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Identifying compatible locations for wave energy exploration with different wave energy devices in Madeira Islands

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ABSTRACT: This paper aims to assess the techno-economic suitability of different marine areas for the nearshore and offshore wave energy exploration in the Madeira Islands, while avoiding conflict with any technical, environmental, legal or other use restriction. A wave energy device is also evaluated, which could constitute the best energetic performance in such specific sea states. The compatibility evaluation of different wave energy conversion technologies is made through the computation of a novel index over the area of study. The location suitability assessment is made in a GIS environment by discarding different locations from the masking process. Later, a multicriteria decision making methodology is carried out over the available areas. The results aim to provide stakeholders and decision-makers with meaningful information on the most suitable locations and wave converters for the potential deployment of a wave energy exploration facility in the Madeira Islands.

1 INTRODUCTION

In a framework of climate change awareness, small islands face demanding energetic challenges due to its isolation from the continental electrical networks and strong dependence on imported fuel. Such is the case of Madeira Islands in Portugal. Electricity demand here has been continuously increasing since 2013 at an average annual rate of 0,5% (ERSE, 2019) and up to 75,4% of the supplied electricity proceeded from fossil fuels, with a lower 24,5% representing renewable energy in the electric share recorded in 2019 (APREN, 2020).

This scenario is encouraging the regional government to set different climate and energy targets for the next decade, inspired by the larger scale National Plan of Energy and Climate 2021-2030 (PNEC, 2020). The main goals focus on the reduction of greenhouse emissions, improving energy efficiency and increasing the renewable energy share in the islands' electric market. One of the most ambitious targets is reaching the scenario of 100% self-Sustainable Porto Santo Island (R20, 2016; Gouveia, 2018).

For both inhabited islands of Madeira, it is crucial to increase the level of energy self-sufficiency. The energy autonomy can only be done by developing all types of indigenous renewable energy sources since the distance and depth to the continental shelf makes underwater electrical connection economically not viable. The main contribution to the renewable energy share on the islands currently comes from an established onshore wind and hydro electrical energy exploration.

However, despite its significant potential (Rusu et al., 2008; Rusu & Guedes Soares, 2012, Silva & Guedes Soares, 2020), the wave energy exploration in these two islands is still inexistent. Consequently, efforts should be driven to make the most of the ocean resource and lead the strategies towards different ways of marine energy exploration. These strategies would contribute to reduce energy dependency and improve competitiveness, economic sustainability and employment.

For the exploration of wave energy, a variety of Wave Energy Converters (WECs) with different working principles, power-take-off systems (PTO) and nominal capacity have been developed around the world (Marquis et al., 2012; Guedes Soares et al., 2012, Silva et al. 2013; Rusu & Onea, 2018;). Several devices reached a full-scale pre-commercial prototype such as Pico OWC (Falcão et al., 2019); Pelamis (Carcas, 2003); Wave Dragon (Kofoed et al. 2006) or WaveRoller (Waveroller, 2019). Also, some WEC farms have been deployed in test facilities around Europe, such as SEM-REV or EMEC (Clément et al., 202; Magagna et al., 2015). Nevertheless, no WEC has reached the commercial market, mainly due to the uncertainty of its economic viability and survivability.

There are two critical steps to promote these devices reaching the commercial market, and this paper will be focused on them. On the one side, not all device technologies are appropriate for every wave environment; thus it is necessary to evaluate which kind of WEC device would perform better considering the specific sea state characteristics at that location. This compatibility between WEC device and location can be expressed by two energy factors: the annual energy production (via the capacity factor, Cf) and availability (Lavidas, 2019).

The WECs under evaluation in this study are six: Pelamis (D1), FHBA (D2), FOWC (D3), BSHB (D4), LNE (D5) and BOF2 (D6) (Lavidas & Venugopal, 2017). These constitute both nearshore and offshore WEC technologies. More details on the technical characteristics of these WECs are discussed in the studies of Babarit et al., (2012), or Silva et al., (2013).

Subsequently, it is essential to find optimal locations for the wave energy exploration, in terms of marine space availability and the techno-economic performance at a specific location. For this purpose, a multi-criteria decision-making methodology was constructed in this study in a Geographical Information Systems (GIS) environment.

This method has been widely used for the marine spatial planning (Calvet et al., 2013), with purposes such as aquaculture (Kaymaz et al., 2017), offshore wind energy (Diaz et al., 2017; Schallenberg-Rodríguez et al. 2017) or tidal energy. Previous studies have also assessed the locations that would optimize the wave energy exploration in different areas around the world (Le et al., 2014; Vasileiou et al., 2017, Xu et al., 2017; Zanuttigh et al., 2016).

