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Achieving Blue Growth through maritime spatial planning: Offshore wind energy optimization and biodiversity conservation in Spain

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ABSTRACT

Spain has a high potential for renewable energy production, being the world's third country by installed on-shore wind power. However, it has not yet fully developed its renewable energy production capacity, with no commercial offshore wind production to date, and remains highly dependent on fossil fuel imports. The country is also one of Europe's most biodiverse, on land and at sea. This study spatially assesses the country's offshore wind energy potential by incorporating the newly designated marine protected areas (MPAs) to the official Spanish strategic environmental assessment for the installation of offshore windfarms (SEA). It also identifies optimal areas for offshore windfarm development according to key physical variables such as wind speed, depth and substrate type. It finally assesses real commercial windfarm projects against current environmental constraints. The results show that nearly 50% of the whole area within 24 nm from the Spanish coast could be suitable for offshore windfarm development at the planning phase. However, only 0.7% of that area is optimal for wind energy production with current fixed turbine technology. Nevertheless, either area would allow Spain to meet its national targets of 750 MW of ocean power capacity installed by 2020 under adequate local wind conditions. Over 88% of all commercial windfarm project area is within the SEA's *Exclusion zone*, thus unfeasible under current circumstances. Technological breakthroughs like floating turbines may soon make the optimal windfarm area (OWA) less restrictive and reduce current environmental impacts of marine windfarms within a truly sustainable Blue Growth.

1. Introduction

A number of reasons have increased global interest in marine renewable energy development: fossil fuel exhaustion risk and price oscillation; high competition for and disagreement on land uses; exclusive or better energy production conditions in the marine environment (e.g., in terms of wave or wind energy, respectively); and a need to abate climate change [24]. Offshore wind energy is one of the most rapidly growing marine renewable sources. In Europe in 2015, there were 84 offshore wind farms (including those under construction), with a 108% increase in net installed, grid-connected capacity respective to 2014, most of it developed by Germany, the UK and the Netherlands in the North Sea [20].

The Directive 2009/28/CE, of the European Parliament and the Council, on the promotion of the use of energy from renewable sources, sets up minimal compulsory targets on the use of at least 20% of the final countries' gross energy consumption coming from renewable sources by the year 2020 [12]. The Directive is part of the European Union's Package on Energy and Climate Change [16], which was recently updated and stiffened for the 2020–2030 period [17]. Following the Directives' dictates, the Spanish Government passed the Law 2/2011 on Sustainable Economy, which established the target of attaining 20.8% of final gross energy consumption from renewable energy sources in the country by 2020. Achieving that target is especially relevant in a country like Spain, which is highly energy dependent, releases high quantities of greenhouse gas emissions, and consumes more energy than the mean of the European Union [34]. In order to achieve that target, a National Plan on Renewable Energy Sources 2011–2020 was produced [34].

Renewable energy sources contributed to 11.3% of the primary energy consumption, and to 13.2% of the final gross energy consumption in Spain in 2010 [34]. Their contribution to electricity gross production was 32.3% in the same year, with a 14.6% contribution of (on-shore) wind energy [34]. Wind energy was the renewable energy source that experienced greater rise between

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2000 and 2010, contributing to meeting 16% of the national electricity demand and sometimes exceeding 50% of the hourly demand in 2010 [34]. It is also expected to be the most important renewable source by 2020. However, by 2015 no offshore windfarms had been established in Spain, although a number of commercial projects in shallow and intermediate waters up to 50 m were proposed during the first years of the 2000's. Depending on the progress of wind turbine technology, wind power production potential in Spanish shallow waters was estimated in nearly 8 GW, with offshore wind energy being expected to be commercially competitive by 2020 [34].

