SAFE WAVE

STREAMLINING THE ASSESSMENT OF ENVIRONMENTAL EFFECTS OF WAVE ENERGY

DELIVERABLE 6.3

Identifying suitable areas for developing wave energy projects in the European Atlantic region

This Project is co-funded by the European Climate, Infrastructure and Environment Executive Agency (CINEA)

WP 6

Deliverable 6.3 Identifying suitable areas for developing wave energy projects in the European Atlantic region

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SAFE WAVE project synopsis

The European Atlantic Ocean offers a high potential for marine renewable energy (MRE), which is targeted to be at least 32% of the EU's gross final consumption by 2030 (European Commission, 2020(European Commission, 2020). The European Commission is supporting the development of the ocean energy sector through an array of activities and policies: the Green Deal, the Energy Union, the Strategic Energy Technology Plan (SET-Plan) and the Sustainable Blue Economy Strategy. As part of the Green Deal, the Commission adopted the EU Offshore Renewable Energy Strategy (European Commission, 2020) which is estimated to have an installed capacity of at least 60 GW of offshore wind and at least 1 GW of ocean energy by 2030, reaching 300 GW and 40 GW of installed capacity, respectively, moving the EU towards climate neutrality by 2050.

Another important policy initiative is the REPowerEU plan (European Commission, 2022) which the European Commission launched in response to Russia's invasion of Ukraine. REPowerEU plan aims to reduce the European dependence amongst Member States on Russian energy sources, substituting fossil fuels by accelerating Europe's clean energy transition to a more resilient energy system and a true Energy Union. In this context, higher renewable energy targets and additional investment, as well as introducing mechanisms to shorten and simplify the consenting processes (i.e., 'go-to' areas or suitable areas designated by a Member State for renewable energy production) will enable the EU to fully meet the REPowerEU objectives.

The nascent status of the Marine Renewable Energy (MRE) sector and Wave Energy (WE) in particular, yields many unknowns about its potential environmental pressures and impacts, some of them still far from being completely understood. Wave Energy Converters' (WECs) operation in the marine environment is still perceived by regulators and stakeholders as a risky activity, particularly for some groups of species and habitats.

The complexity of MRE licensing processes is also indicated as one of the main barriers to the sector development. The lack of clarity of procedures (arising from the lack of specific laws for this type of projects), the varied number of authorities to be consulted and the early stage of Marine Spatial Planning (MSP) implementation are examples of the issues identified to delay projects' permitting.

Finally, there is also a need to provide more information on the sector not only to regulators, developers and other stakeholders but also to the general public. Information should be provided focusing on the ocean energy sector technical aspects, effects on the marine environment, role on local and regional socio-economic aspects and effects in a global scale as a sector producing clean energy and thus having a role in contributing to decarbonise human activities. Only with an informed society would be possible to carry out fruitful public debates on MRE implementation at the local level.

These non-technological barriers that could hinder the future development of WE in EU, were addressed by the WESE project funded by European Maritime and Fisheries Fund (EMFF) in 2018. The present project builds on the results of the WESE project and aims to move forward through the following specific objectives:

1. Development of an **Environmental Research Demonstration Strategy** based on the collection, processing, modelling, analysis and sharing of environmental data collected in WE sites from different European countries where WECs are currently operating (Mutriku power plant and BIMEP in Spain, Aguçadoura in Portugal and SEMREV in France); the SafeWAVE project aims to enhance the understanding of the negative, positive and negligible effects of WE projects. The SafeWAVE project will continue previous work, carried out under the WESE project, to increase the knowledge on priority research areas, enlarging the analysis to other types of sites, technologies, and countries. This will increase information robustness to better inform decision-makers and managers on real environmental risks, broaden the engagement with relevant stakeholders, related sectors, and the public at large and reduce environmental uncertainties in consenting of WE deployments across Europe.

2. Development of a **Consenting and Planning Strategy** through providing guidance to ocean energy developers and to public authorities tasked with consenting and licensing of WE projects in France and Ireland; this strategy will build on country-specific licensing guidance and on the application of the MSP decision support tools (i.e. WEC-ERA[1] by Galparsoro et al., 2021[2] and VAPEM[3] tools) developed

[1] https://aztidata.es/wec-era/;

[2] Galparsoro, I., M. Korta, I. Subirana, Á. Borja, I. Menchaca, O. Solaun, I. Muxika, G. Iglesias, J. Bald, 2021. A new framework and tool for ecological risk assessment of wave energy converters projects. Renewable and Sustainable Energy Reviews, 151: 111539

[3] https://aztidata.es/vapem/

for Spain and Portugal in the framework of the WESE project; the results will complete guidance to ocean energy developers and public authorities for most of the EU countries in the Atlantic Arch.

3. Development of a **Public Education and Engagement Strategy** to work collaboratively with coastal communities in France, Ireland, Portugal and Spain, to co-develop and demonstrate a framework for education and public engagement (EPE) of MRE enhancing ocean literacy and improving the quality of public debates.

Glossary

CA – Consortium Agreement

EMFF - European Maritime and Fisheries Fund

EU – Europe Union

GA – Grant Agreement

M – Face-to-face meeting

MAEP – Mean Annal Energy Production

MP – Management Plan

ONM – On-line meeting

WP – Work Package

WPl – Work Plan

EPE – education and public engagement

MSP – Maritime Spatial Planning

MRE – Marine Renewable Energy

GIS – Geographic Information System

MPA – Marine Protected Area

EEZ – Exclusive Economic Zones

Executive summary

One of the objectives of the European Green Deal is to increase the share of renewable energy sources in the EU's energy mix. Among other energy resources, renewable energy from the seas is a cornerstone of the clean energy transition, especially offshore wind, and ocean energy.

Achieving the renewable energy production objectives will necessitate a notable expansion of the offshore energy industry. One of the main challenges for wave energy projects is to find suitable locations that can provide high and consistent wave power, as well as meet the environmental, social, and economic criteria.

Different approaches of modelling can be implemented to assist during the process of the integrated assessment of suitable areas for the development of wave farms. One of the primary outcomes of such models is the creation of maps. The maps serve to illustrate the spatial distribution of suitable locations for the development of wave energy farms.

The main objective of the present deliverable is the identification and characterization of suitable areas for the development of wave energy projects in the context of Maritime Spatial Planning in the European Atlantic region (Spain, Portugal, France, and Ireland), accounting for a total area of 3,136,073 km^2.

The model was operationalized in a Bayesian Network. The spatial data to feed the model were obtained from different publicly available datasets. It was implemented into a web-based decision support tool called VAPEM (https://aztidata.es/vapem/).

A total of 34 maps representing the spatial distribution of three different dimensions directly related to the suitability of wave energy projects (i.e., technical suitability, environmental risk, and conflicts with other activities) and the final integrated suitability have been produced.

Almost 11% of the study area has been identified as being suitable for wave energy projects, of which 0.41% is considered as being highly suitable. This percentage represents 37,661 km^2 of suitable and highly suitable areas for the development of offshore wave energy projects. The averaged mean annual energy production (MAEP) of our specific WEC, assuming an operation window of 8,760 hour per year (i.e., 365 days, with no stops), is 1,235 ± 80 MWh (mean value for the suitable and highly suitable areas). The maximum and minimum value of the MAEP in this area is 1,605

MWh, and 1,118 MWh, respectively. To achieve the target of 1GW of ocean energy installed capacity by 2030, 7,143 WECs would be needed and to achieve the target of 40 GW by 2050, 285,714 WECs, and in areas with the maximum MAEP, 5,459 WECs and 218,341 WECs respectively.

The results indicate that there is enough space in the European Atlantic region to develop new wave energy farms for the achievement of predefined objectives and that if planned properly and with caution, those developments would fulfil industrial requirements, and would be developed in areas with the lowest environmental risks and limited or no conflicts with other activities.

1. Introduction

The European Green Deal (European Commission, 2019) is a plan by the European Union to become climate-neutral by 2050. It aims to transform the EU into a modern, resource-efficient, and competitive economy, ensuring no net emissions of greenhouse gases by 2050 and economic growth decoupled from resource use.

One of the key components of the deal is to increase the share of renewable energy sources in the EU's energy mix.

Among other energy resources, renewable energy from the seas is a cornerstone of the clean energy transition, especially offshore wind, and ocean energy[4]. Offshore energy has the potential to provide clean, reliable and cost-effective electricity for millions of households and businesses, while creating jobs and boosting innovation (European Commission, 2020).

To ensure that offshore renewable energy can help reach the EU's ambitious energy and climate targets for 2030 and 2050, the Commission published a dedicated EU strategy on offshore renewable energy (European Commission, 2020) which proposes concrete ways forward to support the long-term sustainable development of this sector. The strategy sets targets for an installed capacity of at least 60 GW of offshore wind and 1 GW of ocean energy by 2030, and 300 GW and 40 GW, respectively, by 2050.

Achieving these objectives will necessitate a notable expansion of the offshore wind sector, which is protected to occupy less than 3% of the European maritime expanse (European Commission, 2020). As for wave energy and other sources, their developmental stage and associated uncertainties prevent the provision of estimations at this moment.

One of the main challenges for wave energy projects is to find suitable locations that can provide high and consistent wave power, as well as meet the environmental, social and economic criteria (Galparsoro *et al.*, 2012; Galparsoro *et al.*, 2021b; Maldonado *et al.*, 2022; Quero García *et al.*, 2020). Some of the most relevant factors already identified in Galparsoro *et al.* (2022) in the framework of SafeWAVE,

[4] https://ec.europa.eu/energy/topics/renewable-energy/offshore-renewable-energy_en

that need to be considered in a comprehensive assessment for the identification of suitable locations for the development and deploying of wave energy projects are:

- The wave resource: the availability, variability, and predictability of the wave power at a given location.
- The site characteristics: the bathymetry, geology, hydrodynamics, climate, and accessibility of the site.
- The environmental impacts: the potential effects of the wave energy project on the marine ecosystem, the landscape, the noise and the electromagnetic fields.
- The social impacts: the potential effects of the wave energy project on the local communities, the cultural heritage, the tourism, and the recreation activities.
- The economic feasibility: the costs and benefits of the wave energy project, including the capital, operation and maintenance costs, the revenue streams, the subsidies and incentives, and the risk analysis.

Thus, the comprehensive assessment for the identification of most suitable areas for the development of wave energy projects, requires the consideration of several factors. To facilitate this purpose, models and tools serve as invaluable for identifying suitable areas. An inherent strength of these models and tools is their capability to effectively incorporate explicit spatial and temporal data encompassing ecological and socio-economic factors that must be considered when managing new strategic activities in the actual context of the activities.

A primary outcome generated with these models and tools is the creation of maps. The information geographically represented helps as a comprehensible and interpretable format for different stakeholders. Within the framework of Maritime Spatial Planning (Directive 2014/89/EU), these maps serve to illustrate the spatial arrangement of existing activities or the distribution of vulnerable species and habitats that necessitate avoidance during the allocation of marine uses. Furthermore, maps can also delineate optimal locations for the development of specific sectors based on different parameters.

2. Objectives

The main objective of the present deliverable is the identification and the characterization of suitable areas for the development of wave energy projects in the context of Maritime Spatial Planning in the European Atlantic region (Spain, Portugal, France and Ireland), by using a model developed in task 6.2 (Galparsoro *et al.*, 2022) and implemented in the VAPEM tool (https://aztidata.es/vapem/) for map production.

3. Suitability maps production

The identification of suitable areas for the development of wave energy projects was made by developing a model for the identification of suitable areas for the development of wave energy projects. The model was developed under Task 6.2 *Development of a model for the identification of suitable areas for the development of wave energy projects in the European Atlantic region in the context of maritime spatial planning and its implementation into a Decision Support Tool* (Galparsoro *et al.*, 2022). The scope of such task was the development of a model and a decision support tool for the identification of the most suitable areas for the development and deploying of wave energy projects in European Atlantic region.

The developed model was based on a previous work by Galparsoro *et al.* (2021b), but a number of improvements were applied. The geographical scope of the model was extended to the European eastern Atlantic region, including the Exclusive Economic Zones (EEZ) of Portugal, Spain, France, and Ireland, accounting for a total area of 3,136,073 km^2. The suitable areas for installing WECs was limited to a range of depths between 25 m and 200 m. Areas deeper than 200 m were excluded from the analyses due to the high economic cost of installing at such depths, reducing the study area to 344,539 km^2. The seafloor slope and type were considered as factors conditioning the technical suitability, together with the distance from each production location of the nearest electricity substation onshore.

The original model by Galparsoro *et al.* (2021b), was modified by including wave energy power production based on the Capacity Factor provided by CorPower, and the consideration of the number of operational weather windows (OWW) during a year. OWW was calculated for periods where significant wave height (Hs) lower or equal to 2.5 m. The OWW was calculated using Equation 1.

$$OWW = \left(\frac{Distance\ to\ port}{Outbound\ speed} + \frac{Distance\ to\ port}{Return\ speed} + \text{Contingency time} + \text{Maintenance work time}\right), (1)$$

Where *distance to port* is the mean distance from each cell of the analysis grid to the nearest port in km. The used *outbound speed* was 13 km/h, and the *return speed* was 5.6 km/h, to consider the lower navigation speed of the vessel when towing the WEC.

