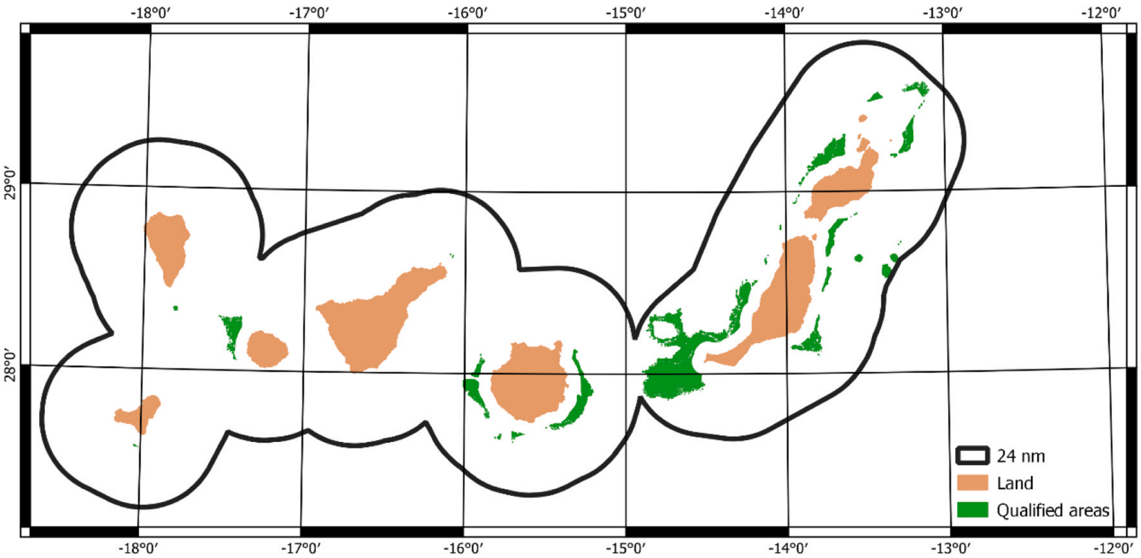

Fig. 8. Net technical offshore resource area (qualified areas) after the exclusion of special protection areas for birds in addition to previous constraints.

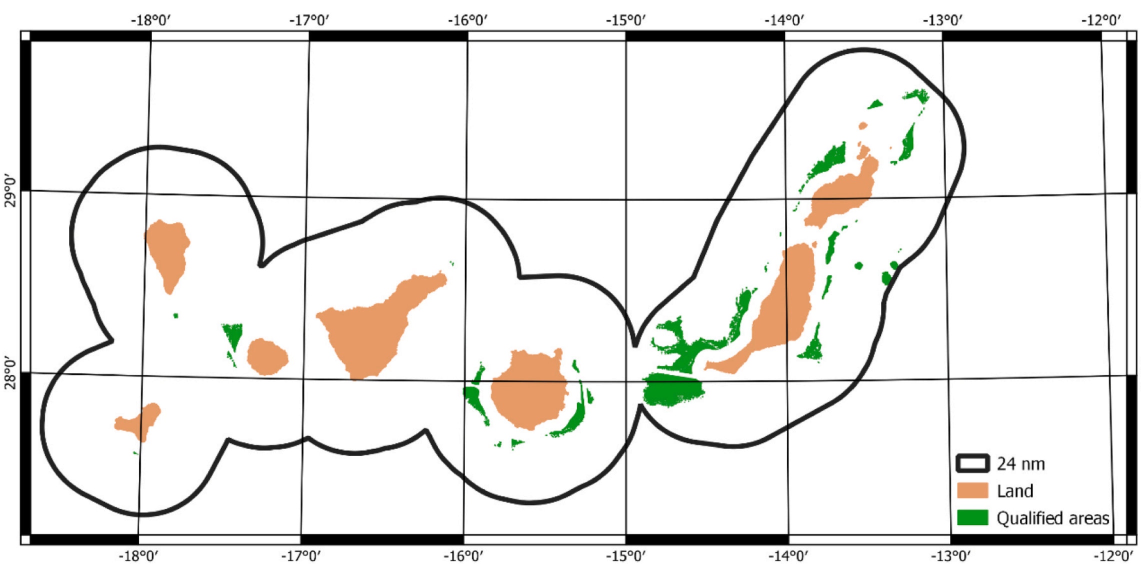

Fig. 9. Net technical offshore resource area (qualified areas) after the exclusion of airport and maritime routes in addition to previous constraints.

offshore wind capacity and energy potential obtained in the studies by Díaz and Guedes Soares [8] are based on the installation of 10 MW turbines, wind speeds measured at 120 m hub height and an average power density of 4.5 MW/km^2.

