Combined exploitation of offshore wind and wave energy in the Italian seas: a spatial planning approach

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Author contribution statement

Azzellino, Riefolo and Lanfredi conceived the study, analysed the data and wrote the paper; Pasquale Contestabile and Diego Vicinanza, supervised the meteo climatic data assessment, revised the paper draft

Keywords

Marine renewabale energy, Wind, wave, Marine Spatial Planning (MSP), Vulnerability Assessment, Cumulative impact assessment

Abstract

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The opportunity to co-locate wind and wave energy exploitation is analysed in the Italian seas grounding on the rationale that benefits are greater when un-correlated resources are combined. The study shows that, although waves and winds are generally strongly correlated, in some conditions their correlation is lower and the combined energy harvesting more interesting. As spatial conflicts of sea use and demand for maritime space are increasingly growing, the development of the marine renewable energy sector needs to be evaluated in the perspective of the complex framework of existing uses, pressures and foresees developments. The early prediction of the areas of potential conflicts creates in fact the ground for mitigation actions or early negotiations between stakeholders. In this study the opportunity of co-locating offshore wind turbines and wave energy converters is analysed through a spatial planning approach. Both the potential for combining different renewable technologies, and the impact associated to such development was considered in the context of the existing pressures (e.g. naval traffic; mariculture activities; submarine cables routes; dredg spoils dumping; offshore activities; windfarms and ocean energy projects) and vulnerabilities (Marine Protected Areas, Key habitat presence) through quantitative indicators. The western coast off Sardinia island, the southern areas of Pantelleria island and the Tunisian coastal waters appear to be the most suitable sites. The study shows how quantitative spatial planning methods may support the selection of the sites of potential interest for the marine renewable energy sector in the perspective of cost-effectiveness and environmental impact minimization.

Ethics statements

(Authors are required to state the ethical considerations of their study in the manuscript, including for cases where the study was exempt from ethical approval procedures)

Does the study presented in the manuscript involve human or animal subjects: No

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Keywords: marine spatial planning, wind energy, wave energy, Mediterranean sea, environmental impact, renewable energy.

Abstract

The opportunity to co-locate wind and wave energy exploitation is analysed in the Italian seas grounding on the rationale that benefits are greater when un-correlated resources are combined. The study shows that, although waves and winds are generally strongly correlated, in some conditions their correlation is lower and the combined energy harvesting more interesting. As spatial conflicts of sea use and demand for maritime space are increasing, the development of the marine renewable energy sector needs to be evaluated in the perspective of the cumulative pressures deriving from present activities or expected from future developments. The evaluation of areas of potential conflicts among human activities, environmental vulnerabilities and marine renewable developments may facilitate the early development of mitigation actions and negotiations between stakeholders. In this study the opportunity of co-locating offshore wind turbines and wave energy converters is analysed through a spatial planning approach. Both the potential for combining different renewable technologies, and the impact associated to such development was considered in the context of the existing pressures (e.g. naval traffic; mariculture activities; submarine cables routes; dredge spoils dumping; offshore activities; windfarms and ocean energy projects) and vulnerabilities (Marine Protected Areas, Key habitat presence) through quantitative indicators. The portion of Tyrrhenian coast south of Elba island, the northern-western Sardinian coast, and the southern Adriatic and Ionian coastal waters appear to be the most suitable sites. Moreover, the study presents a spatial quantitative methodology to identify sites of potential interest for the development of the marine renewable energy sector in the perspective of cost-effectiveness and environmental impact minimization.

1 Introduction

The marine environment represents a vast source of renewable energy. Ocean renewable energy infrastructures could contribute significantly to the future energy power supply (Ocean Energy

Systems, 2017). Among the different developed marine renewable technologies, marine wind energy is the most mature type as regards technological development, commercialization, policy frameworks, and installed capacity (Soukissian et al., 2017; Agora Energiewende and Sandbag, 2018). Actually, most of the interest is focused on the development of new offshore solutions, such as wind turbines with larger rotors, deep water sites and floating platform (e.g. Hywind Scotland project www.statoil.com) (Onea et al., 2017). Floating technology can be considered in fact, as a commercially viable solution in order to harness available wind resource also at greater depth (> 50 m) where the conventional fixed offshore wind turbines are no more economically feasible (McMillan and Ault, 2010). In addition, also Wave Energy Converters (WECs) have been identified as a technology with the potential to offer a significant contribution in the medium to long term (Liu et al., 2017). Globally, in 2017 wave energy deployments have doubled its capacity respect to the previous year, up to 8 MW (Ocean Energy Systems, 2017).