The proposed methodology is new due to two main characteristics: (i) a suitability evaluation of marine areas for the wave energy exploration at this level has never been done in the Maderia Islands up to date (ii) the compatibility evaluation between different WEC technologies and the characteristics of the specific sea state (energy efficiency) is something that has been barely applied in general and never within Madeira Islands.

Overall, the paper aims to determine both the most suitable locations and the optimal device technology, that would constitute a better economic performance when deploying a wave energy farm along Madeira's coastline while avoiding conflict with technical, environmental, legal and other use restriction.

The structure of this paper is organized as follows. Section 2 includes a brief description of the area under study. Section 3 describes the methodology developed in the study, which is also divided into three parts. Section 4 shows and discusses the main results, while Section 5 compiles the main conclusions of the study.

2 AREA OF STUDY

The autonomous region of Madeira is a volcanic archipelago located about 900km to the south-west from the Portuguese continental coast and is formed by three major islands (Figure 1). Madeira, situated to the west and with an area of 741 km², is the largest island of the group; Porto Santo in the north-east, with 42,17 km²; and the inhabited Desert Islands, which are located to the south. The last ones, designed as protected reserves, are out of the scope of this study due to the collateral environmental restrictions and minimal electric demand.

The average population density of the autonomous region is 317 inhabitants per km^2; however, the population is mainly concentrated around its capital (Funchal), located in the south coast of Madeira Island, (PORDATA, 2018). The rich landscape of the region has boosted tourism during the last decades, currently constituting the most crucial sector for Madeira's economy. Other industries that also contribute to the local domestic economy are agriculture, small fishing industries and wine production.

he climate of the islands is generally mild with an average annual temperature close to 20ºC. In the winter half of the year, the islands can be affected by Atlantic depressions. During this period, wave conditions are more energetic, mainly due to the Azores anticyclone, which is dislocated south from its usual position. Therefore, strong winds often occur, leading to a random alternation between swell and wind seas in the surroundings of Madeira and Porto Santo (Rusu et al., 2008). Most observed significant wave heights (H_{m0}) in the wintertime range between 2 and 4 m, while in the summertime the most frequent H_{m0} range between 1 and 2 m (Rusu et al., 2012). However, the wave regime around the islands was observed to be quite constant in terms of significant wave heights, with relevant waves in summertime and not very high average maximum wave heights in wintertime. This constancy of the wave regime might compound a decisive factor for the extraction of the wave energy, which requires a small variability on the wave resource.

The annual average wave power potential reaching the islands is approximately 24 kW/m (own

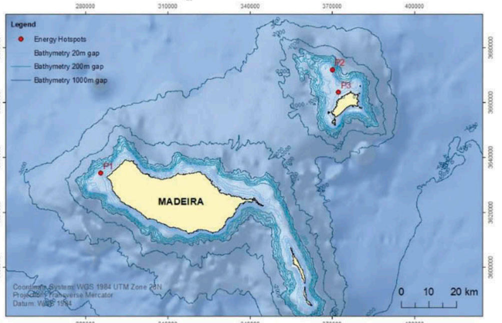


Figure 1. Extent of the area of study over the Autonomous Region of Madeira. Bathymetry contours and location of wave energy *hotspots*.

analysis). However, it can reach up to 55kW/m in a wintertime scenario, while the peak value in the summertime is set around 19kW/m. The power of the wave resource is thought to have its peak on three "*hotspots*" along with the islands which are illustrated on Figure 1, one in the very west side in Madeira Island (P1), one in the northern offshore waters of Porto Santo (P2) and the last one in the nearshore waters of Porto Santo (P3), as also found in (Rusu et al., 2012).

The energy peaks correspond to local changes in bathymetry. Generally, there is a sharp transition from shallow to deep water; especially in the vicinity of Porto Santo, where the bathymetry gets more variable due to tiny rocky islands (Rusu et al., 2008).

As Madeira Islands are constituted by several protected areas, land availability for renewable energy facilities an issue, since they compete with other urban, agrarian or touristic uses. Consequently, offshore wave energy exploration could be a potential alternative for increasing the renewable energy electric share in the islands.

In this study, the full methodology shown in Figure 1 is analysed. However, the marine territory is not fully available within this extent either, and a significative extension is environmentally protected as well. At the same time, other areas are already constricted by other spatial uses, marine traffic, military activities or port activities, among others. The deployment of a wave farm can also have other techno-economic constraints, such as the water depth and distance to land facilities. Therefore, along the next sections of this paper, the actual interest area later considered in this study will be reduced to smaller marine patches after discarding the restricted areas.

3 METHODOLOGY

The methodology is divided into three steps. The first one aims at determining the WEC technology that would optimize the energy performance over the full extension of the interest area, taking into account the average annual energy production on the region and via the capacity factor of the WEC and the resource availability.