In 2023 the official MSP for the Canary Islands was published [35]. This proposal was drawn up by public institutions of the government of Spain and regional authorities. The published document includes a section which describes the interactions between offshore wind energy generation and other uses and activities in marine areas. The document identifies suitable sites for the development of OWE facilities. However, it is clearly specified in the document that there exists a need in all cases to evaluate the environmental impact prior to turbine installation. No estimation is given with respect to the amount of potentially exploitable energy in these areas. Table 8 also includes the offshore wind resource area assigned to the Canary Islands in the official MSP [35].

The study that yields the highest offshore wind resource potential values is that of Schallenberg-Rodríguez and García Montesdeoca [33], while the lowest were obtained in the studies of Díaz and Guedes Soares [8]. This study yields intermediate values, although closer to those obtained in the official MSP [35]. The MSP for the Canary Islands does not indicate the recoverable energy values. The MSP area allocated for offshore wind farms is 562 km^2. This value is higher than that obtained in this study, although it is closer to that of this study than to the values obtained in the study of Schallenberg-Rodríguez and García Montesdeoca [33] and the studies of Díaz and Guedes Soares [8].

The framework adopted in this study, in addition to offering a systematic approach for the calculation of recoverable OWE, facilitates a comparison of results between studies. The use of indicators enables the information to be homogenized and favors the interpretation of results. Table 9 shows the adaptation of the aforementioned works to the framework adopted in this study. The first column shows the gross offshore resource area used as the starting point in each study. It can be seen that different values have been adopted. This is due to the circumstances related to the interpretation of what exactly comprises the territorial waters of the Canary Islands. In the study by Schallenberg-Rodríguez and García Montesdeoca [33], the territorial waters in which offshore wind farms can be installed are assumed to be within a distance of 12 nm from the coastline. In the studies by Díaz and Guedes Soares

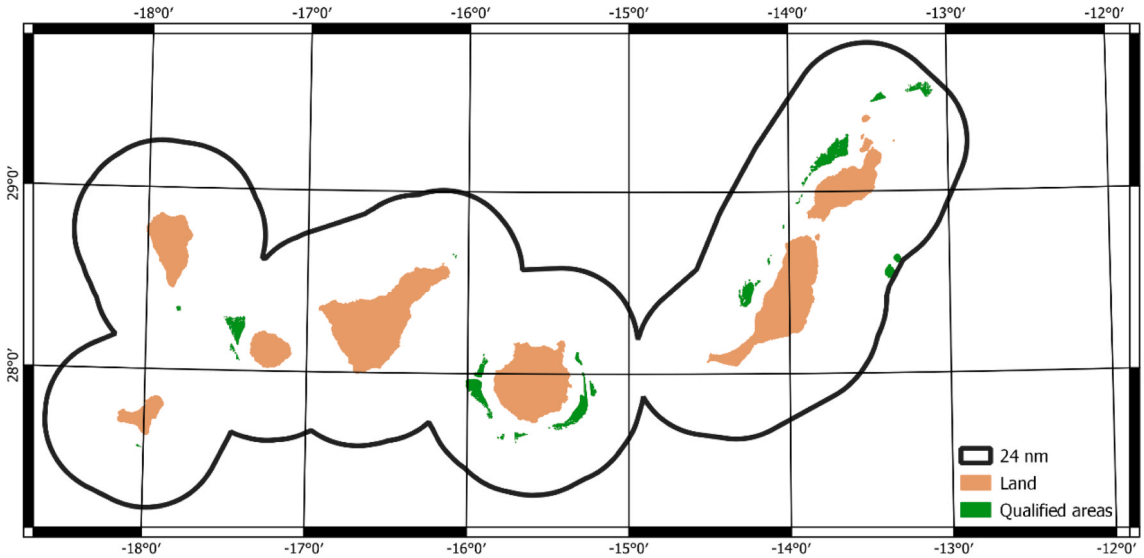

Fig. 10. Net technical offshore resource area (qualified areas) after the exclusion of environmental protection areas in addition to previous constraints.