In Europe, most of the fully operating projects have been developed by the northern countries where there is a high source availability. However, also the Mediterranean sea is considered an attractive hot-spot for future developments of both technologies (Onea et al.2015; 2016a,b,c; Liberti et al., 2013; Vicinanza et al., 2011, 2013; Iuppa et al., 2015a,b). Up to now, no offshore wind installations are operating in the Mediterranean waters, however the first offshore wind farm in the Italian seas has been approved and is going to be built in the Ionian sea off Taranto. It consists of 10 fixed-turbines with a total installed capacity of 30 MW, to power approximately 9,000 households (EIA Report, 2009). Regarding the wave energy, only two typologies of WECs have been considered suitable to be entirely embedded into traditional coastal defence structures: the Oscillating Water Column (OWC) (Torre-Enciso et al. 2009; Arena et al., 2013; Viviano et al., 2016) and the OverTopping Device (OTD). The latest example of the second group is denominated OBREC (Overtopping Breakwater for Energy Conversion) (Vicinanza et al., 2014; Contestabile et al., 2017).

The feasibility of combining a floating wind turbine and a wave energy converters has been already investigated by several authors (Karimirad and Koushan, 2016; Fusco et al., 2010; Veigas and Iglesias, 2013, 2015; Veigas et al., 2014a,b; Gao et al., 2016). wind-wave technology is a viable solution to reduce the intermittence of the wind and wave resources regardless of the time interval, increasing in this way the attractiveness of a site in terms of its overall marine energy potential (Azzellino et al., 2013a; Fusco et al., 2010; Onea et al., 2017; Perez-Collazo et al., 2013). Therefore, the diversification of the mixed renewable energy technologies, determines a reduction of the power’s variability (Fusco et al. 2010; Stoutenburg et al. 2010) and the energy costs (Astariz and Iglesias, 2016, 2017; Astariz et al., 2016).

The alternatives to combine wind and wave energy technologies have been investigated for the Mediterranean region by Pérez-Collazo et al., 2015. In particular, according to the ORECCA project results, the Mediterranean suitable sites are mainly restricted to three possible areas: the Blue Coast (southern France coast), the strait of Sicily (between Sicily and Tunisia) and the Aegean Greek islands. In recent years, the potential marine environmental impacts of renewable energy devices have been reported in different studies (Margheritini et al. 2012; Bailey et al., 2014; Riefolo et al., 2016).

In the EEA assessment of the onshore and offshore wind energy potential of the European seas (EEA, 2009), it is shown that the offshore wind energy potential, between 10 and 30 kilometres from the coast, is concentrated in the Baltic, the North Sea (including the English Channel) and the Mediterranean, respectively accounting for 29 %, 25 % and 20 % of the 2030 projected total offshore wind potential (7,100 TWh). However, some offshore areas at this distance class have sea depths greater than 50 metres that are not so much suitable for wind energy development. The same report states that at 30 to 50 kilometres from the coast, the Baltic, the North Sea (including the English Channel) and the Mediterranean sea respectively account instead for 30 %, 30 % and 20 % of total wind potential, that is estimated as 3,300 TWh in 2030. As far as wave energy is concerned, the closed basins, such as the Mediterranean, the Black and the Baltic Sea, are characterised by low wave power density values (< 5 kW/m), due to the short fetching that does not let long period waves to be created (Kalogeri et al., 2017). In the Mediterranean sea, there are regions where the both wind and wave energy present low, but not negligible average values. Favourable areas for combined exploitation are in fact located in the Gulf of Lions, in the Sicily Straits (Central Mediterranean), off the coasts of Sardinia, off the NE coasts of the Balearic Islands (NW Mediterranean) and in specific sites in the Aegean Sea. The same authors indicated the Gulf of Lions (NW Mediterranean) and the Aegean Sea (NE Mediterranean) as ideal areas for wind power exploitation having wind power potential comparable to the most energetic northern sea areas, included the Baltic Sea (mean wind power potential ~500-800 W/m^2).