In the second step, the marine areas restricted to the wave energy exploration due to technical, environmental or other maritime uses constrains will be discarded. Further, in a third step, a multi-criteria analysis will be carried out over the available areas using ArcGIS 10.4 as the spatial data management primary tool. The result will be a spatial model representing a ranking of suitability for the implementation of a wave energy farm, with the optimal WEC technology, and within available marine areas (Figure 2).

3.1 *Determination of the optimal WEC technology*

The modelling of the sea states at the study extent is required, the significative height (H_{m0}), peak wave

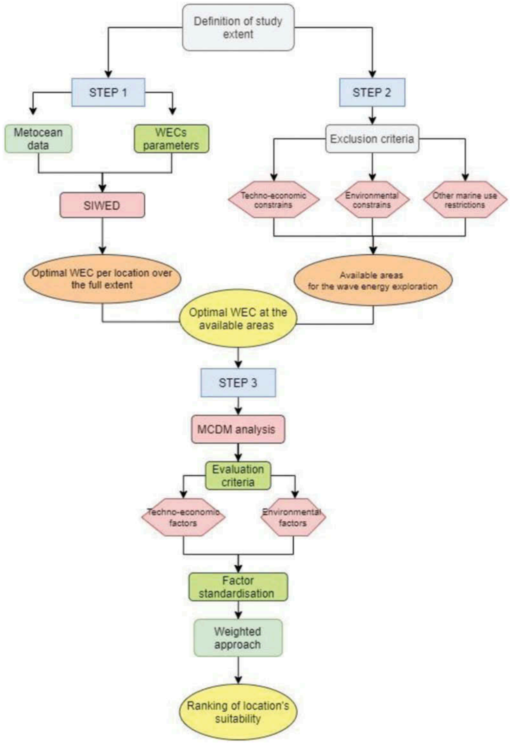


Figure 2. Workflow followed in the methodology of this study (modified from Díaz et al., 2019b).

period (T_{peak}) and the potential wave energy power (P_{wave}) were estimated by using the ERA5 hindcast dataset of the WAM model by ECMWF with a resolution of 10km for the years 2000-2018.

The determination of the most suitable WEC was evaluated through a newly introduced methodology, based on the Selection index for Wave Energy Deployments (SIWED) (Lavidas, 2020).

SIWED provides a robust approach to determine the optimal WEC for a location/region/area. Its process achieves an "optimal" selection, by including long-term met-ocean variations that have adverse effects on annual energy production (AEP) and the Capacity Factor (Cf). It also quantifies the harmful effects of extreme wave values and how they will affect WEC deployment. Once computed these variables, the SIWED index was calculated all over the study region. This novel index relates a WEC's energy capacity factor (dependent on the met-ocean characteristics and WEC's power matrix) with the availability and variability of the wave resource (percentage of time for which the resource allows operation for the WEC).

The technical data about the WECs power matrix, the cut-in and cut-off sea state values and rated capacity was retrieved from numerical models (Babarit et al., 2012; Lavidas, 2020).

3.2 *Application of spatial restrictions*

The spatial constraints that constitute a techno-economic, environmental or other maritime planning restriction for the wave farm implementation were evaluated. Techno-economic limits encompass factors influencing on the productivity of wave devices, and that can affect the energy output and life cycle costs (Castro-Santos et al. 2016, 2017, 2018), such as water depth or remoteness. Environmental constraints involve restrictions such as protected areas or wildlife breeding and transit areas.

However, high-density wildlife areas were not considered here as a constraint but as a weighted factor, as it is not recognized as a restriction for potential marine energy uses in the Portuguese Maritime Spatial Planning Plan (PSOEM, 2020). Other conflicting marine uses considered are high-density maritime routes, military areas, aquaculture areas, underwater cable margins, recreational activities or sand extraction.

In this step, a GIS database containing information about the spatial distribution of all limitations was implemented using data retrieved from various global or local marine spatial planning sources and documentation with a spatial resolution of 225m (Table 1). Figure 3 illustrates the distribution of spatial restrictions where wave resource exploration is unsuitable due to the presence of one or various constraints. These areas were later subtracted to the overall area of interest through a masking process.

This process serves to limit the alternatives under consideration in the next step. Figure 3 also includes the available marine areas after application of constraints, and from now on, those are the only areas of interest considered in the next step.