Table 4
Summary of maritime area reduction per exclusion in percentage terms.

Type of exclusion	Absolute reduction percentage (in relation to the gross offshore resource area (74,855 km^2)
1000 m depth	83.5%
Geology	22.9%
Seabed slope	21.7%
Wind speed	2.6%
Distance to shore	14.2%
Military	6.3%
Fisheries	1%
Bird Protection Areas	6.9%
Airports and ports	1.2%
Maritime routes	11.8%
Special Areas of Conservation	21%

Table 5
Summary of available maritime area reduction after each exclusion.

Type of exclusion	Available area after exclusion (km^2)
24 nm territorial waters	74,855
1000 m depth	12,356
Geology	10,733
Seabed slope	6920
Wind speed	6400
Distance to shore	2091
Military	2082
Fisheries	1926
Bird Protection Areas	1514
Airports and ports	1501
Maritime routes	1366
Special Areas of Conservation	479

[8] and the MSP for the Canary Islands [35], the territorial waters were taken as those that are included up to the point of intersection with the maritime waters of neighboring states and up to 200 nm where no such intersection point is crossed. Even so, there is also a discrepancy between the starting point values used in each study, which is possibly due to the controversy as to whether the waters around the uninhabited islets knowns as the Savage Islands and under Portuguese control should be considered territorial or not. In this study, the marine area within a distance of 24 nm from the coastline of the Canary Islands was adopted as the gross offshore resource area. The gross offshore wind resource capacity (MW) and net technical offshore wind resource capacity (MW)

Table 6
Net technical calculations considering NREL criteria [26] and 4 C Offshore data.

	NREL (average power density: 3 MW/km^2)	4 C Offshore database (average power density: 6.5 MW/km^2)
Net technical offshore resource area (km^2)	479	479
Net technical offshore resource capacity (MW)	1437	3114
Net technical offshore resource energy potential (TWh/year)	6.3	13.6

values given in Table 9 were obtained considering an average power density of 6.5 MW/km^2. The values shown would correspond to the case in which all the studies adopted this average power density, to facilitate comparability between studies, although obviously they do not correspond to the estimations made by their authors.

Table 9 shows the equivalent net technical offshore resource area values (km^2) that correspond to the marine areas that could be effectively used for the installation of offshore wind farms in each study. The differences arise from the restrictions that were taken into consideration in each study. In the study of Schallenberg-Rodríguez and García Montesdeoca [33] and the MSP for the Canary Islands [35] it is considered that the restriction of maintaining a distance of at least 8 km between the coastline and the closest wind farm turbine, as reported in the Strategic Study of the Spanish Coastline [47], is not obligatory, whereas in the study of Díaz and Guedes Soares [8] and in this study it is considered an obligatory restriction. Also, by way of example, the MSP for the Canary Islands does not take into consideration the geological nature of the seabed or its slope. Another restriction that has not been applied in the official MSP to certain parts of the marine area is the non-use of waters that are part of the EU's Natura 2000 network [13]. Fig. 12 shows how the MSP identifies suitable areas for offshore wind farms in a surface protected by the EU's Natura 2000 network [13], which could be considered a conflicting marine use. This study does not adopt as a restriction the presence of underwater cables. This is because the information about their exact location is unavailable to the public for security reasons and only the approximate area where the cable infrastructure reaches the coast is known. The restriction of not situating OWE generation devices within 8 km of the coast ensures that there is no conflict with cable connection areas.