Renewable energy sources are more environmentally sustainable than fossil fuel energy sources, including oil, coal, and natural gas, in the sense that they cannot exhaust and that they produce less quantities of greenhouse gases per unit of energy produced [33]. Renewable energy sources also pose far less risk to human health and the environment than nuclear energy. Marine renewable energy sources include wave energy, tidal energy, ocean thermal energy and offshore wind energy. However, the fact that they are more environmentally friendly and less risky than traditional energy sources does not mean they are totally harmless to the environment during their installation, operation and/or decommission phases [8]. More precisely, marine wind energy's impacts on the environment include: impacts on fauna from collisions; nuisance and displacement from noise, vibrations and electromagnetism; barrier effect; seascape impact; and habitat destruction [29]. In European settings, wind power disturbances are shown to chiefly affect some faunal taxa, namely birds (particularly raptors, migrating birds and waterfowl) and bats [1,42], and marine mammals including small cetaceans, particularly harbor porpoises (*Phocoena phocoena*), and pinnipeds, primarily harbor seals (*Phoca vitulina*) [3]. Additional environmental impacts occur from windfarm associated submarine structures (e.g. submerged power lines connecting energy production and transference sites) and coastal facilities (e.g. power stations).

Spain's marine biodiversity is one of Europe's highest, although still not known in its entirety. The variety of geological, oceanographic and biogeographical conditions determines rich, diverse and complex marine environments. To date, 1000 plant species and over 7500 animal species have been described in the country's continental platform alone [28]. Many invertebrate taxa including *Turbelaria*, *Nematoda* and sand-dwelling organisms remain poorly studied, and the biology of many others is still unknown, so even greater marine biological richness is to be expected as knowledge progresses. To adequately protect such marine biodiversity, in recent years Spain has developed a network of MPAs that has not yet been completed, but which already exceeds international protection coverage targets in the country's Mediterranean inshore and offshore waters [32]. As a result, the network can be considered reasonably well developed, with no massive increases expected.

With the renewable energy source Directive passing in the foresight [12], the Spanish Government carried out a strategic environmental assessment of the Spanish coastal waters for the installation of marine wind farms which accounted for the cumulative and synergetic impacts of individual windfarm projects on environmental values and other human marine uses [33]. The SEA was the most comprehensive study on marine and coastal socioeconomic uses and environmental and cultural values till that date. It divided the Spanish waters up to 24 nm in three zones according to their suitability to host commercial windfarms: *Suitable*, *Suitable with conditions* and *Exclusion zones*. Nevertheless, a key environmental factor, the coverage of the Spanish MPA network, has greatly increased since 2009. For example, the area covered by MPAs in the Spanish Mediterranean has experienced a five-fold rise just between 2014 and 2015 mostly due to the designation of numerous Natura 2000 sites at sea [32], making it necessary to update the assessment of the suitable areas for the installation of future marine windfarms.

The European Union's Blue Growth Strategy [14], which aims at maximizing the sustainable economic potential of Europe's seas and oceans through further developing economic activities such as aquaculture, coastal tourism, marine biotechnology, seabed mining and ocean energy, is likely to put higher pressure on already heavily pressured European marine environments [9]. Thus, this study seeks to spatially estimate the potential offshore wind power capacity to be installed in Spain accounting for the country's environmental conservation needs. More specifically, it has the following objectives:

1. Defining the *potential* (all non-excluded areas, according to the SEA) and *optimal* areas (according to wind speed, bottom depth and seabed substrate) to locate marine wind farms in Spanish waters accounting for new MPA designations;
2. Estimating the theoretical installed wind power capacity from the *potential* and *optimal* areas, and how they would contribute to the country's offshore wind energy capacity installation targets;
3. Determining whether existing commercial marine windfarm project proposals could be carried out considering new environmental restrictions.

2. Methods

The final zoning of the Spanish waters up to approximately 24 nm from the coastal straight baselines included in the SEA [33] was used as a spatial (GIS) cartographic basis for this study. The SEA represents the most comprehensive, country-wise maritime planning study to date. It considered and mapped the following socioeconomic uses and environmental and cultural values of the sea by 2009: fishing resources and activities, coastal public domain areas, biodiversity and protected areas, archeological heritage, maritime and air traffic security areas, and seascape value [33]. The final SEA layer distinguished between: 1) *Suitable zones*: zones where no likely negative environmental impacts or socioeconomic conflicts from marine windfarms were envisaged at the planning phase (SEA), without precluding individual projects' environmental impact assessments (EIAs); 2) *Suitable zones with conditions*: zones where the impacts or conflicts that were detected at the planning phase would have to be assessed in detail by specific EIAs; and 3) *Exclusion zones*: zones that should be excluded from marine windfarm development for their significant environmental impacts or conflict with other marine uses.