The adopted *contingency time* was 6 h and *maintenance work* time 2 h. Finally, the formula was applied spatially using the distance to port of each cell in the analysis grid.

Finally, the suitability classification criteria for each of the three dimensions considered (i.e. technical, environmental and conflicts with other uses), as well as for the integrated suitability, was adopted from Maldonado *et al.* (2022)

The nodes corresponding to technical factors (see Galparsoro *et al.* (2022) for model structure and description), were classified as "High", "Medium", "Low" or "Negligible" based on their relative importance when assessing the total technical suitability. Among the technical factors, the seafloor type, number of operational weather windows and wave power production, were considered as the most relevant ones. And finally, the distance to electrical substation onshore for produced energy evacuation, was adopted as the last factor that module the suitability between "High"-"Medium" and "Low"-"Negligible".

The ecological risk assessment was based on Galparsoro *et al.* (2021a). The model considers the potential pressures produced by the WECs, the spatial location of the installation, the ecosystem components present in the location and the sensitivity of the ecosystem components to the pressures. The ecological risk derived from each pressure to each ecosystem component was defined. Finally, the total ecological risk was assessed by integrating each individual ecological risk. The integrated ecological risk adopted the classes of "High", "Medium", "Low" or "Negligible".

The potential conflicts between WECs farms and other existing infrastructures and uses was considered according to the interaction between them. These were classified as being "Excluding" activities when it was considered that there is no compatibility between both activities (e.g., underwater cables and WECs); "Limiting" activities when potential conflicts could raise (e.g., fishing activity and WECs); or "None", when there is not any infrastructure or activity in the assessed location.

The integrated suitability was classified according to the combination of the three aforementioned factor classes (i.e., technical, environmental and conflict with other uses). A site was classified as being "Highly suitable" when the technical suitability was "High", the ecological risk was "Negligible", and there is no other overlapping marine activity. In turn, a specific location was considered to be "Suitable", when ecological risk is "Negligible" or "Low", the technical suitability is "Medium" or "High", and the conflict with other uses is “Limiting” or “None”. The integrated suitability adopts other classes according to other ecological, technical and/or conflict restrictions.

The spatial data to feed the model were obtained from different publicly available datasets (see Galparsoro *et al.* (2021c) for detailed list of collated and used information layers).

Once the model was fed and operational, it was implemented into a web-based decision support tool called VAPEM (https://aztidata.es/vapem/) which was previously described by Galparsoro *et al*. (2020).

Figure 1. VAPEM tool landing page. The user has the possibility to select different models to run depending on six different marine sectors (https://aztidata.es/vapem/)

The user has the possibility to navigate and explore the different models in a visual interface. First, it is necessary to select the model, and then the specific scenario to run it. Once it runs, the user can visualise the results in the map viewer tab. In the case of the integrated wave energy suitability model, when the current status scenario is selected, the map is provided at 1 km^2 resolution, considering that it is enough for a first area identification. This map can be explored by users moving around and by zoom for a detailed view of results and gives the option to measure distance and areas for own calculations. The cursor in the map shows the geographical coordinates while it moves and by clicking on specific point, it provides the relevant information of that location.

The user can also customize the appearance of the map and download it as a georeferenced raster in Geo TIFF format. This allows the user to process and analyse layers in desktop GIS software.

Due to computational load required by the models, the study area has been divided by countries to speed up the running time of models.

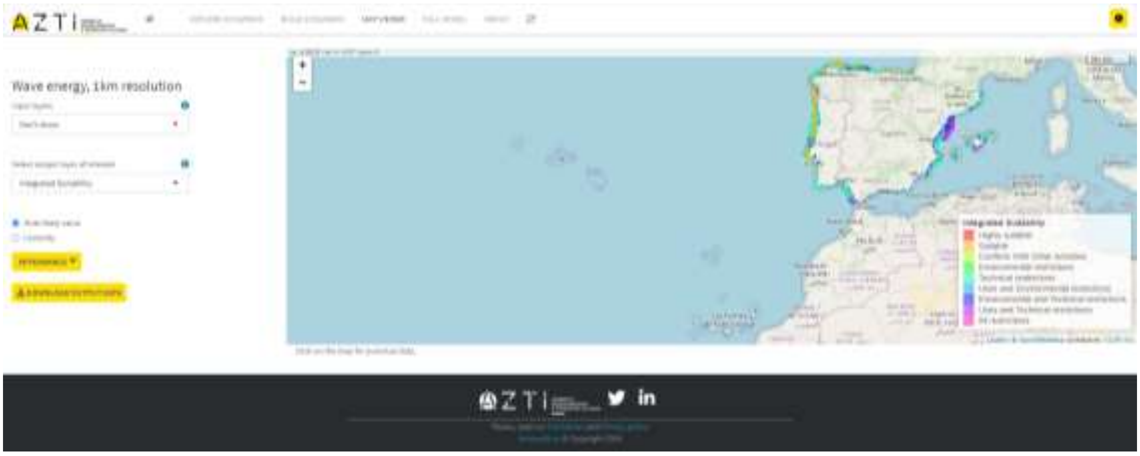

Figure 2. VAPEM tool's map viewer tab. The user can navigate and explore the different models or scenarios. Also, it is possible to change the appearance and download the layers plotted in the map as Geo TIFF. Screenshot obtained from VAPEM tool (https://aztidata.es/vapem/).

4. Mapping suitable areas for developing wave energy projects

A total of 34 maps representing the spatial distribution of the three different dimensions directly related to the suitability of wave energy projects (technical suitability, environmental risk, and conflicts with other activities) and the final integrated suitability have been produced. The maps are limited to the extension of the EEZs of Spain, Portugal, France, and Ireland, with less than 200 m depth, which in turn have been divided into eight sectors for the map production: three in Spain (north, south-west, and Canary Islands), three in Portugal (mainland, Azores, and Madeira), France, and Ireland.

4.1. Suitability level distribution based on technical factors

The spatial distribution of highly, moderate, low and negligible areas according to technical factors for CorPower´s offshore oscillating water column point absorber device is shown from Figure 3 to Figure 10.

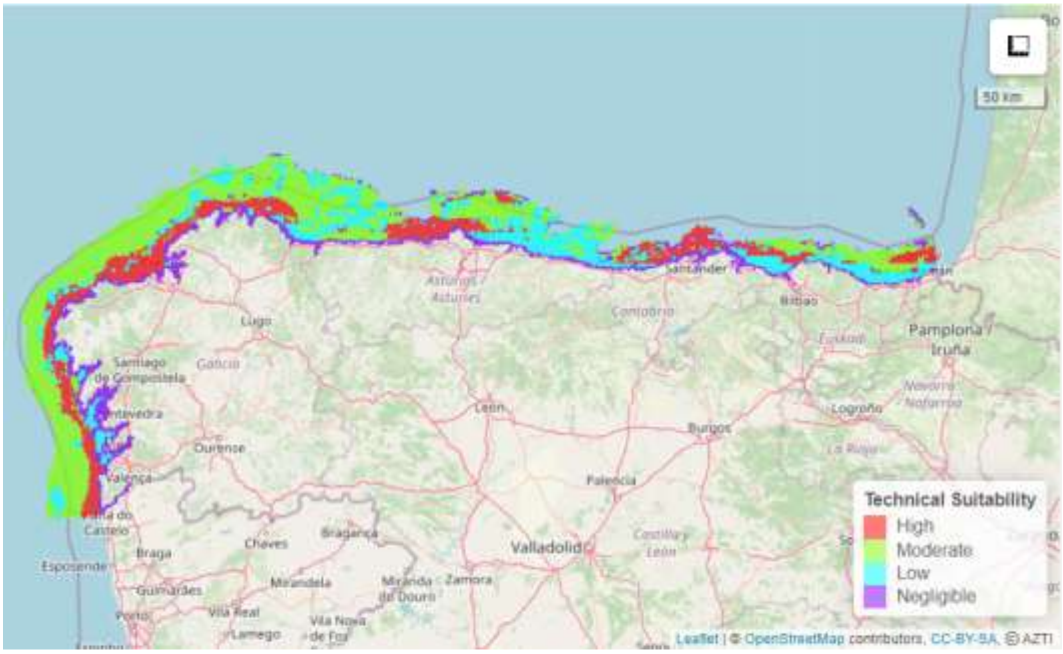

Figure 3. Spatial distribution in the northern Spain of suitability levels, based on technical factors, for developing wave energy projects.

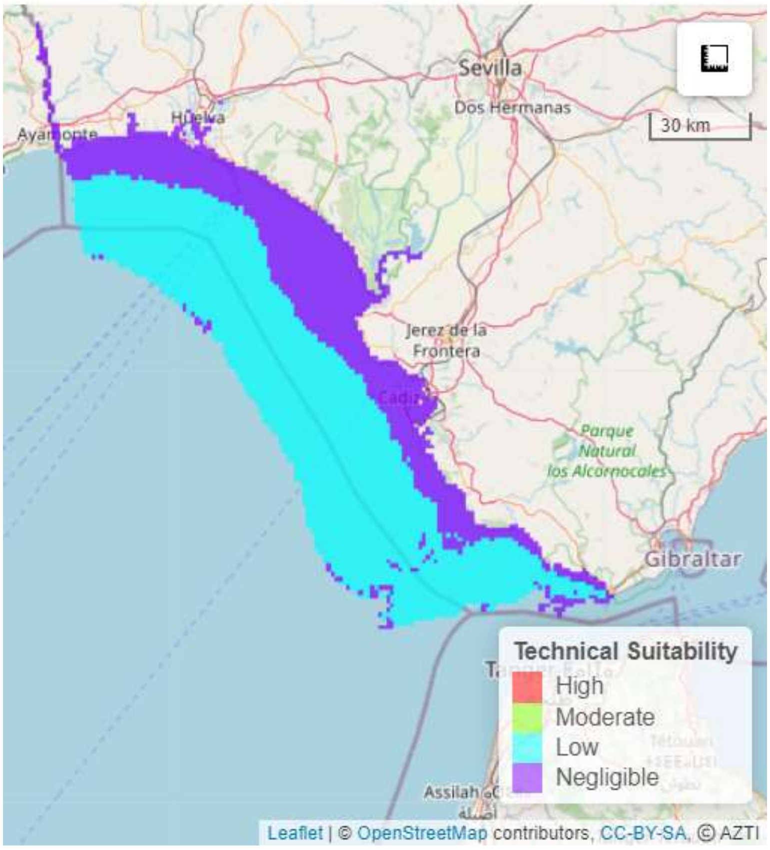

Figure 4. Spatial distribution in the southwestern Spain of suitability levels, based on technical factors, for developing wave energy projects.

Figure 5. Spatial distribution in the Canary archipelago (Spain) of suitability levels, based on technical factors, for developing wave energy projects.

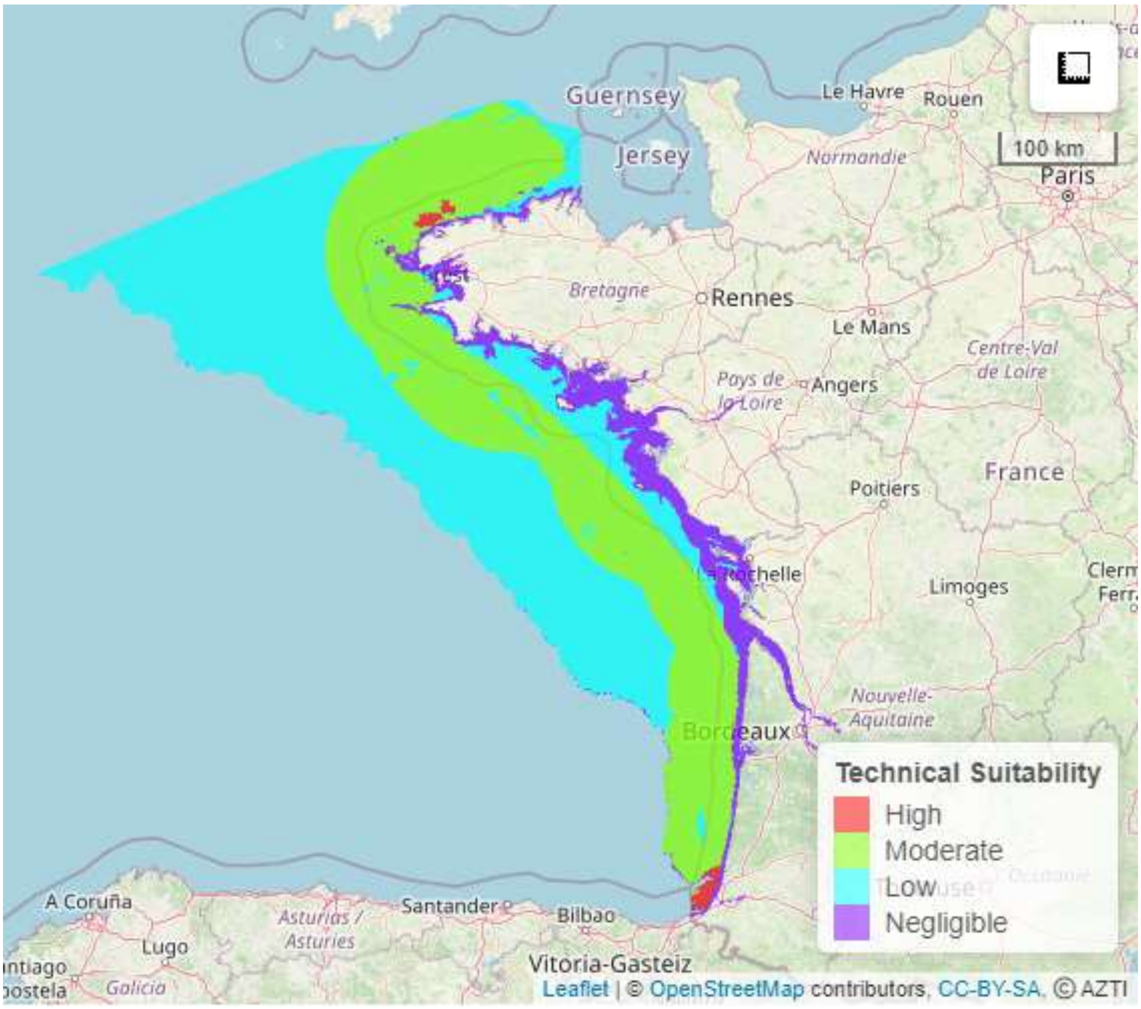

Figure 6. Spatial distribution in the French Atlantic coast of suitability levels, based on technical factors, for developing wave energy projects.