Regarding the OWE generation, if 6.5 MW/km^2 is adopted as the

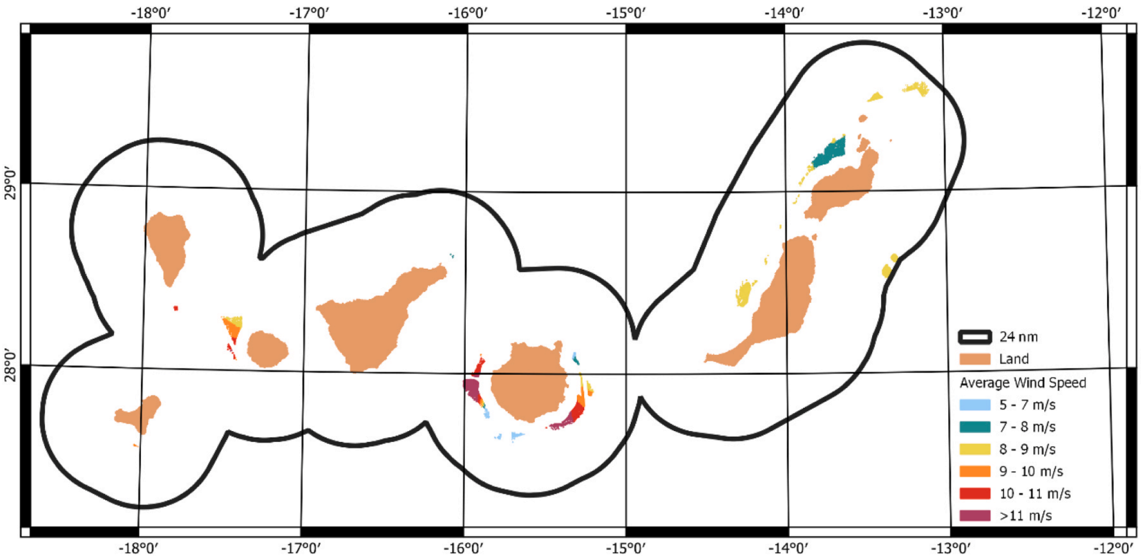

Fig. 11. Average annual wind speed distribution in the net technical offshore area.

Table 7
Distribution of the net technical offshore resource area (km^2) by average annual wind speed and depth.

		Average annual wind speed						
		5-7 m/s	7-8 m/s	8-9 m/s	9-10 m/s	10-11 m/s	> 11 m/s	Total
Depth	50 m	0	0	1	0	0	0	1
	100 m	0	0	38	0	0	1	39
	200 m	0	2	21	14	6	7	50
	300 m	0	4	9	7	9	6	35
	400 m	1	13	17	6	15	11	63
	500 m	2	4	3	7	14	20	49
	600 m	1	5	1	9	12	24	52
	700 m	1	12	1	7	5	8	33
	800 m	0	13	4	3	1	2	25
	900 m	1	15	15	1	1	2	35
	1000 m	3	19	64	4	4	2	96
	Total	9	87	176	57	67	82	479

Table 8
Results obtained in academic studies and in the official MSP on the offshore resource area, the offshore wind resource capacity potential and the offshore wind resource energy potential in the Canary Islands.

	Offshore resource area (km^2)	Offshore wind resource capacity potential (MW)	Offshore wind resource energy potential (TWh/year)
Schallenberg-Rodríguez and García Montesdeoca,[33]	3950	57,225	195
Díaz and Guedes Soares[8]	144	652.3	2.136
MSP for the Canary Islands Spanish government[35]	562	-	-
This study	479	1437 - 3114	6.3 – 13.6

average power density value over the net technical offshore resource area, it is found that all the studies, with the exception of those of Díaz and Guedes Soares [8], reach net technical offshore wind resource capacity values that could cover 100% of the maximum demand for electrical power in the Canary Islands, which in 2019 was 1428 MW [19]. The final column of Table 9 reflects in all the studies the multiple limitations on the marine use of the Canary Islands. This column shows the reduction percentage of the gross offshore resource area to obtain the net technical offshore wind resource area. In two of the studies and the MSP this value exceeds 99%. In the study of Schallenberg-Rodríguez and García Montesdeoca [33], while this value is lower, the starting point is also a lower gross offshore resource area value.