All MPAs designated or proposed for designation (but with a preventive protection regime) from April 2009 (publication date of the SEA) and up to the end of November of 2015 that lay within the 24 nm inshore SEA area were considered to update the *Exclusion zones* for the establishment of marine windfarms. These included 45 new MPAs: 36 marine Special Protection Areas (SPAs) designated in 2014 [36], six Sites of Community Importance (SCIs) proposed for designation in 2014 [37,38], one SCI proposed for designation in 2015 [41], one marine Ramsar site designated in 2011 [39], and one Marine Protected Area and Special Area of Conservation designated in 2011 [35]. The main characteristics of these MPAs are shown in Appendix A. Official GIS data for MPAs were collected from the Spanish Ministry of Environment's website [27], and merged in a single Spanish 'new MPA layer'. Some studies on the effects of terrestrial windfarms have suggested negative effects on fauna, especially birds and bats, up to 10 km from windfarms' boundaries [1,33], and even beyond that distance in the case of specific marine fauna [3]. Thus, applying a precautionary approach to marine windfarm development, ten-kilometer

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buffers around the marine parts of the new SPAs and Ramsar sites designated since April 2009 were applied in our study and considered also as exclusion zones in the 'new SEA zoning layer', as done in the original SEA [33]. This layer was dissolved to prevent overlaps and later intersected with the final SEA zoning layer including all the Spanish MPAs designated previously to April 2009 and other marine values and uses to produce the 'new SEA zoning layer'. It was assumed that all other marine values and uses of the SEA (e.g., submerged cultural features) have not changed much since 2009. All calculations were done in ArcGIS v.10.2 [10].

The OWA was defined by a mean annual wind speed threshold (≥ 6 m/s at 80 m above the sea level), bathymetry limit (≤ 50 m for fixed wind turbine technology), and sandy, soft-sediment bottoms [25]. Wind speed data were obtained from the European Centre for Medium Range Weather Forecasts (ECMWF) ERA-Interim data set [6]. This dataset is the global atmospheric reanalysis product of the ECMWF initiated in 2006, providing surface and upper air as well as oceanic numerical data since 1979. According to the US National Renewable Energy Laboratory, wind resource is categorized into seven classes based on annual mean wind speed (at 80 m above sea level) as follows: Class 1: 0–5.9 m/s, Class 2: 5.9–6.8 m/s, Class 3: 6.8–7.5 m/s, Class 4: 7.5–8.0 m/s, Class 5: 8.0–8.6 m/s, Class 6: 8.6–9.4 m/s, and Class 7: 9.4–12.6 m/s. The specific choice that was made in this work refers to potential areas for offshore windfarm development characterized by wind speed classes equal to or greater than Class 2, also considering that the ERA-Interim data set underestimates (sometimes significantly) wind speed in the Spanish seas [5]. A mean turbine array density of 6 MW/km^2 was used to estimate the theoretical installed energy production capacity in both *potential* and *optimal* windfarm areas. This is considered an adequate power average value obtained from existing projects that depends on the turbine spacing (usually ranging between 7–12 rotor diameters) and the specific wind turbine type [23].

After testing different spatial interpolation techniques, ordinary linear Kriging resulted in the most accurate wind speed interpolation technique for our data. Wind speed across the Spanish part of the Iberian Peninsula and the Balearic Islands was modeled using the four nearest wind speed points for a default cell size of 4.2 km. Lack of wind speed data for the Canary Islands impeded us to incorporate them to the optimal windfarm area analysis. The GEBCO, 400 m-resolution 2014 global 30 arc-second interval grid was used to obtain bathymetry data of the Spanish seas [21]. From it, areas of 50 m of depth or less were selected, as 50 m is the maximal depth at which actual commercial windfarm technology (fixed turbines) can operate [23]. The following 1 km^2-resolution layers of broad types of ecosystems were used as surrogates for soft substrate and later merged in a 'soft substrate layer': subtidal soft bottom (0–60 m), soft shelf (60–200 m), soft slope (200–2000 m) and deep soft benthic (>2000 m) [30]. Both, the resulting wind speed raster layer and resolution bathymetry layer were transformed to vector layers and intersected with the soft substrate layer within the 24 nm SEA area to produce the 'OWA layer'. The 'OWA layer' was then intersected with the 'new SEA zoning layer' and possible *optimal* offshore windfarm development areas were identified.