3.3 *Multi-criteria decision making and suitable locations*

In this stage, a Multi-Criteria Decision Making (MCDM) process is performed. This method allows

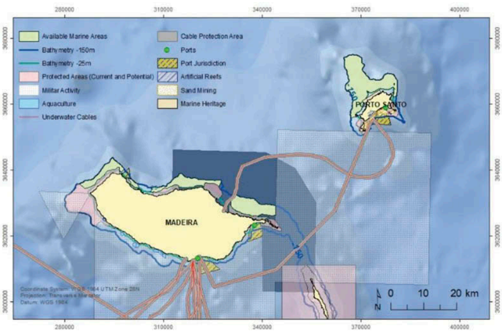


Figure 3. Spatial distribution of restricted areas over the area of study. Green areas represent the potential available areas for the wave energy exploration after application of constrains.

decision-makers to determine the best, among several possible management alternatives. The preferable option is chosen by evaluating a set of selection criteria. When this method is spatially applied and coordinated in a GIS environment, it is possible to find a suitability ranking by location for the purposed goal (the wave energy exploration).

The first step in this MCDM process is setting a variety of criteria factors influencing on the energetic and techno-economic performance of a potential wave farm. Secondly, the spatial information was treated in ArcGIS to create raster layers containing classified information on each factor.

Subsequently, the layers are standardised to a scale from 1 to 10 as per Table 2 (being 1 the less favourable conditions and 10 the most desirable). This table also includes the ArcGIS management tools used for analysing each factor's data, the data source, classification criteria and data range.

Five criteria factors are considered:

1. Distance to ports (D_p): The distance to port facilities have a strong influence on the cost of installation, operation and maintenance of the wave farm.

The closer a location is from a port facility; the better will be the wave farm's economic balance. Funchal, Caniçal and Porto Santo are the three main ports in the Madeira Islands, two located in the south coast of Madeira Island and one in Porto Santo Island respectively.

Despite the existence of other smaller harbours in the region, those three are the only ones that could host the infrastructure required for the WECs offshore installation together with other logistics.

A raster layer was created containing information on the distance of each location within the available areas to the nearest point (Figure 4a).

2. Distance to onshore electric substations (D_{sub}): The distance to electrical connection points is the most crucial criterion to estimate the cost-effectiveness due to the high price of transmission cables (Kim et al., 2012). The electric network layout of the islands is illustrated in Figure 4. A raster layer was created containing information on the water distance of each grid cell to the closest electric landing substation (Figure 4b). The distance range was scaled down to 1 (less favourable), as it would incur higher submarine cable installation and maintenance expenses. The closest distance was scaled to 10 as the most desirable locations (Table 2).

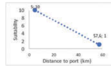
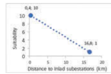
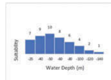
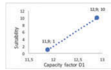
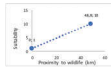
3.Water depth (WD): constitutes a techno-economic factor for the decision making, as in areas with water depths lower than 25m and higher than 150m (Figure 4c) it is not technically possible so far to install near-shore and offshore WECs (Koka et al., 2012).

Device D1 chosen as the most suitable for this area in section 3.1, is an offshore WEC whose optimal function water depth has been set up in 50-60m. Therefore, this was the range given the highest rating on the standard scale from 1 (less suitable) to 10 (most appropriate). The other water depth ranges were rated, as seen in Table 2.

Table 1. Constraint factors from the area of interest.

Type	Constrain	Description	Source	Format/ Geographic system	Restricted Threshold	Reference	ArcGIS tool/method
Techno-economic	Water depth	Nearshore and offshore WECs considered in this study are constrained to depths between 25m and 150m.	EMODnet	ESRI ASCII Raster/ GCS_WGS_1984	WD<25m; WD> 150m	(Koka et al., 2012; Falcão, 2014; Lavidas&-Venugopal, 2017)	Project to WGS_1984_UTM_-Zone_28N; Contour polygons in 25m and 150m; Erase
Environmental	Protected areas	Restricted marine space reserved and managed to achieve the long-term conservation of its nature due to their associated ecosystem and cultural values.	Natura 2000; EMODnet	Shapefile/ GCS_WGS_1984	Full extent	(RN2000; Díaz et al., 2019)	Erase
Other marine uses	Military exercises	Areas used for training, test, evaluation, surveillance and monitoring of potential threats activities.	Portuguese Navy; PSOEM	VRT Raster	Full extent	(Díaz et al., 2019)	Geo-referencing; Vectorize; Erase
	Aquaculture	Farming of fish, seafood, algae, and other organisms in marine environments under controlled conditions.	PSOEM	VRT Raster	Full extent	(Díaz et al., 2019; Le et al., 2014; Zanuttigh et al., 2016; Galparsoro et al., 2012)	Geo-referencing; Vectorize; Erase
	Marine traffic	Areas of high-density vessel and ship traffic or well-established commercial routes.	EMODnet	VRT Raster	Full high-density traffic extent	(Díaz et al., 2019; Le et al., 2014; Zanuttigh et al., 2016)	Geo-referencing; Vectorize; Erase
	Underwater lines/cables	Submarine communications/electric cables and oil/gas pipes	PSOEM	VRT Raster	0,5km width around cable layouts	(Galparsoro et al., 2012)	Geo-referencing; Vectorize; Distance Buffer; Erase
	Port jurisdiction	Areas restricted due to state legislative exercises, high traffic density and enforcement jurisdiction over foreign vessels within the ports.	PSOEM	VRT Raster	Full extent	(Díaz et al., 2019)	Geo-referencing; Vectorize; Erase
	Artificial Reefs	Man-made underwater structures, typically built to promote marine life, control erosion, block ship passage, improve surfing, etc.	PSOEM	VRT Raster	Full extent	(Díaz et al., 2019; Le et al., 2014; Zanuttigh et al., 2016; Galparsoro et al., 2012)	Geo-referencing; Vectorize; Erase
	Sand Mining	Underwater marine areas of sand extraction.	PSOEM	VRT Raster	Full extent	(Díaz et al., 2019; Le et al., 2014; Zanuttigh et al., 2016; Galparsoro et al., 2012)	Geo-referencing; Vectorize; Erase
	Marine Heritage	Physical resources such as historic shipwrecks, prehistoric archaeological sites, archival documents and oral histories.	PSOEM	VRT Raster	Full extent	(Díaz et al., 2019; Le et al., 2014; Zanuttigh et al., 2016; Galparsoro et al., 2012)	Geo-referencing; Vectorize; Erase