It should be noted that all the academic studies analyzed, as well as the official PSM, consider social, technical, economic and environmental aspects. The methodologies used in all of them are rigorous, although the different results obtained point to the fact that different sets of criteria have been used in all of them. The results of the study by Schallenberg-Rodríguez and García Montesdeoca [33] suggest a greater emphasis on maximizing the suitable area for offshore wind facilities, and minimizing investment and operating costs. The advantages of this approach are that suitable sites for OWE are identified, which more than cover the annual electricity demand of all the Canary Islands. In addition, by allowing a minimum distance of 1 km from the coast, a significant percentage of the wind turbines to be installed would be of the bottom-fixed type. This configuration is much less costly than floating turbines, which are required due to the geographical characteristics of the territory when the distance from the coast is somewhat greater. The results of their study show that the cost of electricity could even be lower than the current cost based on conventional generation. Likewise, the set of criteria adopted in that study ensures that all inhabitants of the islands of the archipelago could benefit from this clean energy. On the contrary, the limitation of the set of criteria adopted in the study by Schallenberg-Rodríguez and García Montesdeoca [33] is that the short distances to the coast allowed for offshore wind turbines could be the

Table 9
Adaptation of some of the values obtained in academic studies and the official MSP on the potential for offshore wind power generation in the Canary Islands to the framework adopted in this study (average power density: 6.5 MW/km^2).

	Gross offshore resource area (km^2)	Gross offshore wind resource capacity (MW)	Net technical offshore resource area (km^2)	Net technical offshore wind resource Capacity (MW)	Area reduction percentage (%)
Schallenberg-Rodríguez and García Montesdeoca[33]	31,901	207,357	3950	25,675	87.62
Díaz and Guedes Soares[8]	478,333	3109,165	144	936	99.97
MSP for the Canary Islands[35]	486,000	3159,000	562	3653	99.98
This study	74,855	486,558	479	3114	99.36

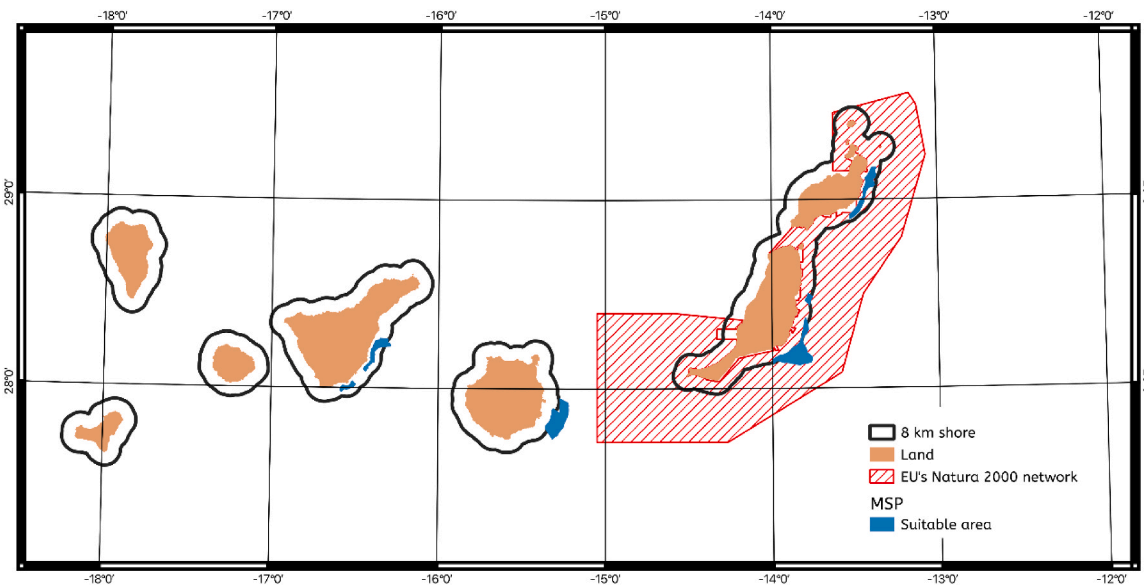

Fig. 12. Suitable areas identified in the official MSP for the installation of offshore wind farms.

subject of significant socio-economic controversy. Opposition could come from stakeholders defending other uses of the marine area (e.g., fishing and aquaculture), as well as from possible conflicts with tourism activities, which are very important in the archipelago (e.g., coastal tourism activities and environmental impacts on the marine landscape).