Environmental impact studies (EISs) of commercial windfarm projects proposed to the Spanish Ministry of Environment were retrieved by consulting the EISs hard copies at the Ministry's headquarters in Madrid. GIS polygons were digitized after projecting the UTM coordinates of each georeferenced project on ArcGIS. Fifteen projects were projected and intersected with the 'new SEA zoning layer' including MPAs designated since April 2009. Five projects could not be projected because of lack of coordinates. Different windfarm project's names, not project phases, were considered as different projects, even if most of them consisted of different phases (Appendix B). The area covered by the 15 projects was calculated after dissolving them to prevent double counting and later on intersected with the 'new SEA zoning' and 'OWA' layers. The projects' minimal distance to the shore was calculated using the 'Near' function in ArcGIS v.10 [10].

3. Results

3.1. New SEA zoning

3.1.1. Maximal (theoretical) windfarm area

139,324 new km^2 of marine waters were protected or proposed for protection in Spain since 2009, including the 10 km marine buffers surrounding SPAs and Ramsar sites. Of them 88,489 km^2 (63.51%) fell within the SEA area, of approximately 223,739 km^2 (Fig. 1). The distribution of new MPA area by SEA zones is shown in Table 1.

The *potential* offshore wind production area in Spain would then roughly be of 111,931 km^2, or 50.03% of the original SEA area. By adopting a mean wind turbine array density of 6 MW/km^2, the potential installed power production capacity could approximately be (local wind speed depending) of 671,586 MW.

3.1.2. Optimal windfarm area

The OWA covers 5714 km^2 within the SEA area, excluding the Canary Islands. Of this area, 5141 km^2 (89.97%) are within the 8 km SEA's seascape restriction band from the shoreline. Of the OWA, only 753 km^2 (13.18% of the OWA) is within the new SEA's *Suitable* or *Suitable with conditions* zones, representing just 0.7% of both zones. By adopting a mean wind turbine array density of 6 MW/km^2, the total installed power production capacity in this physically optimal and environmentally feasible area would roughly be (depending on local wind conditions) of 4518 MW.

3.2. Commercial windfarm project assessment

The 15 windfarm project proposals covered a joint area of approximately 445 km^2, with a mean size of 30.24 ± 22.33 km^2. The mean distance from the coast was 4.66 ± 2.92 km, ranging from 0.82 to 12.04 km. Just 93 km^2 (roughly 21%) of the commercial project area is within the OWA (Fig. 2). Only 1 project of 92 km^2 lies outside the 8 km inshore seascape restriction band of the SEA. Just over 51 km^2 of all the projects' area (11.54%) is within *Suitable* (4.27%) or *Suitable with conditions* (7.27%) zones and only four projects (Miñarzo, Marina, La Janda and Trafalgar) have some area in those zones. This windfarm area, if developed, could amount to approximately 306 MW of installed theoretical production capacity, at a mean wind turbine array density of 6 MW/km^2.

4. Discussion

4.1. New SEA zoning analysis

Recent MPA designations in Spain resulted in a major expansion of the SEA *Exclusion zone*, mostly at the expense of *Suitable with conditions* areas. Almost 55% of the new MPA area occurred in such zone. However, *Suitable* areas did not decrease much, still allowing for a wide potential sustainable expansion of offshore wind energy in the country under adequate physical conditions. This expansion could theoretically exceed the Spanish target of 750 MW of installed offshore power by 2020 [34] and place the country on the right path to meeting its environmental and renewable energy obligations under the European law [11,12,15] and the Climate and Energy Framework for 2030 [17] while at the