Table 2. Criteria factors classified within the area of interest.

Type	Factor	Retrieved data	Source	Format/GCS (resolution)	ArcGIS tool/ method	Grid resolution	Data Range	Standardization Method	
Techno-economic	Distance to ports	Location of Ports	APRAM	GSC WGS_1984	Project to WGS_1984_UTM_28N; Cost Distance Tool.	225m	Min: 5.0km Max: 57.6 km	Inverse Linear: Min=57.6km=1 Max = 5km= 10	
	Distance to inland substation	Islands' Electric Network	EEM	PDF	Georeferencing; Vectorize substations; Cost Distance Tool	225m	Min: 0.4 km Max: 16.8 km	Inverse Linear: Min = 16.8km=1 Max = 0.4km = 10	
	Water depth	Bathymetry	EMOD net	ESRI ASCII Raster/ WGS_1984 (225m)	-	225m	Min: 25 m Max: 150 m	Non-linear: 25-40m = 7; 40-50m= 9; 50-60m = 10; 60-80m=8; 80-100m= 6; 100-120m= 4; 120-140m =2; 140-150m =1	
	Capacity factor	Capacity factor	Calculated in Step 1	.txt/ WGS_1984 _UTM_28N (10km)	Radial Basis Function interpolation	225m	Min: 11.9km; Max: 12.9 km	Linear: Min = 11.9=1 Max =12,9= 10	
Environmental	Proximity to high-density wildlife	High-density wildlife areas	PSOEM	VRT Raster	Georeferencing; Vectorize; Euclidean distance	225m	Min: 0km; Max: 41.8 km	Linear: Min = 0 km=1 Max =41.8km = 10	