The results of the studies by Díaz and Guedes Soares [8] suggest the adoption of a set of criteria to minimize environmental impacts and reduce conflicts between stakeholders. The benefits of this approach are evident in the identification of suitable sites for OWE development that do not affect protected areas. It also ensures that there is no conflict between current and potential marine uses by establishing separation buffers of at least 1 km between the different uses assigned to marine areas. Similarly, by establishing minimum distances from the coast of more than 8 km, the potential for socio-economic controversies, derived mainly from the impact on tourism activities, is reduced. On the contrary, the set of criteria adopted in the study by Díaz and Guedes Soares [8] has the limitation that the suitable sites for the development of OWE can only cover a part of the annual electricity demand of the archipelago. In addition, the minimum distances from shore that have been established imply that floating wind turbines must be used in all cases. This configuration results in higher investment and maintenance costs, in addition to the fact that the technology is not yet mature. With this configuration, the cost of offshore electricity generation could be higher than at present, which would imply the need to provide incentives or subsidies with public funds to promote investment in OWE facilities. Another limitation of the results of the study is that the suitable areas identified would only allow the supply of electricity to three of the seven islands of the archipelago, since it is not possible to transfer energy between the islands due to the considerable depth of the seabed. This result would mean that, in the case of authorizing the development of offshore wind farms in the identified areas, the energy contribution would be unequal for the different islands of the archipelago. Such conditioning factors may be an obstacle to subsidizing this type of installation with public funds as the public investment would not benefit all the inhabitants of the archipelago equally. The resulting likelihood of a controversial socio-political debate would complicate even further the already complex decision-making process.

Considering the results of previous academic studies and those of this study, it can be deduced that the development of the official MSP [35] has followed a set of criteria that seek a balance in social, technical, economic and environmental terms. Possibly, the search for balance is the main strength of this instrument, although it can also be its weakness, since it implies trade-offs between sectoral growth. The advantages of this approach are that the sites identified as suitable for the development of OWE make it possible to supply renewable energy to the islands where most of the population of the archipelago is concentrated. This decision avoids potential socio-political controversies regarding the use of public funds to encourage investment in this type of facility. Some marine areas have also been designated for the development of OWE near the coast and near onshore facilities for the reception and distribution of the electricity generated offshore. This reduces investment and maintenance costs. It should be noted that all the islands have harbors where vessels can dock for maintenance of the wind turbines. This factor, together with the fact that the islands are relatively close to each other, means that the criterion of proximity to ports is not relevant when deciding on suitable sites for OWE. The main limitations of the official MSP [35] are the allocation of areas protected by the EU's Natura 2000 network for offshore wind development and the proximity of some of the planned areas to the coast, with distances of around 3 km. In the latter case, some stakeholders related to fishing and tourism activities have already publicly expressed their disagreement.

The suitable sites for OWE development identified in this study are located in areas very similar to those identified in the studies by Díaz and Guedes Soares [8], with the exception of an area near an island that was not identified in their study and that does not present restrictions. Another difference is that it was not considered necessary to establish a buffer of 1 km between zones with different uses. This avoids leaving a significant amount of marine area unallocated for use. In this study, it was decided to maintain the separation buffer with the transportation routes in order to ensure the safety of maritime traffic. Therefore, this study shares many of the advantages and limitations of the studies by Díaz and Guedes Soares [8]. Of all the limitations, the most critical is that the exclusions considered in this study mean that offshore wind farms cannot be installed near the coasts of three islands that represent 47% of the population of the archipelago.

The results obtained in the academic studies analyzed, in the official MSP and in this study show the difficulty associated with the identification of suitable sites for OWE that simultaneously satisfy social, technical, economic and environmental criteria in an optimal manner. This complexity is evidenced by the fact that several studies have been carried out in the same area, using different methodologies and with different results. The coincidence of different studies in the same geographical area can help to draw conclusions that are relevant not only for the Canary Islands, but also for other islands and coastal regions that are also characterized by high population density, scarcity of territory and dependence on conventional energy. In this regard, it can be concluded that the use of proven methodologies and frameworks, supported by the use of geographic information systems, to identify suitable sites for OWE is not in itself sufficient to meet all the criteria. Decisions on suitable sites for OWE should also include negotiations on coexistence of uses, land-sea interactions, stakeholder involvement, political leadership and transboundary cooperation. This study informs about the official MSP and identifies its limitations, although in the light of the discussion of the results, it seems to offer a balance between all decision criteria.