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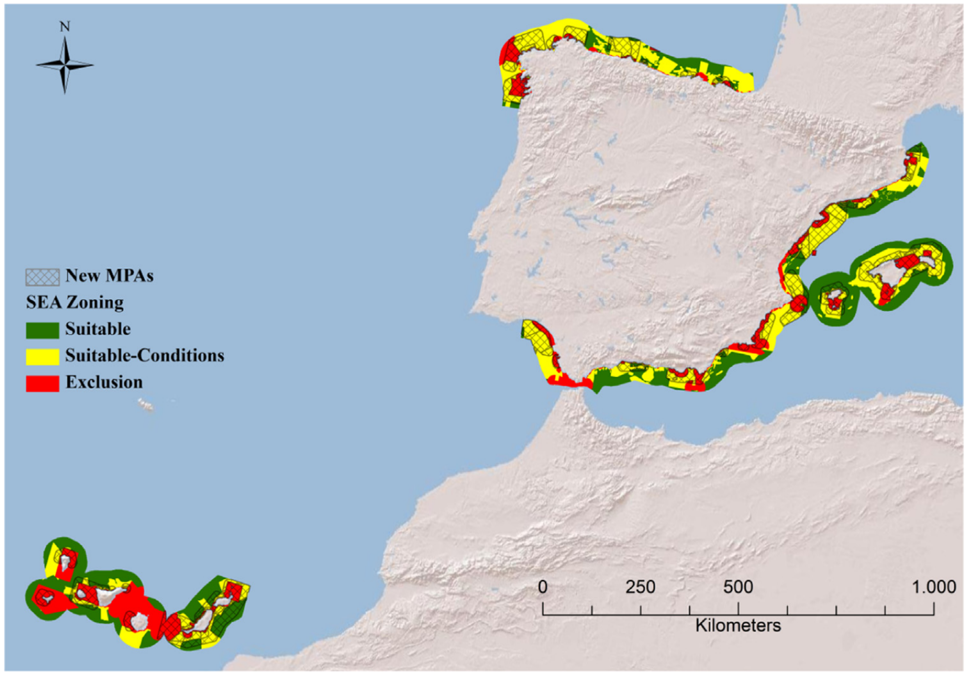

Fig. 1. Original Strategic Environmental Assessment zoning and new marine protected area. designated between April 2009 and November 2015 (in gridded gray).

Table 1
Distribution of new marine protected area in the zones defined by the Strategic Environmental Assessment.

Zone	SEA Zone extent (km^2)	SEA Zone extent (%)	New protected area (km^2)	New protected area (%)	New Zone extent (km^2)	New Zone extent (%)
Suitable	83,119	37.15	12,570	14.21	70,549	31.53
Suitable with conditions	89,638	40.06	48,256	54.53	41,382	18.50
Exclusion	50,982	22.79	27,663	31.26	111,808	49.97
Total	223,739	100	88,489	100	223,739	100

same time meeting international biodiversity commitments in terms of MPA coverage [32]. Nevertheless, *Suitable* or *Suitable with conditions* zones in areas with optimal physical characteristics for windfarm development are scarce and spatially very restricted. The conditions to create the OWA resulted in a small, chiefly coastal area that was mostly excluded from windfarm development by environmental planning constraints. Thus, the installed power production capacity in those theoretically optimal areas under current mainstream technological capabilities would be rather limited, as stated previously [23]. Additionally, windfarm developmental legal issues might arise with neighboring countries in the 12–24 nm stripe of the Alboran Sea, as Spain has not yet declared an Exclusive Economic Zone in that area.

In terms of sustainable energy development, Spain has established a regulatory framework that introduces a set rate of return for renewable energy mainly on the land side [18]. On the marine side, Spain seems to be positioning itself for floating wind efforts by several companies in deep offshore projects [19]. Technological innovations such as floating turbines will allow the country's OWA to expand to locations with greater depths up to 200 m and harder seabed substrates, although commercial mainstream development of floating turbines remains in the midterm, with most exiting structures being still in an experimental phase [19].

4.2. Commercial project assessment

The commercial windfarm project proposals analysed here are largely unfeasible due to environmental or socioeconomic constraints. All the proposals date from before the SEA and thus did not consider the specifications set up there, such as the general (though not always excluding) restriction to windfarm development within the first eight kilometers seaward from the shoreline relative to seascape impact [33]. In fact, all the projects but one (Al-Andalus I-X) are within that distance. It is noteworthy that just one fifth of all the commercial windfarm area is within our modeled OWA. This probably reveals the coarse character of our analysis that did not consider important factors at local scale such as wind speed at the proposed locations.