*GCS=Geographic Coordinate System

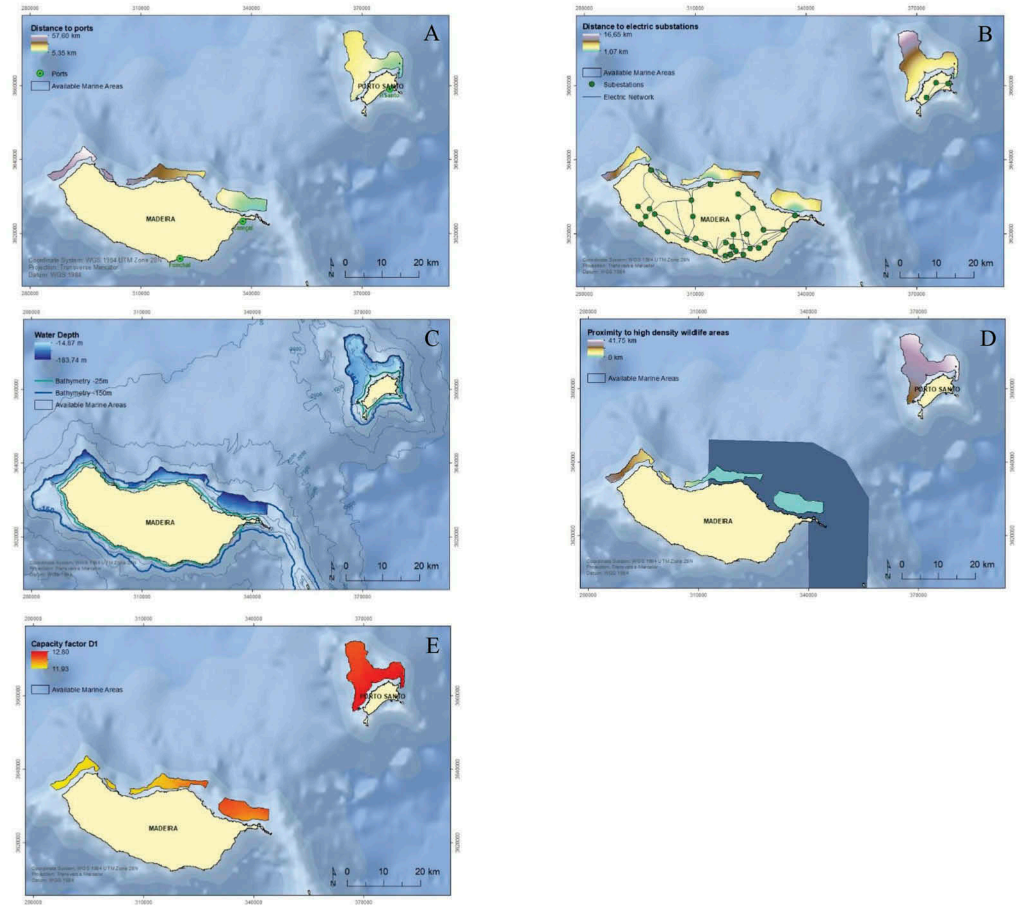


Figure 4. Spatial distribution of the criteria factors within the available areas: a) distance to port b) distance to onshore electric substations c) water depth d) proximity to wildlife e) capacity factor. (Grid resolution: all layers resampled to 225m. Coordinate System: WGS_1984_UTM_Zone_28N).

4. Capacity factor (Cf_1): the capacity factor is defined as the actual electricity production divided by the maximum possible electricity output of a WEC, over some time. The higher the Cf, the higher the electric output, hence better the expected economic performance. The spatial distribution of the Cf of the chosen device is shown in Figure 4e.

5. Proximity to wildlife routes (P_{WL}): The proximity to the areas with high wildlife density (Figure 4d) is considered an environmental factor.

Longer distances from those areas minimise the probabilities of impact caused by the wave farm on the existing wildlife. The higher water distances from those areas were rated on 10 (most favourable), and the closest cell grids were rated 1 (less favourable).

Energy factors such as wave power potential (P_{wave}) or wave height (H_{m0}) were not included in this MCDM assessment as criteria factors as they have been already taken into account for the calculation of the WECs capacity factor in the SIWED with higher fidelity (section 3.1).

Finally, each criterion was assigned a weight according to its importance and influence on the decision-making process for the installation of a wave farm.

The weight is a relative percentage that is here determined by rating each criterion with values on a normalised scale from 0 to 1 with an overall summation of 1. The lowest weight is given to the less influencing factors and highest for the elements having the most significant importance on decision making.

The judgement for the assignation of weights for the techno-economic factors (D_p, D_{sub}, WD, C_f) is based on the “Levelized Cost of Energy” (LCOE) as an economic performance indicator. Due to the scarce of real cost data coming from existing commercial wave farms, the estimation on the relationships between these spatial factors and the LCOE was based on its similitude with the parametric equations calculated in some previous studies applied to the offshore wind energy industry. Ramos et al., (2020) analysed the LCOE of deploying a wind farm facility, also in the coast of Madeira Islands. Here, there some parametric equations are compiled showing the relationship of the spatial variables (WD, D_p, D_{sub} and Cf_1) with each cost involved on the wind farm life cycle. From these equations, some influence relationships can be observed: the distance to port (D_p) have a direct influence on the installation and assembly costs as well as on the O&M costs. The water depth (WD) directly influences on the installation costs as well but also in the mooring costs. The distance to the electrical network substations (D_{sub}) has a robust straight influence on the export system costs, and the capacity factor inversely influences on the total LCOE values.

Overall, the distance to the electric substation is observed to be the most influencing factor on the total LCOE, followed by the distance to port, bathymetry and the WEC capacity factor.

Considering the existence of a reasonable similitude on how spatial parameters influence the life cycle costs of a wave and a wind exploration facility, the same ranking was used in this paper to evaluate the magnitude of influence of each spatial factor in the economic performance. Therefore, the elements were assigned in the same order with the following weights: 0.4 was given to D_{sub}, 0.3 was given to D_p, and the WD was rated with 0.15. The capacity factor (Cf_1) was considered to have a minor influence on the overall economics due to the small spatial variability of the Cf_1 over the area of interest. Consequently, it was rated with a 0.05 weight.

Finally, even though the P_{WL} environmental factor is not considered a restriction for the potential exploration of offshore renewable energy in the local maritime spatial planning (PSOEM, 2020), in this study, this factor is given a certain importance. The deployment of a wave farm is considered that might have a low/moderate impact on the wildlife (overall weight of 0.1).