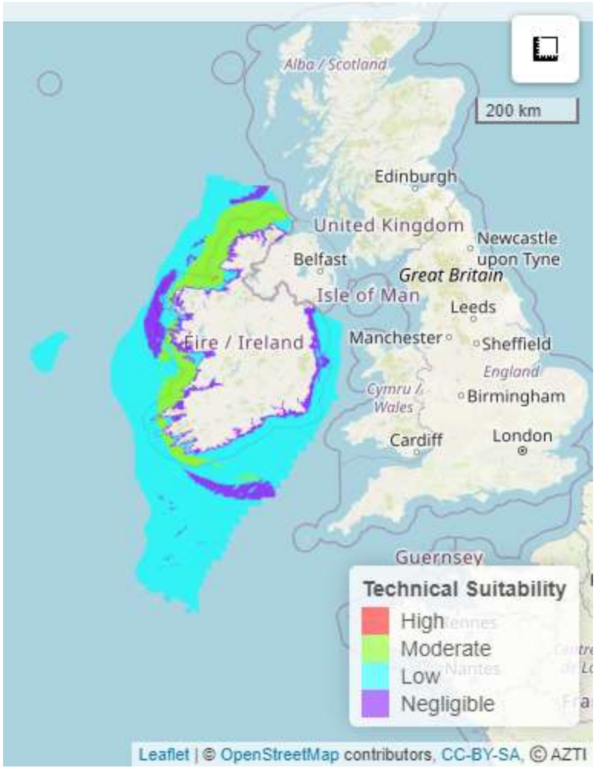

Figure 7. Spatial distribution in Ireland of suitability levels, based on technical factors, for developing wave energy projects.

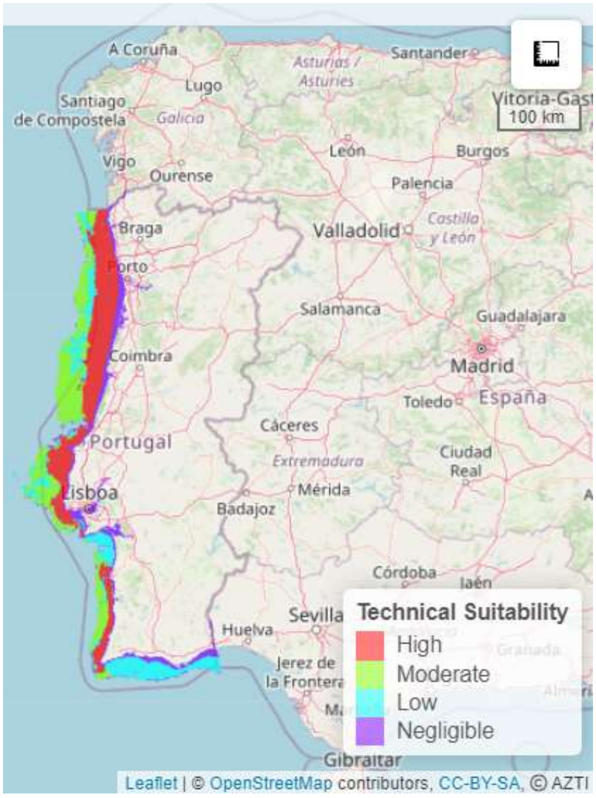

Figure 8. Spatial distribution in Portugal (mainland) of suitability levels, based on technical factors, for developing wave energy projects.

Figure 9. Spatial distribution in Azores of suitability levels, based on technical factors, for developing wave energy projects.

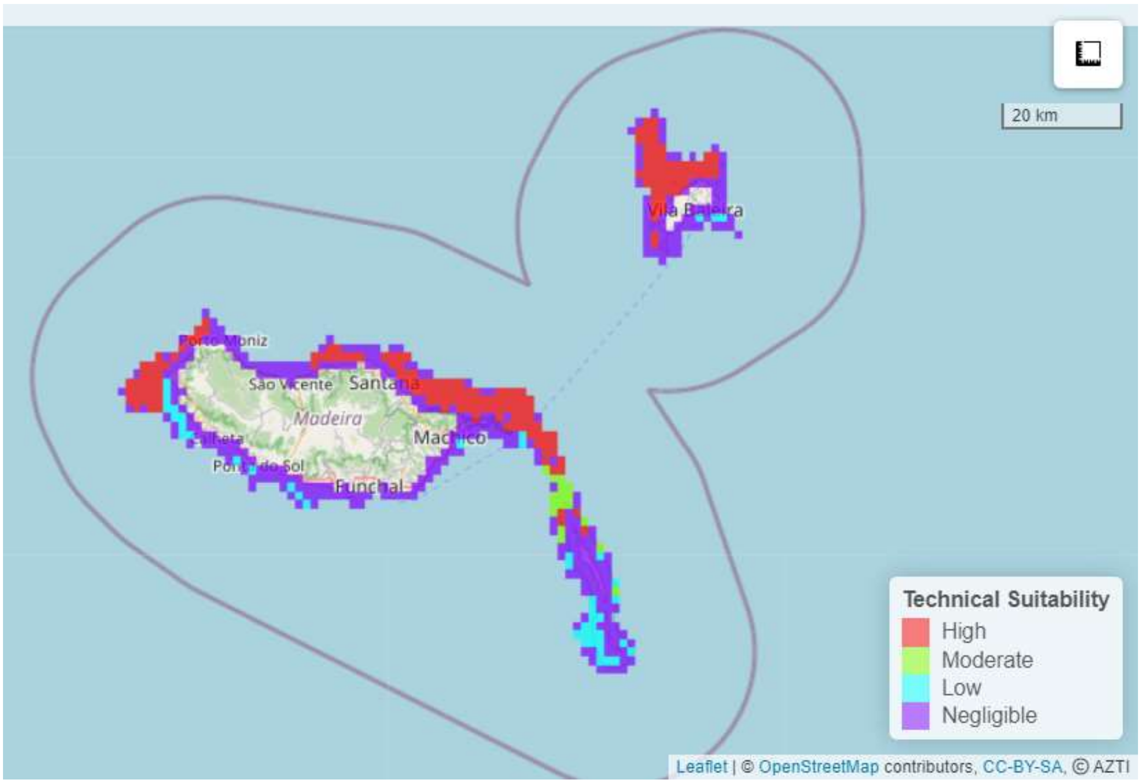

Figure 10. Spatial distribution in Madeira of suitability levels, based on technical factors, for developing wave energy projects.

Almost 40% of the area shows "Negligible" or "Low" suitability for the development of wave energy projects. The factors that pose highest restrictions are the depth (in this case limited to 30 to 200 m), the number of good weather windows for installing and maintenance operations of the wave farm, and the distance between the wave farm and the electric substation on land (due to construction costs). Nevertheless, almost 5% of the area shows high suitability, which corresponds to 16,000 km^2, while more than 55% of the area (more than 191,000 km^2) shows a moderate suitability in terms of technical factors for the development of new wave energy projects (Figure 11).

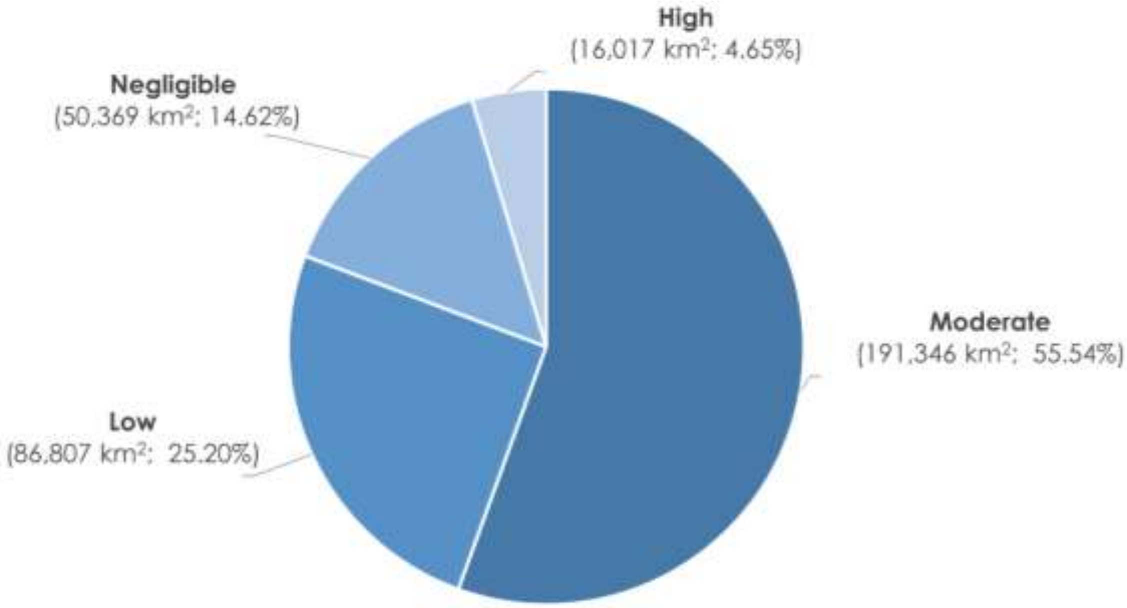

Figure 11. Percentage of European Atlantic sea space for different levels of suitability for developing wave energy projects according to technical factors.

4.2. Suitability level based on environmental risk assessment

The spatial distribution of the environmental risks related to wave energy projects is shown from Figure 12 to Figure 19. The environmental risk is classified into four levels: "High", "Moderate" and "Negligible" (no area has been as showing "Low" environmental risk to wave energy projects).

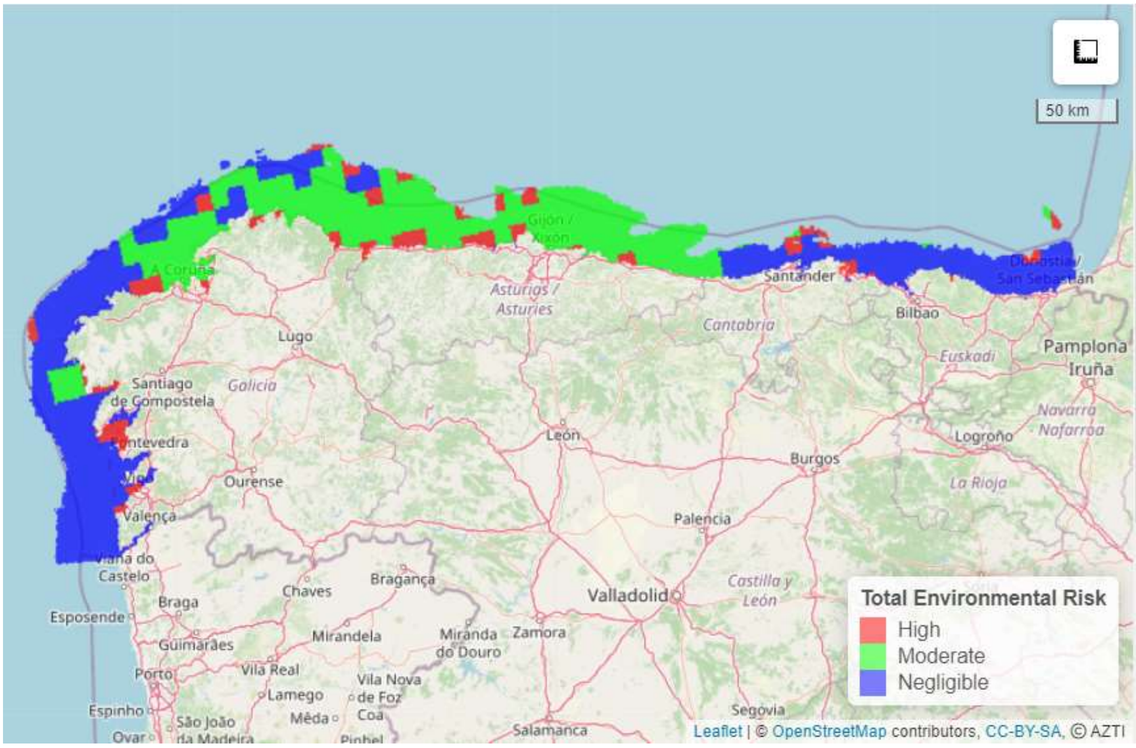

Figure 12. Spatial distribution in northern Spain of environmental risk linked to wave energy projects.