5. Conclusion

This study provides results that can be useful for marine policy decision-making. The results show the low fraction of the marine territory that can be used for wind power generation, less than 1%. The regional government of the Canary Islands has set targets for OWE installations of 430 MW by 2030 and 2499 MW by 2040. These values are within the theoretical achievable range according to the results of this study.

This study does not intend to substitute the official MSP for the analyzed territory. It informs the official MSP, taking as a reference previous academic studies, as well as the results of this study. The conclusions could serve as a reference for future modifications to the official MSP or as recommendations for other territories that share similar characteristics.

The first conclusion of this study is that the official MSP of the Canary Islands includes marine areas that are not suitable for the installation of offshore wind farms, according to the restrictions considered. The official planning includes feasible areas located in areas protected by the EU's Natura 2000 network. In addition, areas less than 8 km from the coast are considered suitable, contrary to what was recommended in the Strategic Study of the Spanish Coast.

The decision on suitable sites for OWE is a complex one, which makes it difficult to satisfy simultaneously social, technical, economic and environmental criteria in an optimal way. The second conclusion of this study is that the decision on suitable sites for OWE must also involve negotiation on co-existence of uses, land-sea interactions, stakeholder involvement, political leadership and transboundary cooperation. In this sense, the proposal of the official MSP of the Canary Islands manages to strike a balance between all decision criteria.

In future studies, as a recommendation, additional factors should be considered, such as the impact of offshore wind farms on the tourist sector and hence on the main source of income of the Canary Islands. This could require an additional restriction in terms of the available marine area for the installation of offshore wind farms. An in-depth economic feasibility study is needed to evaluate the profitability of offshore wind farms and the potential negative effects on tourism. It would also be of interest in future studies to determine how many of the legal constraints (e.g. fishing and others) could be changed and, depending on the possible modifications made, what the resulting net technical offshore resource area would be.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgments

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Annex A. . Main data legislation and maps sources

Data	Map/Data source
Islands outline	Official cartography of the Canary Islands 1:5000 updated in March 2021. https://opendata.sitcan.es/dataset/islas-y-municipios/resource/c2d1d0df-2cfb-48e2-a42d-0a8196e423fc
Jurisdictional waters [61]	Own creation based on the official cartography of the Canary Islands 1:5000
Bathymetry Seabed slope Marine geology	European Marine Observation and Data Network (EMODnet) https://emodnet.ec.europa.eu/geoviewer/
Legal issues (authorization of electricity facilities in marine areas)[48]	Own creation based on the coordinates described in the Spanish legislation
Military areas [56]	https://ideihm.covam.es/portal/servicios-web/ https://ideihm.covam.es/wfs/CartaOF?SERVICE=WFS&VERSION= 1.0.0&REQUEST=GetFeature&TYPENAME=aereos,submarinos,superficie,anfibios&SRSNAME=CRS:84&OUTPUTFORMAT=application/shapefile
Fish farms [37,44,50–52,54,55]	Own creation from the coordinates described in the Spanish legislation, official cartography of the Canary Islands 1:5000, and the bathymetry maps

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Data	Map/Data source
Marine protected areas[5,20,39,40,43,53]	Canary Islands Government http://www.gobiernodecanarias.org/medioambiente/piac/descargas/Biodiversidad/Red-Natura/Planes-ZEC/Cartografia-ZEC.rar
Airports [36,38,41,42,45,46,49,57]	https://www.seguridadaerea.gob.es/es/ambitos/servidumbres-aeronauticas/reales-decretos-ssaa-aeropuertos-y-radioayudas
Ports [42]	https://geoserver.puertos.es/wms-inspire/puertos?SERVICE=WMS&REQUEST=GetCapabilities&SERVICE=WMS&VERSION= 1.3.0
Maritime routes	https://www.vesselfinder.com/densitymaps http://ideihm.covam.es/wms/cartaENCp2?service=WMS&request=Getcapabilities

Annex B. World offshore wind installations with a power equal to or greater than 200 MW, licensed or starting operations during the period 2017-2020 (4coffshore, n.d.)