Finally, each grid cell over the interest area is assigned a suitability score (Ss).

$$S_S = \sum w_i x_i \tag{1}$$

where:
Ss = composite suitability score
w_i = weights assigned to each factor c_j
x_i = factor scores (cells)

This score results from aggregating all criteria in a weighted linear combination process. Each standardized factor is multiplied by its respective weight and later summed up altogether:

$$Ss = (0.3\ x\ D_p) + (0.4\ x\ D_{sub}) + (0.15\ x\ WD) + (0.05\ x\ C_f) + (0.1\ x\ P_{WL}) \tag{2}$$

where:
D_p = Standardized distance to port.
D_{sub} = Standardize distance to electric substations.
WD = Standardize water depth
Cf_1 = Standardize capacity factor of D1.
P_{WL} = Standardize proximity to high-density wildlife areas.

4 RESULTS AND DISCUSSION

4.1 *Optimal WEC technology type*

The result of this analysis pointed at device 1 (D1) as the most suitable for this region's sea state conditions. A 10km resolution model representing the wave power (P_{wave}) (Figure 5), the significant wave height (H_{m0}) and the capacity factor of this optimal WEC (Cf_1) was also determined.

Mean H_{m0} values in the region are from 1-8-2.5, with nearshore depths experiencing ≈2 meters. Maxima values of significant wave height in our domain are from 6-8, predominately in the winter. T_{peak} in the region is dominated by swell generated waves, as expected. Mean values throughout the years are from 8-11 sec, with maxima values up to 21 seconds, indicating more significant low frequency swells with large wave fronts.

Mean P_{wave} is high for the investigated period with a range from 15-27 kW/m, higher values are in deeper locations and due to large swells. The harsh Atlantic environment is also underlined by the high maxima P_{wave} values that the coastlines are also exposed. The region during winter months is exposed up to 400 kW/m, with nearshore areas often

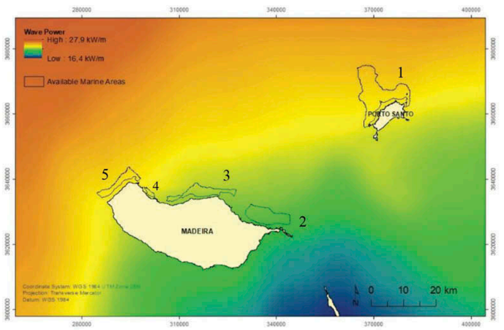


Figure 5. Average annual wave power, in kW/m, resulting from the hindcast data model for the years 2000-2018.

exceeding 250 kW/m, indicating large forces on the WEC. The SIWED as an index takes into account the interactions of energy production, maxima and variability of the resource, assessing all six WECs. It is found that the preferable device is the D1 which has a Cf from 8-12%. Other applied WEC achieved Cf from 4-8% with most of them, due to extremely high waves shutting down and being in survival mode.

The selected device in the study has the most persistent performance in combination with its power t matrix information and interaction with dominant met-ocean conditions.

4.2 *Best locations for the implementation of a wave farm*

Different results are achieved along with the suitability evaluation for wave energy exploration. On one side, a compilation of spatial distribution models is created for the various factors and constraints associated with each stage of the decision-making process (Figure 3 & 4). A GIS-compatible database has been created containing this information, which might be useful for future marine spatial research.

On the other side, after the application of restrictions, five main areas are detected to be feasible and available for the exploration of the wave energy resource (Figure 5). The biggest one (121 km^2) is located in the north-west coast of Porto Santo (1). The other four areas account for an extension of 54 km^2 (2), 39 km^2 (3), 4 km^2 (4) and 28km^2 (5) from east to west, all of them are located in the north coast of Madeira Island. Due to the small extension of the area represented by number 4 in Figure 5, it might only be suitable for the installation of a small quantity of WEC devices.

In general, the south coast of both islands is not available for the wave energy exploration due to a high concentration of other marine uses, high-density maritime traffic, underwater cables or a significative presence of protected and sand extraction areas.

With the application of the multi-criteria methodology and the assignment of suitability scores, a ranked spatial distribution was created, containing information about the suitability level of each location for the implementation of a wave farm, within the available marine areas (Figure 6).