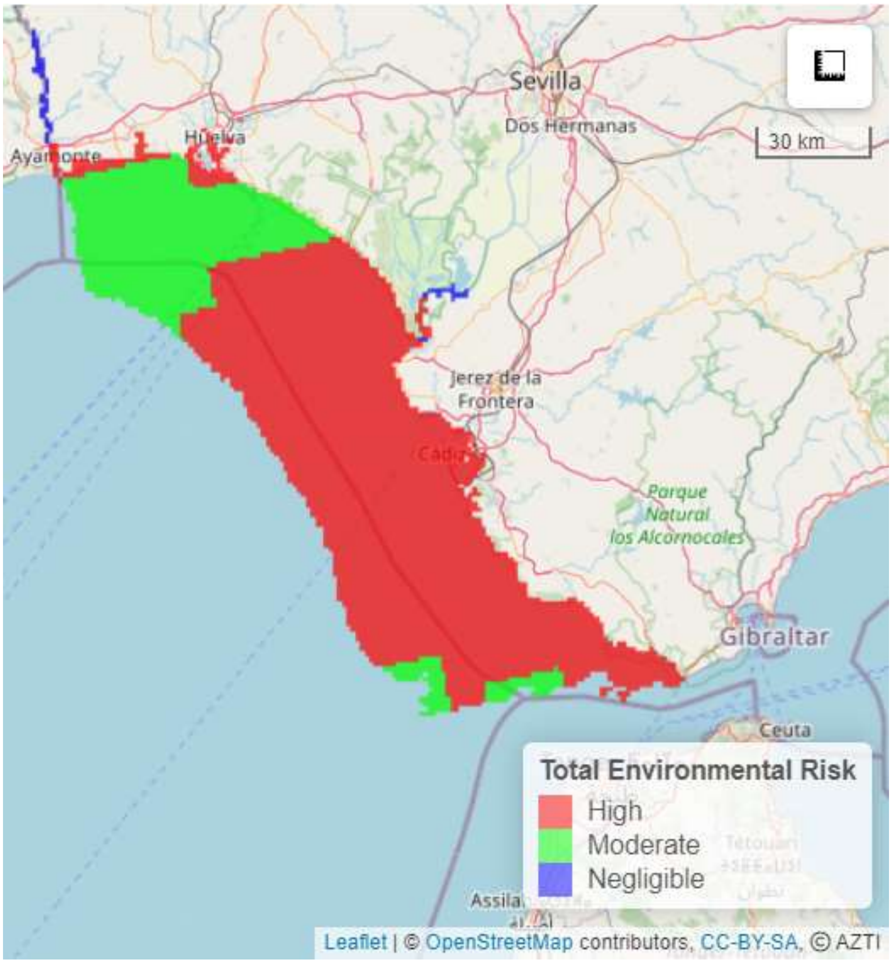

Figure 13. Spatial distribution in southwestern Spain of environmental risk linked to wave energy projects.

Figure 14. Spatial distribution in Canary archipelago (Spain) of environmental risk linked to wave energy projects.

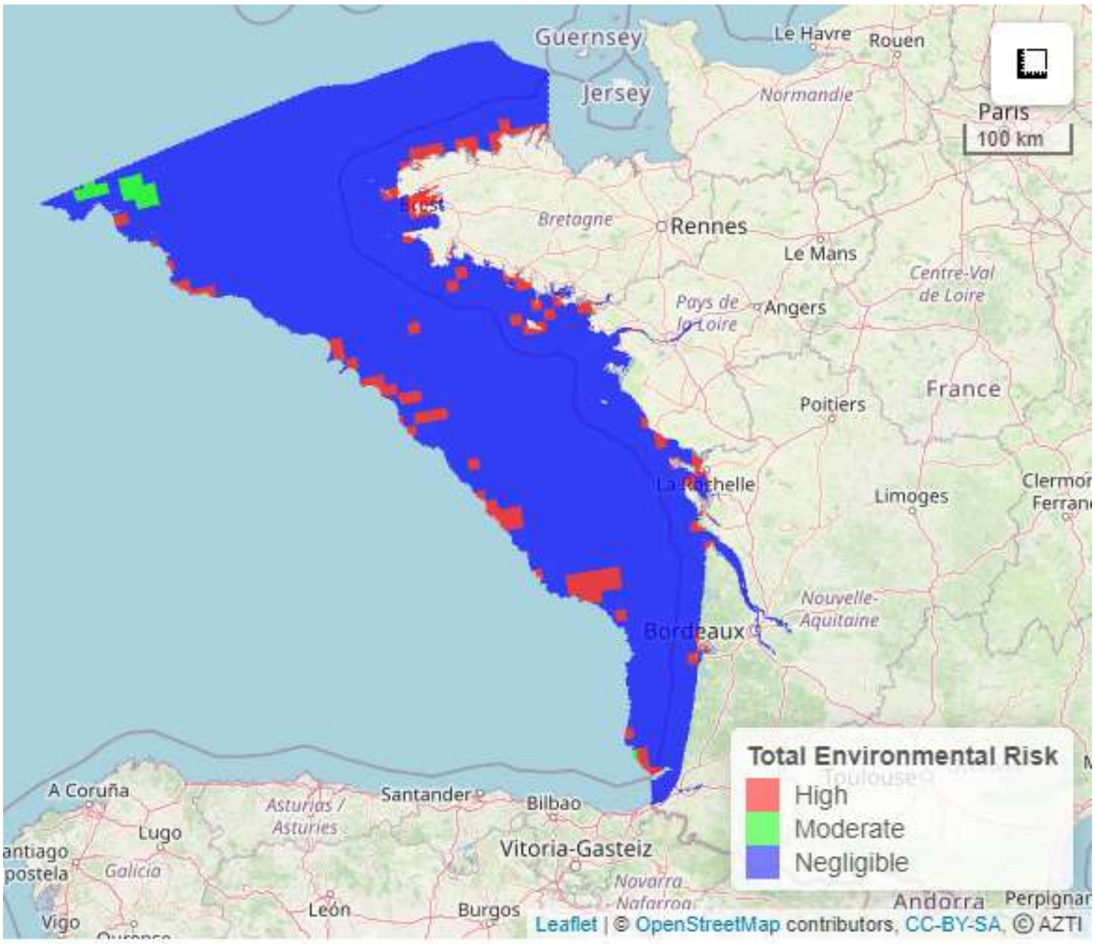

Figure 15. Spatial distribution in the French Atlantic coast of environmental risk linked to wave energy projects.

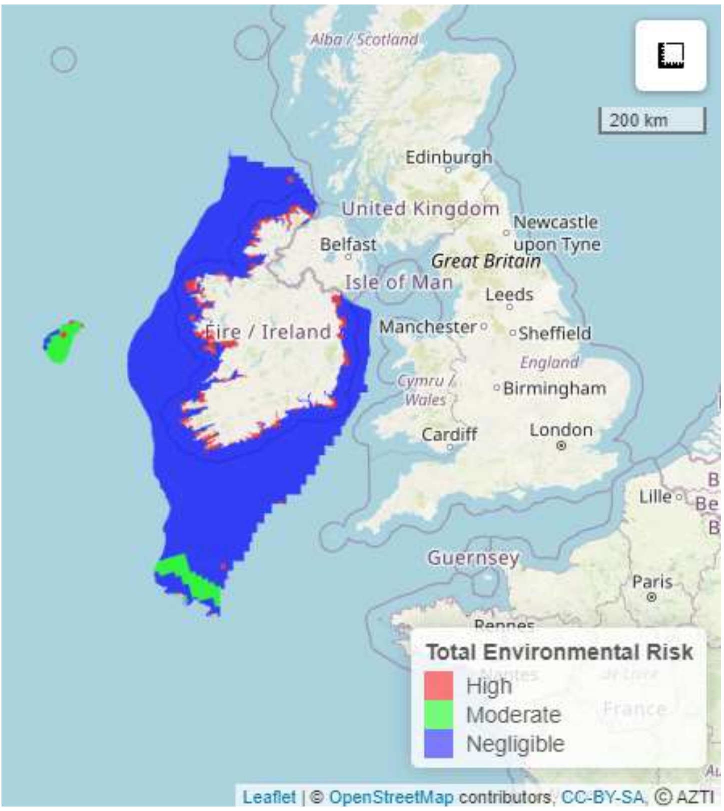

Figure 16. Spatial distribution in Ireland of environmental risk linked to wave energy projects.

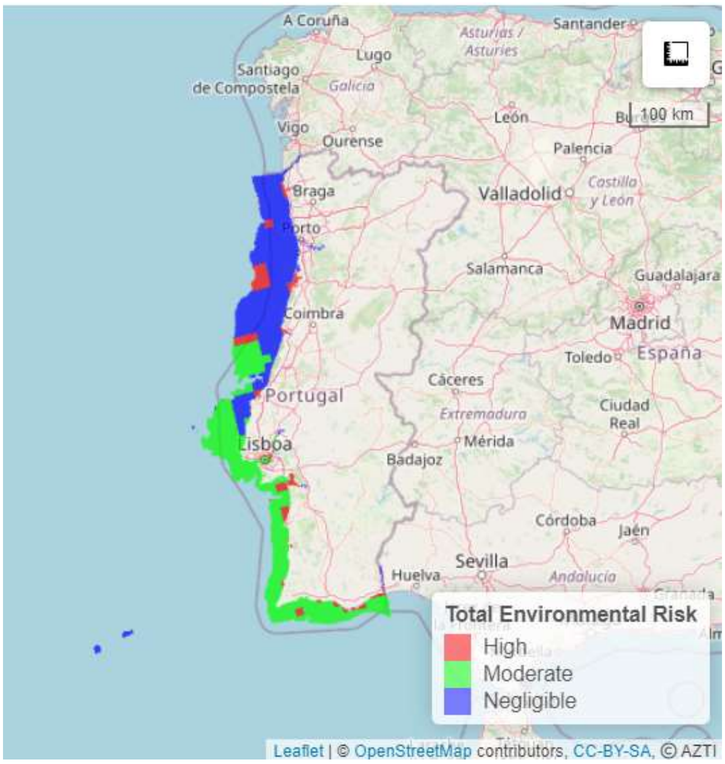

Figure 17. Spatial distribution in Portugal (mainland) of environmental risk linked to wave energy projects.

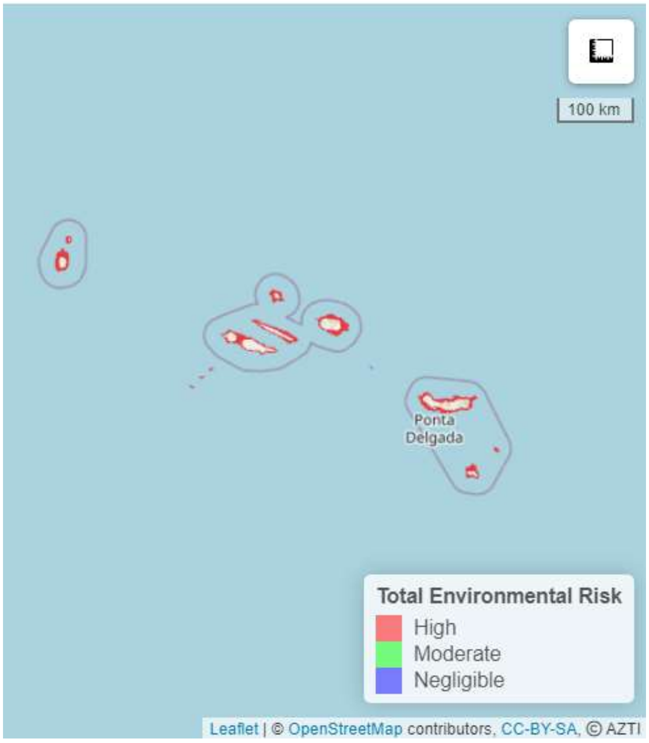

Figure 18. Spatial distribution in Azores (Portugal) of environmental risk linked to wave energy projects.

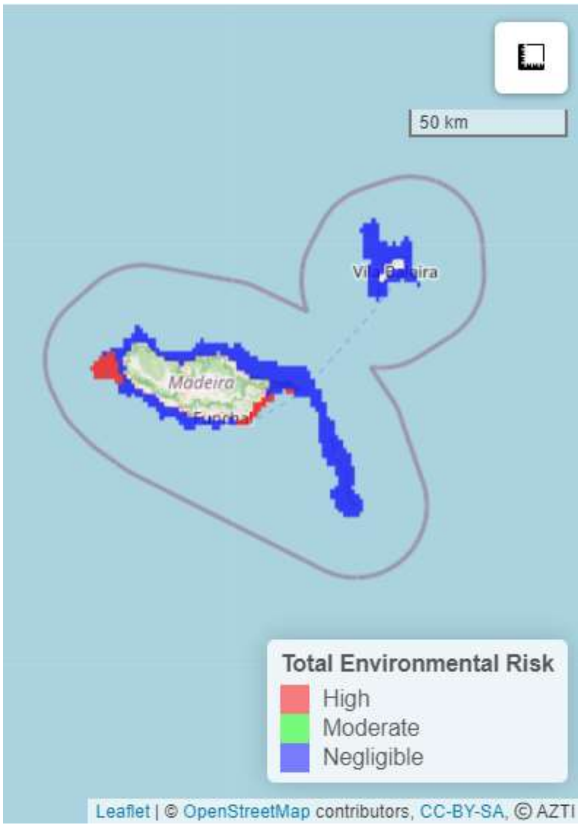

Figure 19. Spatial distribution in Madeira (Portugal) of environmental risk linked to wave energy projects.