Wind farm	Power (MW)	Total area (km^2)	Density (MW/ km^2)	Wind turbine model	Number of wind turbines	Blade diameter (m)	Wind turbine area in the farm (km^2)	Year
Gemini Wind Farm	600	69.58	8.62	Siemens SWT-4.0	150	130	27.45	2017
Gode Wind (phases	582	69.37	8.39	Siemens SWT-6.0-154	97	154	30.15	2017
Dudgeon	402	55.13	7.29	Siemens SWT-6.0-154	67	154	34.70	2017
Veja Mate	402	50.91	7.90	Siemens SWT-6.0-154	67	154	32.04	2017
Nordsee One	332	29.79	11.14	Senvion 6.2M126	54	126	34.75	2017
Huaneng Rudong	300	85.82	3.50	Siemens 4.0 MW	38	130	133.63	2017
Sandbank (Phase 1)	288	47.13	6.11	Siemens SWT-4.0-130	72	130	38.73	2017
Burbo Bank Extension	258	39.64	6.51	Vestas V164-8.0 MW	32	164	46.06	2017
Jiangsu Luneng Dongtai	200	34.03	5.88	Siemens SWT-4.0-130	50	130	40.27	2017
Race Bank	573	62.36	9.19	Siemens SWT-6.0-154	91	154	28.90	2018
Rampion	400	74.14	5.40	MHI Vestas V112-3.45 MW	116	112	50.95	2018
Binhai North H2	400	132.9	3.01	Siemens SWT-4.0-120	100	120	92.29	2018
Galloper	353	113.58	3.11	Siemens SWT-6.0-154	56	154	85.52	2018
Wikinger	350	32.24	10.86	Adwen AD 5-135	70	135	25.27	2018
SPIC Jiangsu Dafeng	302.4	112.46	2.69	Envision 4.2 MW	72	136	84.45	2018
Jiangsu Longyuan Chiang Sand	300	61.22	4.90	Envision EN136/ 4.0 MW	75	136	44.13	2018
Hornsea 1	1218	407	2.99	Siemens SWT-7.0-154	174	154	98.63	2019
Beatrice	588	131.33	4.48	Siemens SWT-7.0-154	84	154	65.92	2019
Borkum Riffgrund 2	450	35.97	12.51	MHI Vestas V164-8.0 MW	56	164	23.88	2019
Horns Rev 3	407	116.24	3.50	MHI Vestas V164-8.3 MW	49	164	88.20	2019
Merkur	396	39.33	10.07	GE Haliade 150-6 MW	66	150	26.48	2019
Rentel [de]	294	23.25	12.65	Siemens SWT-7.0-154	42	154	23.34	2019
Dongtai Four	302.4	131.2	2.30	Siemens SWT-4.0-130	63	130	123.23	2019
Datang Jiangsu Binhai	301.8	50.45	5.98	Mingyang MySE3.0-135	50	135	55.36	2019
Liuheng (Guodian Zhoushan Putuo)	252	35.56	7.09	Siemens SWT-4.0-130	63	130	33.40	2019
East Anglia ONE	714	162.82	4.39	Siemens SWT-7.0-154	102	154	67.31	2020
Laoting Bodhi Island	300	70.54	4.25	Siemens SWT-4.0-130	75	130	55.65	2020

Annex C. Percentage of overlapping technical resource area and net technical resource area by type of exclusion

Exclusion	1000 m	Geology	Seabed slope	Wind speed	Distance to shore	Military	Fisheries	Bird Protection Areas	Airports and ports	Maritime routes	ZEC
1000 m	100%										
Geology	18.6%	100%									
Seabed slope	13.5%	76.8%	100%								
Wind speed	15.4%	77.4%	78.8%	100%							
Distance to shore	6.3%	76.2%	81.7%	98.9%	100%						
Military	17.2%	78.6%	77.8%	97.2%	85.3%	100%					
Fisheries	15.7%	76.9%	78.2%	97.4%	86.5%	93.7%	100%				
Bird Protection Areas	12.2%	75.7%	79.4%	98.1%	89.6%	93.3%	99.9%	100%			
Airports and ports	15.9%	77.3%	78.6%	97.4%	86.6%	93.6%	99.0%	93.1%	100%		
Maritime routes	16.5%	77.2%	78.8%	97.4%	86.2%	93.1%	98.9%	93.4%	99.0%	100%	
ZEC	10.4%	72.5%	77.9%	98.1%	89.4%	92.2%	100%	95.6%	98.8%	88.1%	100%

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