A number of reasons seem to have discouraged development of commercial offshore windfarms in Spain to date: wide environmental constraints; limited physical conditions for the development of windfarms; uneven distribution of wind resources; technical and cost restrictions as a result of additional submerged and land infrastructures such as cables or power stations; greater operational and maintenance costs compared to terrestrial windfarms; excessive administrative processes; conflicting administrative decisions at different levels; uncertain regulatory and economic frameworks; and notable social opposition to punctual commercial projects, such as in the Andalusian Atlantic area (Juan Ramón Ayuso, comm. pers.). In addition to this, the present transitory situation in Spain, characterized by a relative ease in energy supply, reduced energy consumption as a result of the economic crisis, and low energy prices [40] might be also slowing the progress towards developing the country's offshore wind energy potential. Nevertheless, regional instability in the Middle East, the Gulf region and Russia is questioning the reliability of these sources in the future for Europe [7].

Diversifying energy production sources and increasing energy efficiency and self-production through renewable energy sources are effective ways of reducing European countries' vulnerability to external energy imports, chiefly of fossil fuels [13]. Reducing external energy dependence strengthens countries' resistance to price shocks, supply shortages and geopolitical instability which

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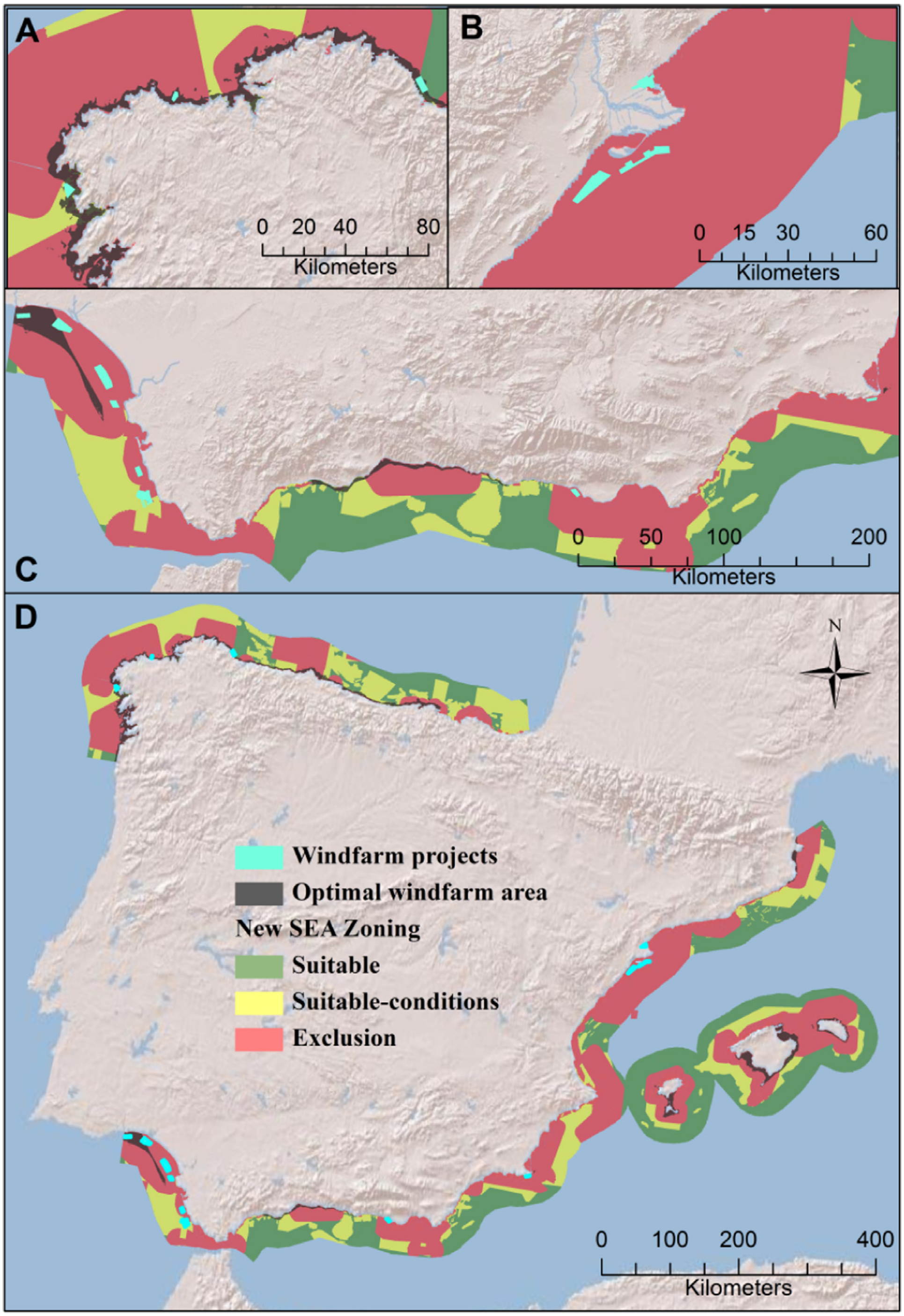