Total environmental risk linked to wave energy projects could be considered as being "Negligible" in 80% of the total area, while 10% of the area shows moderate risk and 9% is showing "High" potential environmental risk (Figure 20). This may seem that environmental risk is not a limitation for the development of wave energy projects according to existing information and knowledge of the potential ecological risks of wave energy converters (Galparsoro *et al.*, 2021a), and the publicly available information on the spatial distribution of the ecosystem components showing highest sensitivity to pressures produced by wave energy converters. Nevertheless, special attention should be put on those areas showing high environmental risk potential and, in those regions, showing moderate environmental risk potential according to precautionary principle.

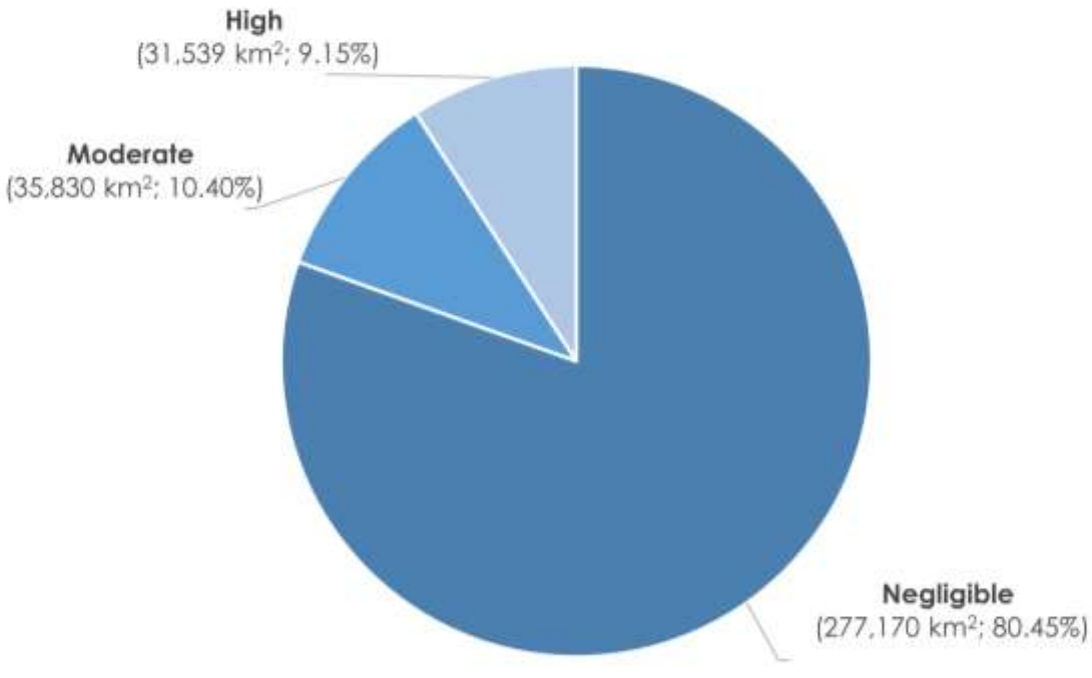

Figure 20. Percentage of European Atlantic sea space showing different levels of environmental risk to wave energy projects.

4.3. Suitability level based on conflicts with other activities and uses

The spatial distribution of excluding and limiting activities are shown in Figure 21 to Figure 28. The activities or uses are classified as "Excluding" or "Limiting", and areas with no or no significant presence of this activities are classified as "None".

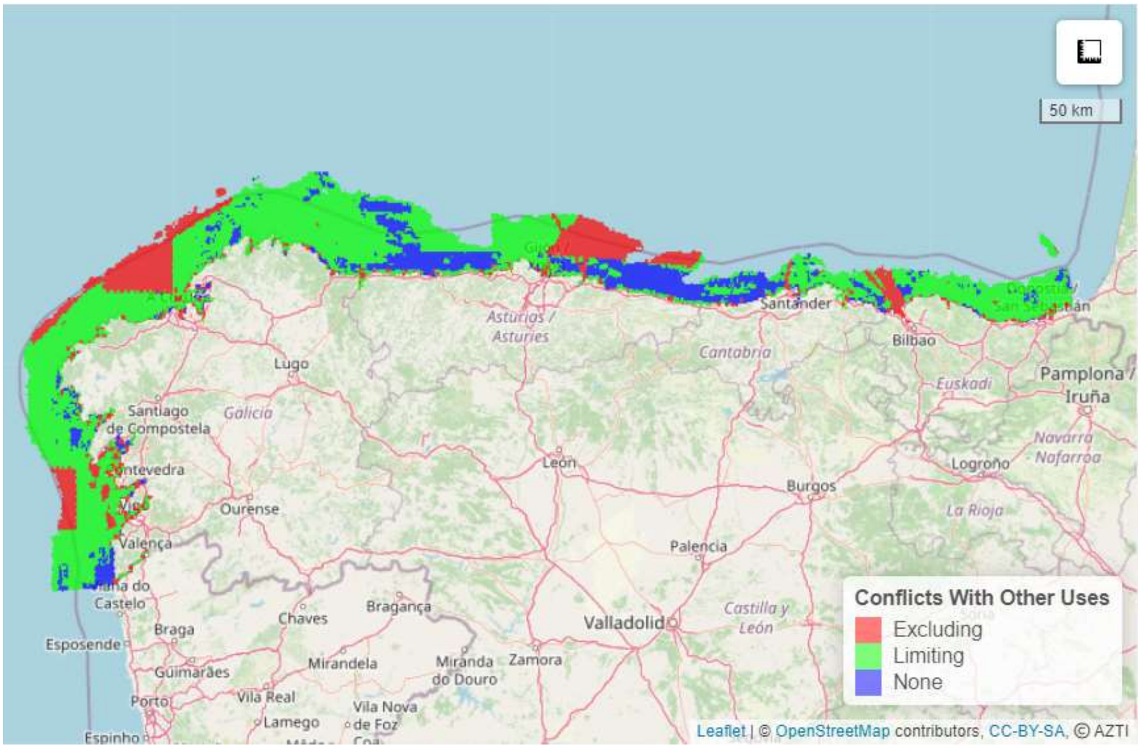

Figure 21. Spatial distribution in northern Spain of conflicting activities with ocean energy projects.

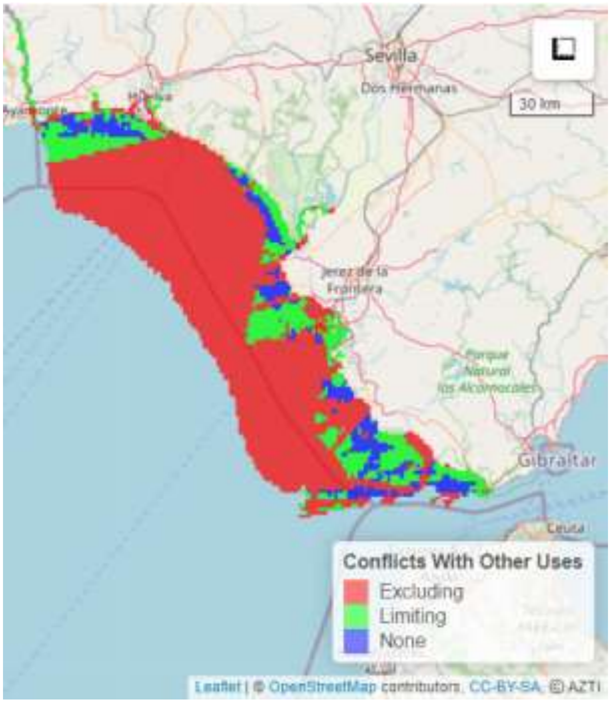

Figure 22. Spatial distribution in southwestern Spain of conflicting activities with ocean energy projects.

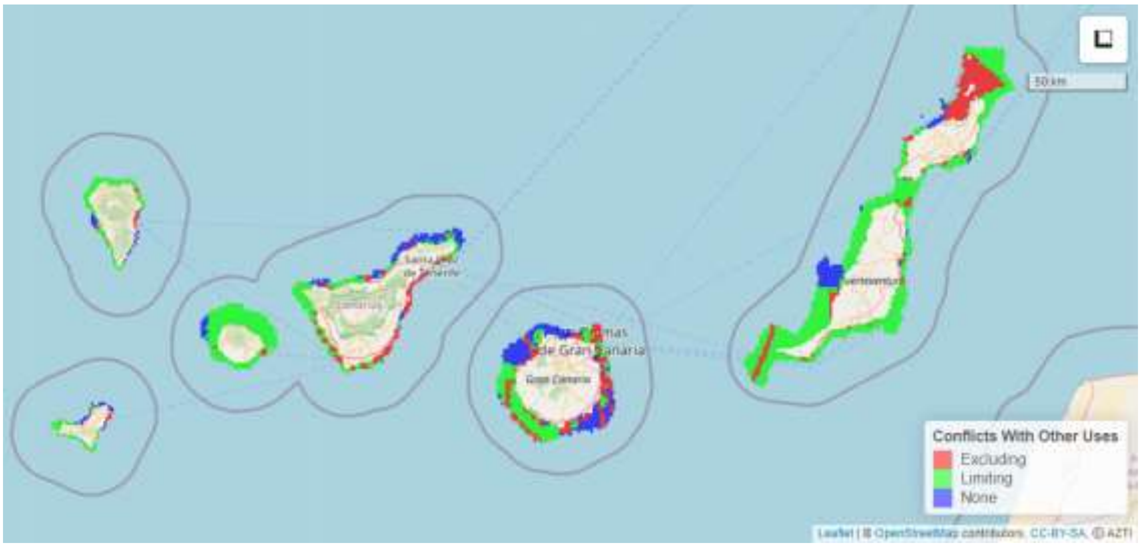

Figure 23. Spatial distribution in Canary archipelago (Spain) of conflicting activities with ocean energy projects.

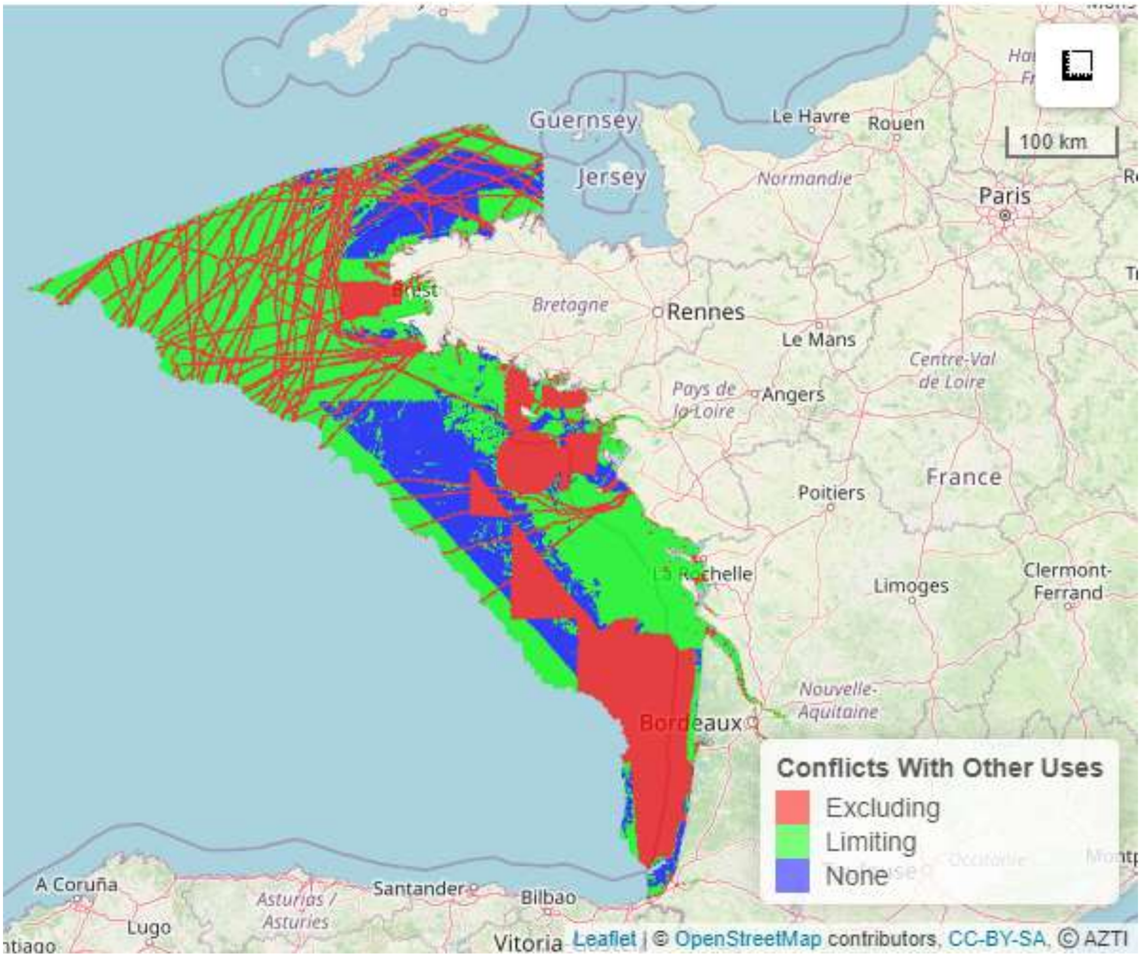

Figure 24. Spatial distribution in French Atlantic of conflicting activities with ocean energy projects.