It is worthwhile to stress the fact that any ocean energy development is likely to result in further transformation of the selected sites, already affected by other pressures. The Mediterranean Sea is known to be one of the world's most impacted marine environments (Micheli et al., 2013; Stock and Micheli, 2016). In this perspective, both the possible combination of different renewable technologies, and their potential impact on the environment, should be considered in the context of the existing pressures through a Marine Spatial Planning (MSP) approach (Backer 2011; Azzellino et al. 2013b; Douvere an Ehler, 2008; Ehler and Douvere 2009; Jay 2010).

Focal point of this planning process is the analysis of the spatial data of the different vulnerabilities, the assessment of levels of vulnerability occurring in the area of interest and the quantification of the cumulative impacts affecting the area (Douvere an Ehler, 2008; Ehler and Douvere 2009). The combination of vulnerability and cumulative impact can be used as a decision support tool to identify areas where ecosystem vulnerability and cumulative impact levels meet the objective of maintaining healthy ecosystems or where they are mismatched. The early prediction of the areas of potential conflicts creates the ground for mitigation actions or early negotiations between stakeholders. The exchange between decision makers, stakeholders, experts allow an integrated management of sea uses in the perspective of an optimized spatial decision support systems.

In this study the opportunity of co-locating offshore wind turbines and wave energy converters in the central Mediterranean area is analysed and their environmental sustainability is evaluated through a quantitative Marine Spatial Planning approach.

2 Materials and methods

2.1 Study area

The area considered in this study encompasses the waters around Italy in particular the Adriatic Sea, Ligurian Sea, Tyrrhenian Sea, and partially the Ionian, Sardinia Sea, as well as the northern part of the Strait of Sicily, from 36 to 46 degrees of Latitude and 6 to 20 degrees of Longitude (see Figure 1).

FIGURE 1

2.2 Data gathering and preparation

An analysis grid of 425 cells of 60 x 50 kilometres size was created (Figure 2) and data about wind and wave meteo climatic conditions, bathymetry and a set of vulnerability indicators and human pressures were gridded and used for the purpose of the spatial analysis. Bathymetry data were obtained through the GEBCO (General Bathymetric Chart of the Oceans) One minute Digital Atlas.

Wind and wave data have been extracted from the database ECMWF ERA-Interim Data Set (http://www.ecmwf.int/en/research/climate-reanalysis/era-interim). Data, available for 164 stations (Figure 2) covering a 10-year time series from 2005 to 2014 were considered. Wind data were available every 3 hours while wave data every 6 hours, so the latter was assumed as reference unit for the study. Data used for this study were: horizontal and vertical components of wind speed at 10 m, mean wave direction, mean wave period, significant wave height.

FIGURE 2

The following set of vulnerabilities were used for the analysis:

- Marine Protected Areas presence;
- Posidonia beds;
- Cymodocea beds;
- Mediterranean coralligenous communities.

Marine Protected Areas (MPA) presence was considered based on the dataset available from the World Database on Protected Areas (WDPA, https://protectedplanet.net/) (UNEP, 2016).

Posidonia and Cymodocea beds as well as Mediterranean coralligenous communities have been considered among the vulnerable seabed habitats. These data, updated in September 2016, were extracted from the European Marine Observation Data Network (EMODnet) Seabed Habitats project (http://www.emodnet-seabedhabitats.eu/access-data/download-data/). Seabed habitats have been derived from EUSeaMap which provides polygons based on individual survey habitat classified according to the EUropean Nature Information System (EUNIS).

As far as human pressure indicators were concerned, data on human activities at sea were extracted from the EMODnet data portal (http://www.emodnet.eu/ updated to 2017) which includes a substantial amount of regionally compiled and freely downloadable geo-referenced data related to different aspects of human impacts (http://www.emodnet.eu/human-activities). Data in the following set of human activities was obtained from the EMODnet geoportal:

- Main ports;
- Mariculture activities (finfish and shellfish farms at sea);
- Submarine cables routes;
- Dredge spoils dumping;
- Dredging;
- Hydrocarbon extraction (Active Licences);
- Boreholes Crude oil and Natural gas (Active);
- Oil and gas offshore installation (Operational and Closed down);
- Ocean Energy projects (wave, tidal, salinity gradient, wave/wind);
- Windfarms projects (Planned and Authorized).

In addition, data on naval traffic was derived from the results of PASTA-MARE project (https://webgate.ec.europa.eu/maritimeforum/en/node/1603) which processed AIS (Automatic Identification of Ships) data and provide estimates of maritime traffic density.