Fig. 2. Windfarm projects and optimal windfarm area in the new Strategic Environmental Assessment study area zoning. A: North-west area; B: North-east area; C: South area; D: Whole country (except the Canary Islands).

may result in substantial losses to competitiveness and GDP, inflationary pressures and trade balance deterioration [13]. This is especially relevant in Spain, whose energy dependence reached approximately 73% of all the primary energy used by the country in 2014 [40]. Spain, in that sense, has the potential to increase its share of sustainable energy sources by making use of its offshore energy potential and the support provided through the European Commission's Blue Growth Strategy [14]. Offshore, deeper windfarm developments with new floating turbines seem more promising in terms of a wide expansion of this energy source, as less environmental impact and conflicts with users are expected. This potential in terms of blue energy will become even more relevant as future primary energy consumption rises are expected (as much as 37% over 2014 data by 2040; [40]) as the country's demography evolves and its economic activity and thus production and consumption patterns return to normal.

4.3. Environmental considerations

Although environmental impacts of offshore windfarms are well known [31], research suggests some contradicting results where changes in species assemblages at artificial structures in comparison with natural habitats are registered [2]. Specifically, changes in some fish species and community composition over time after windfarm structure establishment indicated that fish variations are mainly driven by the same environmental factors as those in surrounding areas, rather than being linked to direct disturbance from the built structures [4]. However, changes at finer scale suggested the need for enhanced environmental control near the foundations [4]. Actually, offshore windfarm structures acting as artificial reefs may also have some positive effects on some marine species as a result of new habitat creation and fishing restrictions, chiefly trawling, within sites [24,26]. As a result of higher survival rates of marine organisms and bigger individuals within windfarms' boundaries, spillover to surrounding areas can be expected, although biological invasions can also occur because of new habitat creation [25]. Some of the windfarm project developers even suggested installing fish farms in the perimeter of windfarms, an innovative idea that could maximize gains from this combined spatial use of the ocean.

4.4. Limitations

This study is not without limitations. Some basic information for the production of the SEA was incomplete, inconsistent or inadequate for GIS representation; for instance, some protected species and habitat distribution data. Thus, that information was not included in the SEA [33]. Additionally, some data for modeling the OWA (e.g. soft habitat types) came from previous interpolations from global datasets that integrated different data sources and resolutions [22] and may result inaccurate for a fine scale analysis. Also, the resolution of some of the digital layers produced in the study (e.g. wind speed data) is coarse and should be refined for a fine scale analysis. It was, however, conditioned by the incomplete original wind speed point data layer (with some points separated more than 100 km along the coast) and resulted useful for the country-wise analysis done. Moreover, marine values or uses other than MPAs might have spatially evolved to some extent since the SEA date, possibly making our analysis slightly inaccurate. Finally, our calculated *potential*, *optimal* and feasible areas represent the maximal theoretical expansion of marine wind energy at the strategic planning phase. However, these areas will later be subject to specific EIAs, thus further restricting available areas for windfarm development.

5. Conclusions

Spain has limited potential for offshore wind development, mainly due to current environmental and technical constraints. However, the country could easily meet its modest offshore installed power targets from renewable wind energy sources by 2020 while, at the same time, protecting valuable marine biodiversity. Even if the country's MPA network is still expected to be enlarged to some extent, the area covered by windfarm *Suitable* zones could still allow marine wind energy to meet the country's renewable energy installation and production targets by 2020 [34]. Additionally, new technologies such as floating turbines are likely to generate new suitable areas for energy production as well as reduce some of the current common impacts of offshore windfarms (e.g. those related to fixed turbine foundations). Positive socioeconomic effects of Blue Growth could be enhanced by combining productive uses of the ocean spatially (such as energy production and fish farming). However, for this Growth to be really Blue, proper EIAs should be carried out to ensure the sustainability of specific developmental initiatives at sea and on the coast.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2016.07.022.

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