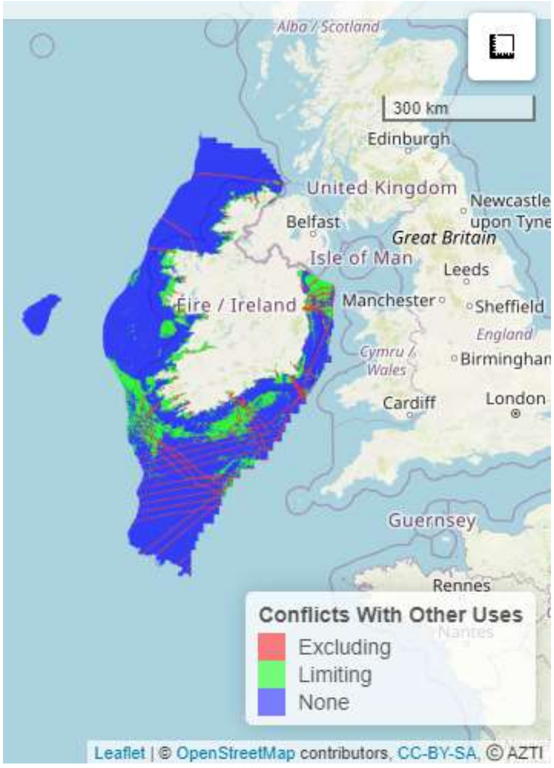

Figure 25. Spatial distribution in Ireland of conflicting activities with ocean energy projects.

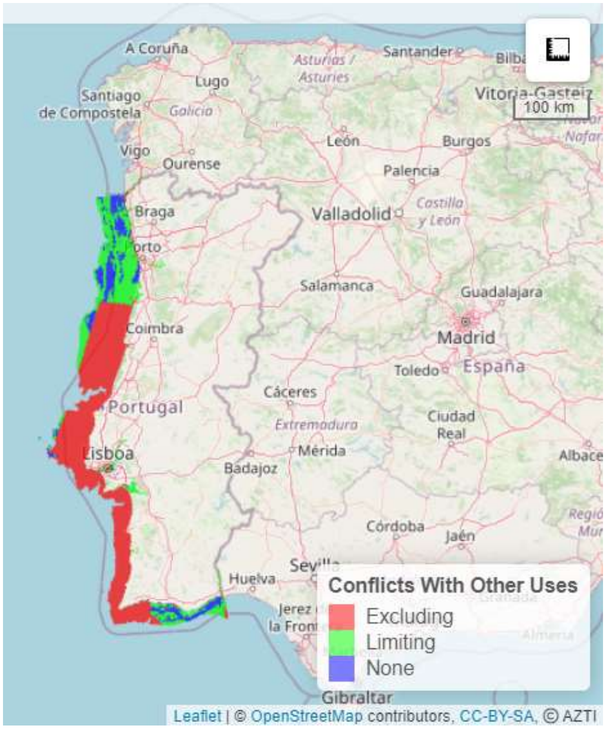

Figure 26. Spatial distribution in Portugal (mainland) of conflicting activities with ocean energy projects.

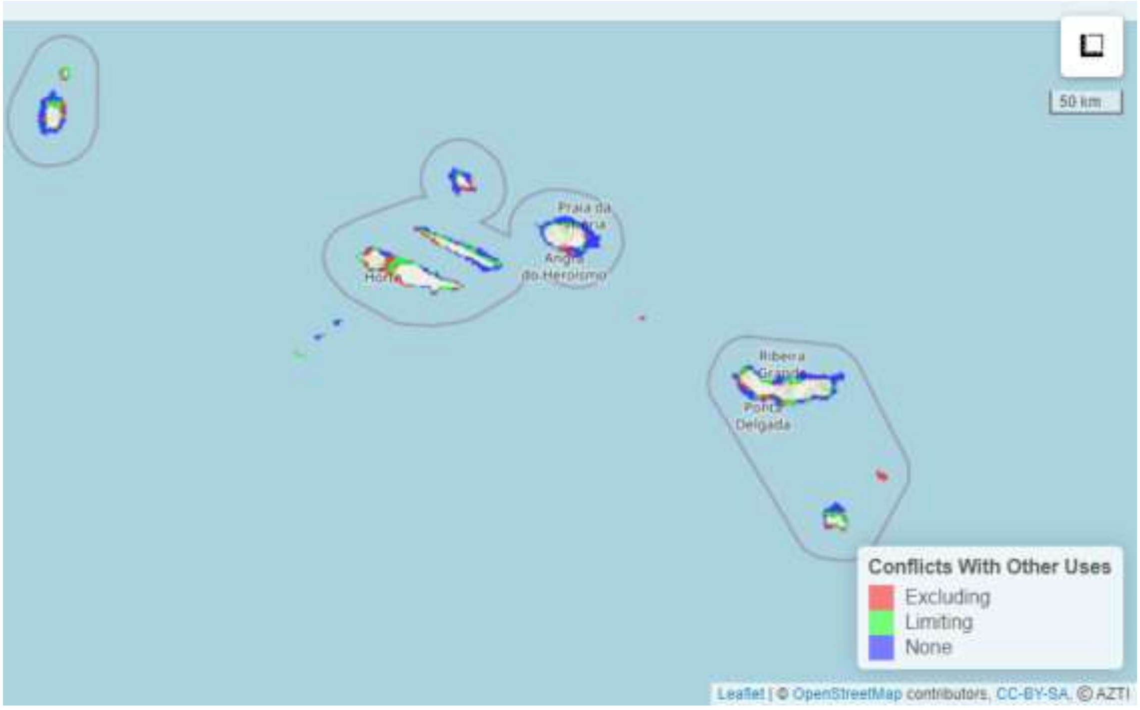

Figure 27. Spatial distribution in Azores (Portugal) of conflicting activities with ocean energy projects.

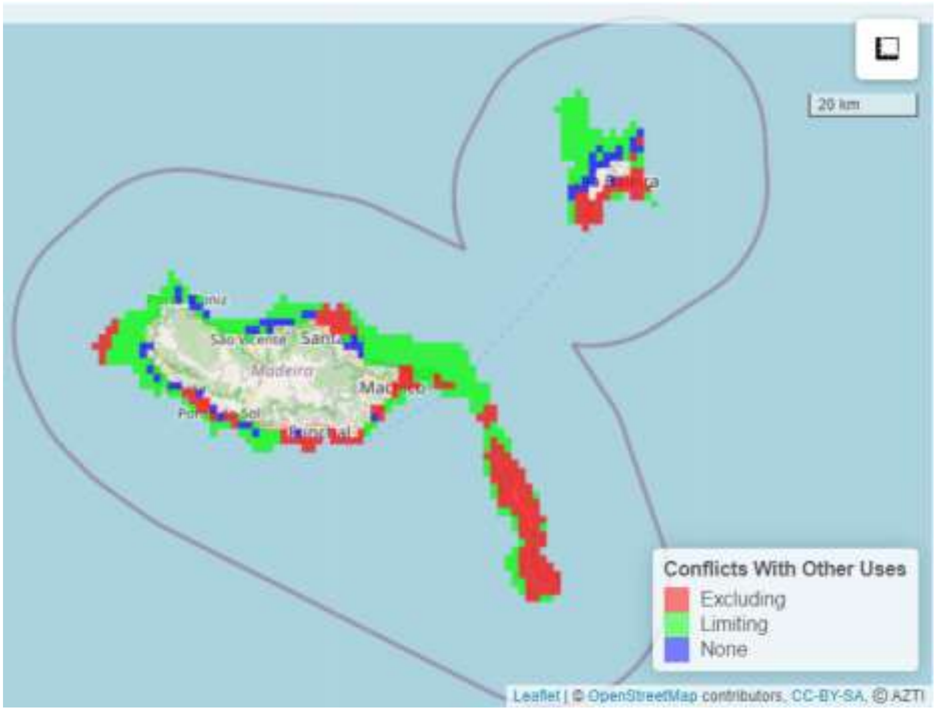

Figure 28. Spatial distribution in Madeira (Portugal) of conflicting activities with ocean energy projects.

More than 25% of the area is not compatible with the development of wave energy projects due to the presence of "Excluding" maritime activities (e.g. military areas) or infrastructures (e.g. underwater cables), while 31% of the area shows certain degree of conflicts with other existing activities considered as "Limiting" (Figure 29). That does not mean that wave energy farms could not be constructed in those "Limiting" areas, but it raises that there are existing activities that should be considered and analysed in detail in case a wave farm is going to be constructed. A clear example of such conflicting and limiting factor is the fishing activity.

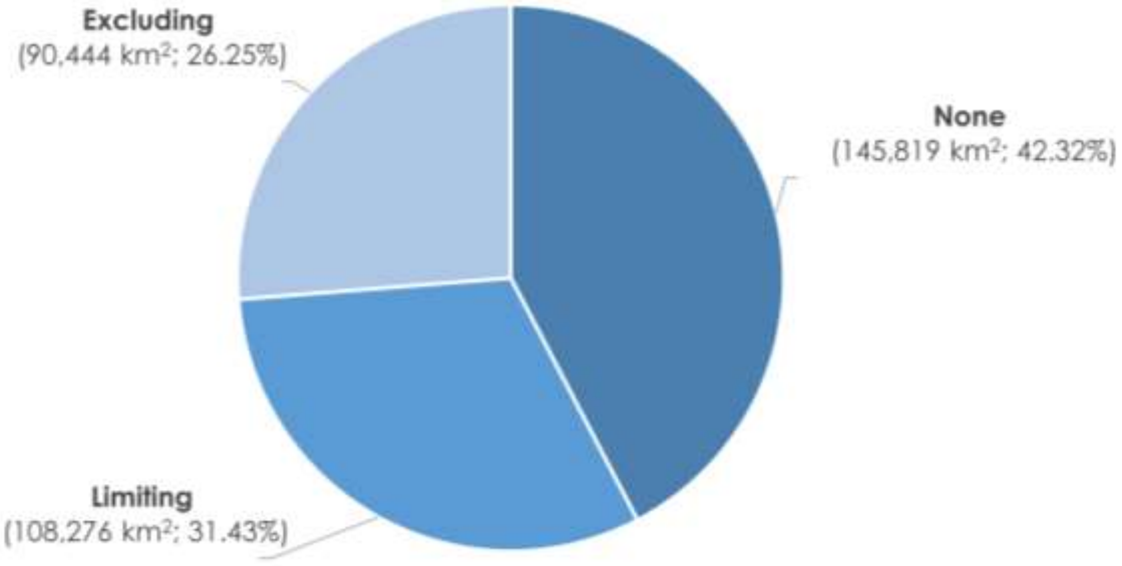

Figure 29. Percentage of European Atlantic sea space showing conflicts of wave energy projects with existing maritime activities and infrastructures.

4.4. Integrated assessment of suitable areas for developing wave energy projects

An integrated suitability assessment was performed for identifying most suitable areas for the development of wave energy projects and the identification of main constraints according to technical, environmental, and due to conflicts with existing activities and infrastructures. The resulting maps are shown from Figure 30 to Figure 37.

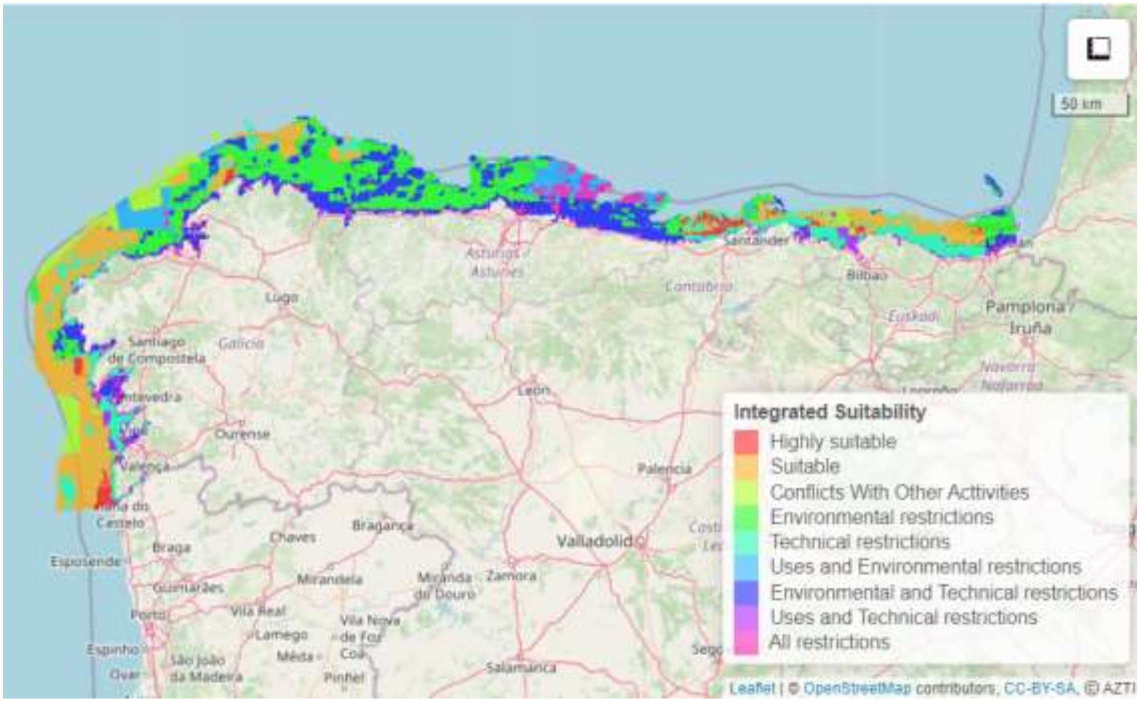

Figure 30. Geographical distribution in northern Spain of the suitability levels for the development of wave energy projects and main restrictions.