The model has a 225m grid resolution and the suitability values resulting within the areas of interest range between a minimum of 3.48 and a maximum of 9.36 in a scale from 1 to 10. Cells containing the lowest values, from 3.48 to 4, represent the less favourable or "poorest" locations for the wave energy exploration and are depicted in red in Figure 6. Conversely, the areas coloured in dark blue and containing values from 8 to 9.36, represent the most suitable locations. The other areas were considered as poor (from 4 to 5), low moderate (from 5 to 6), moderate

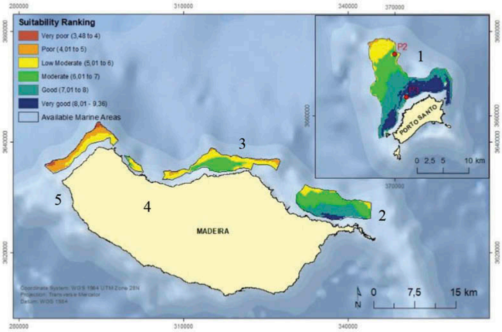


Figure 6. Spatial suitability ranking for the wave energy exploration within the available areas in the Archipelago of Madeira. Grid resolution: 225m.

(from 6 to 7) or good (from 7 to 8), in terms of suitability for the deploying of the WECs. Table 3 contains information about the characteristics of each one of the five areas of interest.

The most suitable locations result in higher scores than 8, and are mainly located to the N-NW of Porto Santo. They cover an approximate area of 32 km^2 and are mostly concentrated between the 25m and 50m bathymetries. In a small area of about 3.3 km^2 in the most north-eastern coast of Madeira Island, an excellent location was also found, between 25m and 60m water depth.

The north-west corner of Madeira Island, as well as the very north waters of Porto Santo, are found to be the poorest regions for the exploration of wave energy in terms of spatial, techno-economic and environmental suitability. Main reasons are its deep depths, remoteness, and long distances to main ports and electric substations. It is interesting to compare these results with the average power of the wave resource observed in Figure 5.

It is possible to see that the ideal locations in terms of techno-economic performance do not always coincide with the areas of the highest potential of the wave energy resource.

Such is the case of the north-west coast of the biggest island of Madeira. There, the most energetic area corresponds to the most western side of the island (Figure 5). However, resulting in available area number 5 in Figure 6, also located here, is the poorest recognized region for the wave energy exploration if we consider other technical, economic spatial and environmental constraints. On the contrary, in Porto Santo, the area 1 identified as "most suitable" for the wave exploration in this study falls within a region where a high wave power potential was recorded in Figure 5 (approx. 24 kW/m). This area should, therefore, be the one receiving more attention from decision-makers and stakeholders.

Table 3. Characteristics of the areas of interest.

			Water depth (m)		Distance to Port (km)		Distance to inland electric substations (km)		Capacity factor D1		Proximity to wildlife (km)		Suitability Score		
Area	Location	Extent (km^2)	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Final rank
1	P.Santo (N)	121.4	-25 to -150	-57.5	5.4 to 25.0	16.1	2.2 to 16.8	8.2	12.5 to 12.8	12.6	23.4 to 41.8	34.5	4.0 to 9.4	7.2	Good
2	Madeira (NE)	54.3	-25 to -150	-92.2	6.2 to 17.1	11.2	0.63 to 8.4	5.0	12.2 to 12.5	12.4	0 to 0	0	3.3 to 8.4	6.9	Moderate
3	Madeira (N)	39.1	-25 to -150	-29.3	22.7 to 44.0	31.6	1.69 to 10.0	8.3	12.0 to 12.5	12.2	0 to 6.6	0.5	4.5 to 6.8	5.8	Low moderate
4	Madeira (NW)	3.7	-25 to -139	-70.0	47.4 to 51.0	48.9	1.46 to 5.2	3.7	12.0 to 12.1	12.1	10.4 to 13.3	11.8	4.9 to 6.2	5.6	Low moderate
5	Madeira (W-NW)	27.5	-27 to -150	-79.1	46.2 to 57.6	51.9	2.48 to 13.0	10.5	11.9 to 12. 0	12.0	14.9 to 29.4	21.7	3.5 to 6.0	4.8	Poor

CONCLUSIONS

This evaluation about the suitability of Madeira Island's maritime waters for the potential wave energy exploration, and about the optimal WEC technology to be used, is expected to provide stakeholders and policymakers meaningful information during a possible decision making and spatial planning process.

This assessment has been done in a multidisciplinary scope, considering not only the potential of the energy resource but also various technical, spatial, economic and energetic factors, which intend to increment the value of the results.

From the results retrieved in this assessment, it can be concluded that the north shore waters of Porto Santo Islands, located between 650 m and 4 km from the shore, should be the regions receiving more attention in a scenario of potential exploration of the wave resource. Furthermore, the wave energy converter type "D1" was the device showing higher compatibility with the average sea states that characterize these areas. Moreover, the proximity to onshore electric substations was determined to be one of the most important criteria to consider when estimating the cost-effectiveness of the wave farm.

Overall, it can be concluded that the ideal location for the wave energy exploration is not always the one having the highest wave resource power potential. Other spatial, environmental and techno-economic criteria also need to be assessed.

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