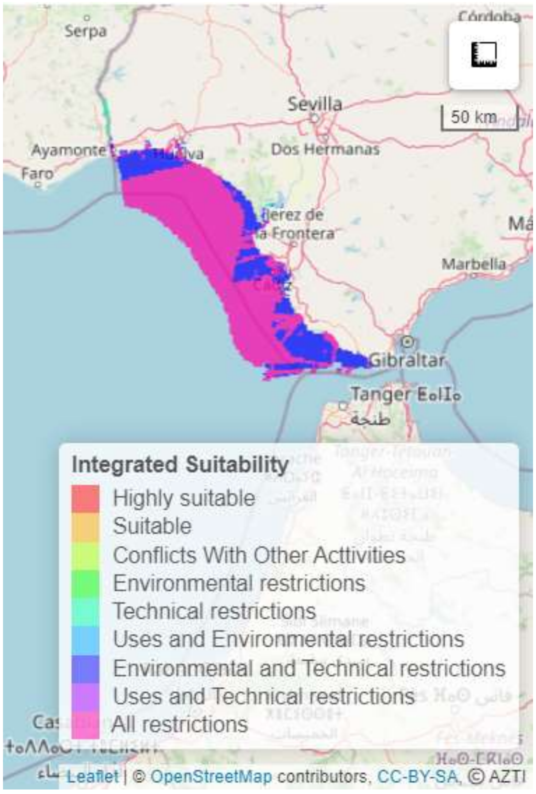

Figure 31. Geographical distribution in southwestern Spain of the suitability levels for the development of wave energy projects and main restrictions.

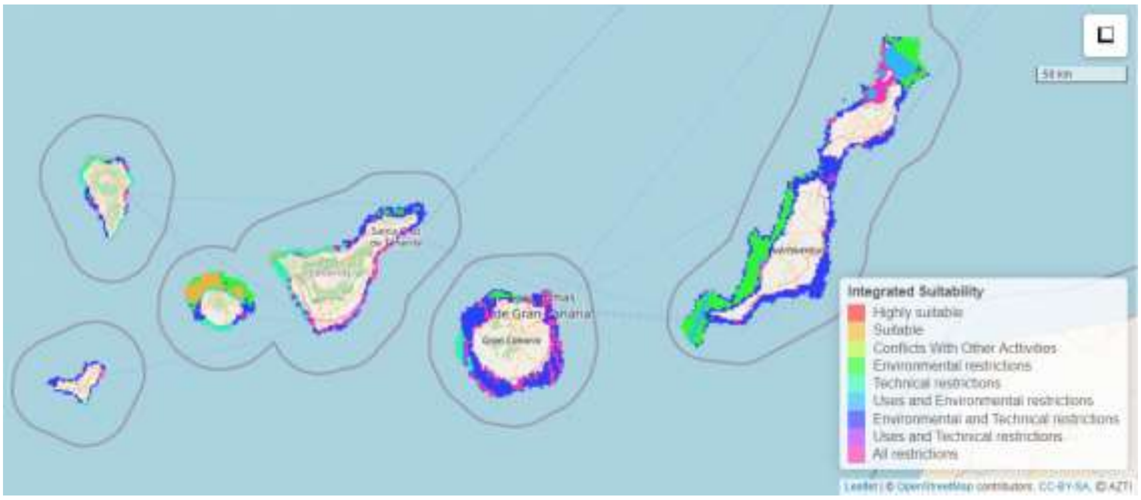

Figure 32. Geographical distribution in Canary archipelago (Spain) of the suitability levels for the development of wave energy projects and main restrictions.

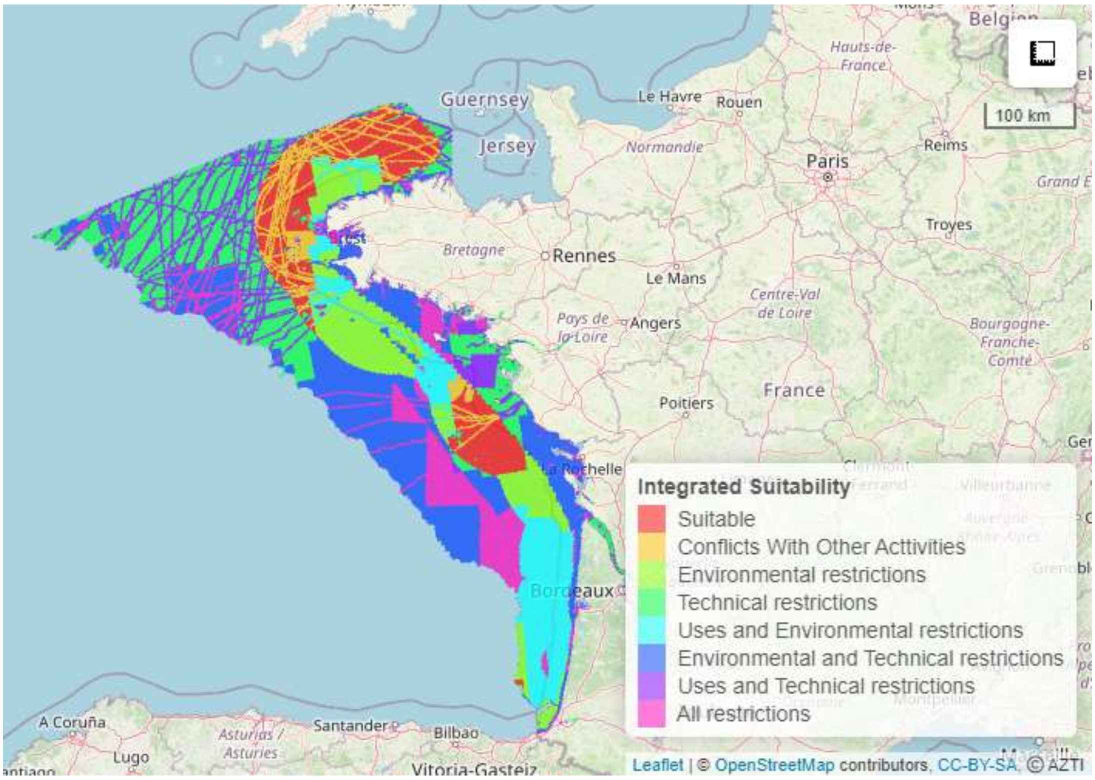

Figure 33. Geographical distribution in French Atlantic region of the suitability levels for the development of wave energy projects and main restrictions.

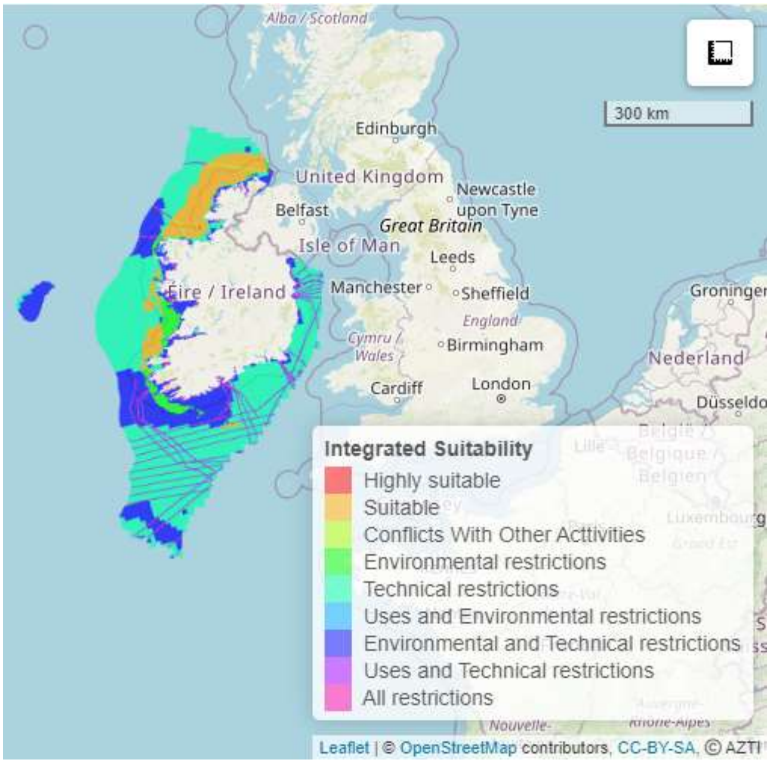

Figure 34. Geographical distribution in Ireland of the suitability levels for the development of wave energy projects and main restrictions.

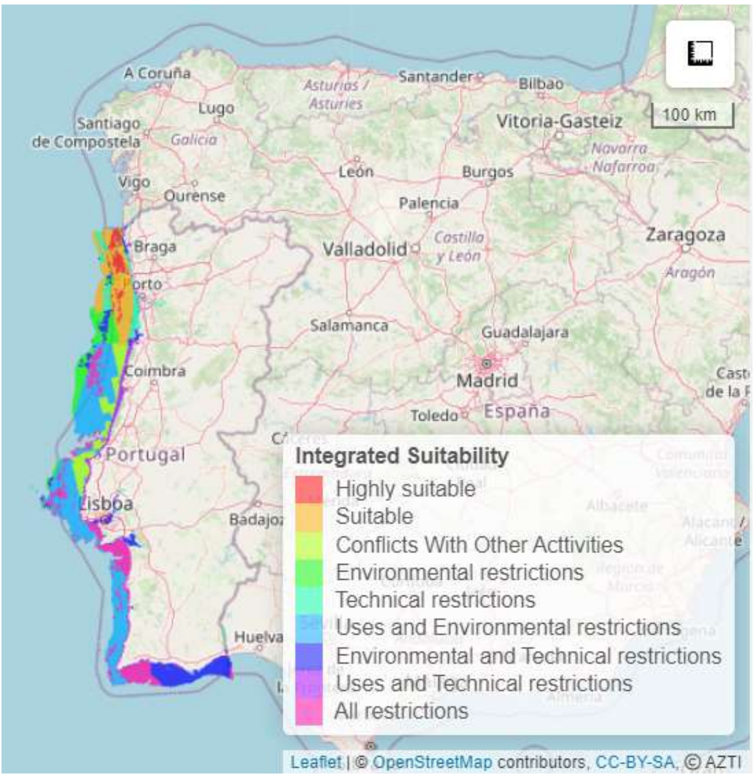

Figure 35. Geographical distribution in Portugal (mainland) of the suitability levels for the development of wave energy projects and main restrictions I.

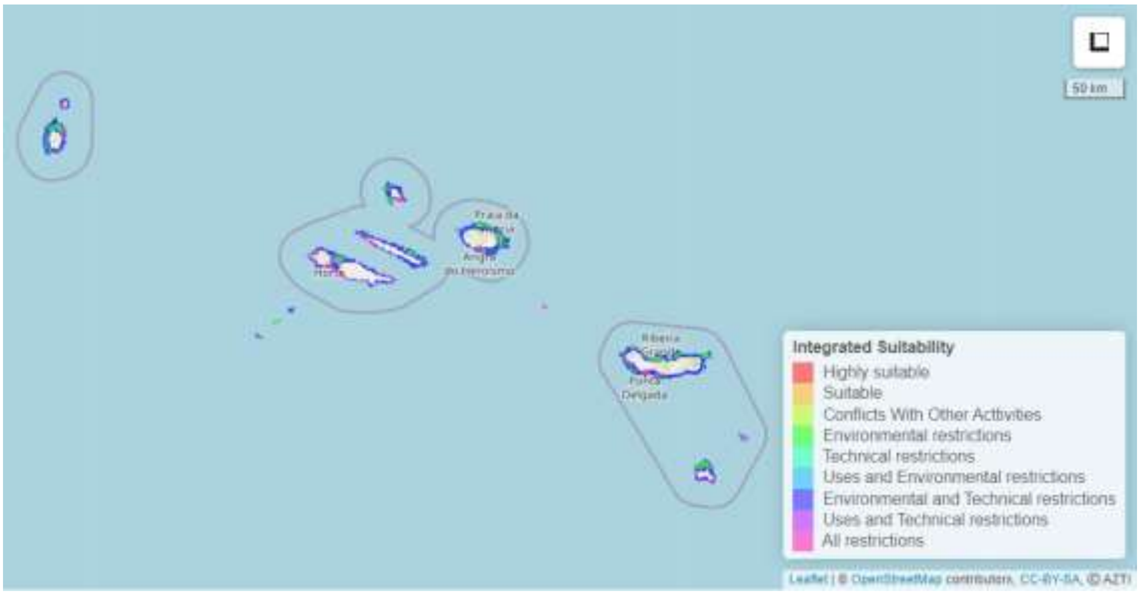

Figure 36. Geographical distribution in Azores (Portugal) of the suitability levels for the development of wave energy projects and main restrictions.

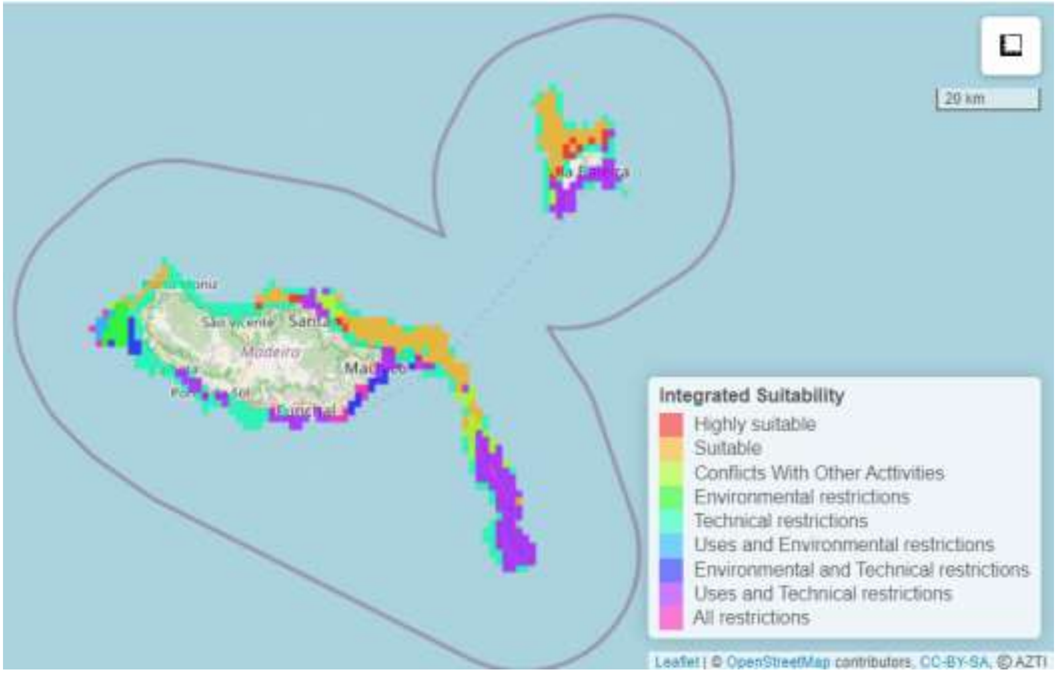

Figure 37. Geographical distribution in Madeira (Portugal) of the suitability levels for the development of wave energy projects and main restrictions.

Almost 11% of the study area has been designed as suitable for wave energy projects, of which 0.41% is considered as highly suitable. This percentage represents 37,661 km^2 of suitable and highly suitable areas in for the development of offshore wave energy projects (Figure 38).

According to this, the technical factors are the most restrictive ones when assessing the spatial suitability. 32.5% of the study area is considered unsuitable due to technical factors, 21.9% because of environmental and technical unsuitability, 7% on account of technical unsuitability and conflicts with activities, and in 8.7% of the area classified as all restrictions, the ecological risk is “High” or “Medium”, the technical suitability “Low” or “Negligible”, and there is presence of excluding activities (Figure 38).

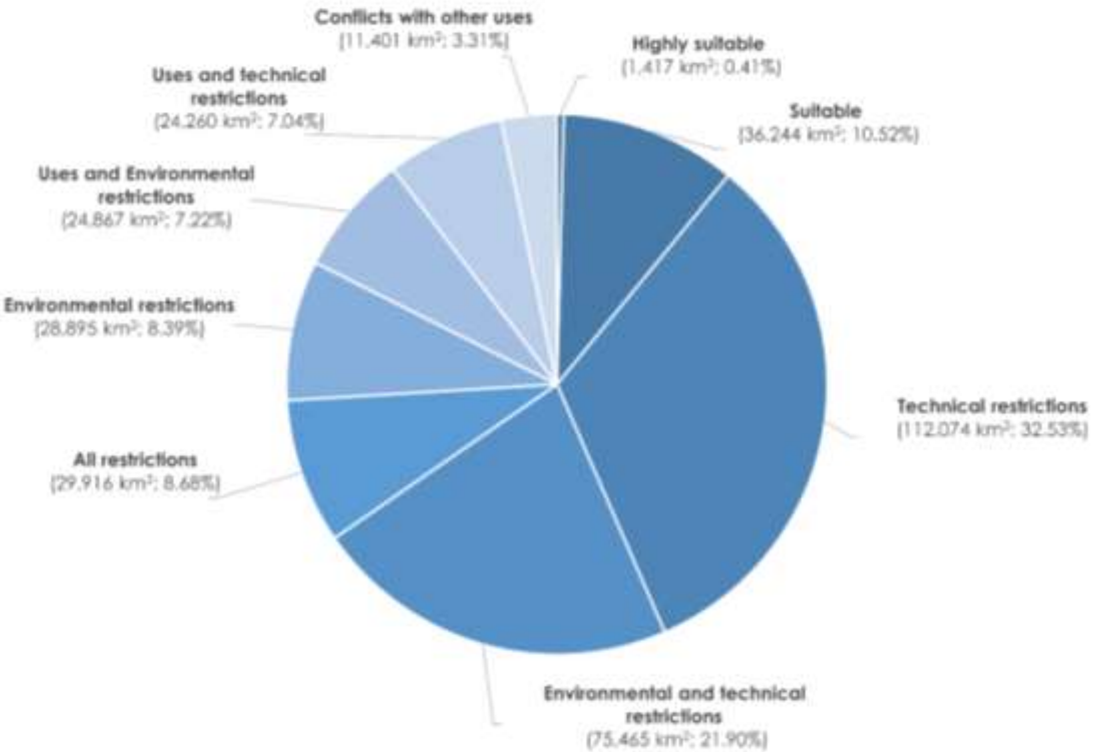

Figure 38. Percentage of European Atlantic sea space, suitable for the development of wave energy projects and main restrictions.

The estimated mean annual energy production from waves considering the production capacity of our specific WEC in highly and suitable zones is 1,308 MWh, and 1,230 MWh, respectively, in average (Table 1). To achieve the target of 1GW of ocean energy installed capacity by 2030, 7,143 WECs would be needed and to achieve the target of 40 GW by 2050, 285,714 WECs. In the areas with the maximum MAEP, 5,459 WECs would be needed for 1GW of installed capacity, and 218,341 WECs to achieve the target of 40 GW of installed capacity.

The energy production data provided in Table 1 were calculated on the assumption that the WEC would operate all year round. This amounted 8,760 hours per year of 365 days. According to this, in average, 50 WECs are needed to produce the equivalent of a 7MW wind turbine generator, considering that both operate the same number of hours. In the more productive cell, 39 WECs would be needed, and in the lower productive cell 56 WECS (Table 1) (Pereira and Silva, 2020).

Table 1. Averaged mean annual energy production for our specific wave energy converter per square kilometre and total production in locations identified as being suitable and highly suitable in the European Atlantic region.

	Averaged mean annual energy production (MWh)	Maximum of mean annual energy production (MWh)	Minimum of mean annual energy production (MWh	Area (km^2)
Highly suitable	1,308 ± 78	1,522	1,118	1,417
Suitable	1,230 ± 77	1,605	1,120	36,244
Total	1,235 ± 80	1,605	1,118	37,661

5. Conclusions and future works

The work presented provides a first integrated assessment to identify suitable areas in the European Atlantic region, for the development of wave energy projects based on technical (and economic) economic factors, environmental risks and potential conflicts with maritime activities and infrastructures. The analysis covers the EEZs of Ireland, France, Spain and Portugal, excluding areas deeper than 200 m, and accounting for a total area of 344,539 km^2, with an analysis resolution of 1km^2 resolution grid.

This is a first insight into suitable areas in an extensive region, based on expert judgement for the elaboration of a model for integrating all the most relevant factors conditioning the suitability for development of new WECs farms, and the use of publicly available information layers. The approach implemented and the maps produced, can serve to identify the most suitable areas, but it should be acknowledged that the final selection of areas should be based on a more detailed assessment and with higher resolution information layers. However, the results obtained, provides and general view of the most suitable areas in a regional scale, and serves to identify areas showing restrictions.

The model integrates most relevant conditioning factors and has been developed and validated by several experts, including scientists and engineers (see Galparsoro *et al.* (2021c)). Most relevant technical factors have been considered. In particular, and in close cooperation with the industrial partners of the SafeWAVE project, the potential energy power production capacity has been incorporated into the assessment. In addition, other factors such as the distance to port, operable weather window have been considered, which helps to obtain realistic results. However, other factors, such as the timing and distribution of weather windows through a year has not been considered, which would help to optimise the identification, and prevent year-round windows from accumulating in the summer season. Another interesting variable to incorporate could be the Levelized Cost of Energy (LCOE).

Regarding environmental aspects, the focus lies on the possible impacts arising from the operation of an oscillating water column point absorber device in offshore areas based on a previous work by Galparsoro *et al.* (2021a), which in turn, was based on expert judgement on the pressures produced by wave energy converters and ecosystem components sensitivity to such pressures to estimate the potential impacts of WECs. The spatial assessment of the environmental impacts, and the reduction of uncertainty in such evaluation, would require the incorporation of further quantitative assessment of environmental impacts based on monitoring plans in existing WECs testing sites (Imperadore *et al.*, 2023; Muxika *et al.*, 2023; Uriarte *et al.*, 2022; Vinagre *et al.*, 2021). The present study relies on open data sources (e.g., Aquamaps, EMODnet) that offer insights into the potential distribution of several ecosystem components. However, it is crucial to handle this data with care, as these maps are broad approximations derived from modelling techniques and not empirical data sources (i.e., AquaMaps). In addition, when assessing the geographical distribution of the potential environmental risks, it is necessary more detailed information on the spatial and temporal distribution of the most sensitive ecosystem components.

In addition, the approach used in this study does not account for the individual sensitivities of different species to the pressures resulting from WECs. Instead, it amalgamates all known species data, using it to approximate the potential geographic range of potentially vulnerable or sensitive species and habitats across the entire study area. Hence, when pointing zones suitable for project development, it is imperative to gather comprehensive data regarding the distribution of sensitive and vulnerable habitats and species. This might involve compiling existing information or even conducting surveys as mandated by the authorization processes (O'Hagan, 2021; Verling *et al.*, 2023; Verling and O'Hagan, 2021).

The implementation of wave energy projects or other offshore energy sources will necessitate marine space, which would generate conflicts with other activities. This could potentially lead to clashes with existing uses and activities. For example, our approach encompasses general information about the fishing activities by publicly available AIS data layers, but this represents commercial vessels and industrial fisheries, particularly bottom trawling fisheries. As offshore wave energy projects are likely to be installed closer from coastline, the artisanal fisheries and wave energy devices space will overlap. This type of information is limited, especially for broad study areas as this case. Consequently, more detailed information is needed to predict socioeconomic implications and outcomes. Moreover, in terms of socioeconomic considerations, the incorporation of more detailed data and new information about other activities or uses that have not been considered in this study will improve the model.

While our approach adequately addresses primary factors, it is important to exercise caution concerning other aspects such as the social acceptance, as it might limit wave energy development in coastal areas (Dunphy *et al.*, 2021a; Dunphy *et al.*, 2021b; Smith *et al.*, 2021; Uyarra *et al.*, 2021).

The model produced permits the consideration of future planning scenarios by including additional human activities geographical distribution or considering future stages of progress in the technology development (e.g., modifying the depth ranges in which WECs can be installed).

The work presented provides a first assessment of the most suitable areas for future potential development of wave energy projects, based on an integrated assessment of technical (and indirectly economic), environmental and conflicts with other maritime activities and infrastructures. The results obtained indicate that there is enough space in the European Atlantic region to develop new wave energy farms for the achievement of predefined objectives of 1 GW estimated by the (European Commission, 2020). Almost 11% of the study area has been identified as being suitable for wave energy projects, of which 0.41% is considered as being highly suitable. This percentage represents 37,661 km^2 of suitable and highly suitable areas for the development of offshore wave energy projects. The averaged mean annual energy production (MAEP) of our specific WEC, assuming an operation window of 8,760 hour per year (i.e., 365 days, with no stops), is 1,235 ± 80 MWh (mean value for the suitable and highly suitable areas). The maximum and minimum value of the MAEP in this area is 1,605 MWh, and 1,118 MWh, respectively. To achieve the target of 1GW of ocean energy installed capacity by 2030, 7,143 WECs would be needed and to achieve the target of 40 GW by 2050, 285,714 WECs, and in areas with the maximum MAEP, 5,459 WECs and 218,341 WECs respectively. If the space is planned properly and with caution, those developments would fulfil industrial requirements, would be developed in areas with lowest environmental risks and limited or no conflicts with other activities.

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