Figure 3 and 4 show the maps of vulnerabilities (i.e. MPA and habitats) and pressures (i.e. human activities) used in this study.

FIGURE 3

FIGURE 4

2.3 Statistical methods

The correlation between wind and wave parameters at the different locations was investigated by means of the Pearson's correlation coefficient:

$$r = \frac{1}{N}\sum_{k=1}^{N}\frac{[x(k)-\mu_x][y(k)-\mu_y]}{\sigma_x\sigma_y}$$

where μ_x, μ_y, σ_x, σ_y are the mean and the standard deviation of the variables x and y, of k observations and N is the total sample size.

In order to reduce the dimensionality of the meteo-climatic dataset, Principal Component (PCA) and Factor (FA) and Cluster Analyses (CA) (Afifi and Clark, 1996) have been used. Particularly, PCA and FA were chosen to reduce the dimensionality of the wind and wave statistics. PCA extracted the eigenvalues and eigenvectors from the covariance matrix of the original variances. A Varimax rotation criterion allowing to reduce the contribution of the less significant parameters within each principal component, and rotating the axes defined by the preliminary PCA extraction. The Varimax rotation maintains the axes orthogonality condition. The number of factors to retain was chosen on the basis of the "eigenvalue higher than 1" criterion (i.e. all the factors that explained less than the variance of one of the original variables were discarded).

Cluster Analysis (CA), both hierarchical (HCA) and the not hierarchical K-means (Afifi and Clark, 1996), were used to analyse the similarities of meteo-climatic data groups. The Euclidean Distance was chosen as distance measure:

$$\boldsymbol{d_2(x_i, x_j) = \sqrt[2]{\sum_{k=1}^{q}(x_{ik}-x_{ik})^2}}$$

K-means was used when the data set was constituted by several thousands of records (i.e. time resolution year-month across the decade) whereas HCA was preferred when the data set accounted only some hundreds of records (i.e. time resolution: decade). When the hierarchical procedure was run, the Ward linkage method was selected as agglomeration criterion. K-means CA, on the other hand, was run three times: the final cluster centroids of the solution obtained after the second run were in fact used as initial centres in the third run. Only the third run results are showed in the present study.

3 Results and Discussion

3.1 Wind and Wave conditions

The main descriptive statistics of wind speed v_w, mean wave direction, mean wave period T_z and significant wave height H_s have been calculated (see Table 1) and their temporal variability has been also investigated. It can be observed in Figure 4 that data in the study area are characterized by a certain degree of inter-annual (Figure 5a) and seasonal (Figure 5b) variability in terms of wind and wave patterns.

FIGURE 5

Table 1. Main Statistics of the wind and wave parameters

		v_w (m/s)	Wave Direction (°)	T_z (s)	H_s (m)
N	Valid	28800	17496	17496	17496
Mean		4.0329	214.3284	4.8587	0.8696
Median		3.7351	221.8300	4.9004	0.8019
Std. Deviation		1.73520	50.92970	0.88049	0.41124
Minimum		0.74	2.65	2.30	0.15
Maximum		9.73	357.31	7.88	2.36
Percentiles	25	2.5534	181.8035	4.2962	0.5619
	50	3.7351	221.8300	4.9004	0.8019
	75	5.2447	251.3968	5.4599	1.1227

The correlations among parameters and their correlation with time (month and year) were investigated. As expected, mean wave period and significant wave height were found correlated to each other and both correlated with the wind speed (Table 2).

Table 2. Correlations Matrix of wind speed (m/s), mean wave direction (°), wave period T_z (s) and significant wave height, H_s (m), month and year. Higher correlations are highlighted in bold.

		Wind speed	Wave Direction	T_z	H_s	month	year
Wind speed, v_w	Pearson Corr.	1					
	Sig. (2-tailed)						
	N	28800					
Wave Direction (°)	Pearson Corr.	0.138**	1				
	Sig. (2-tailed)	0.000					
	N	15552	17496				
Wave Period, T_z (s)	Pearson Corr.	**0.661****	0.243**	1			
	Sig. (2-tailed)	**0.000**	.000				
	N	15552	17496	17496			
H_s (m)	Pearson Corr.	**0.862****	0.218**	**0.889****	1		
	Sig. (2-tailed)	**0.000**	0.000	**0.000**			
	N	15552	17496	17496	17496		
Month	Pearson Corr.	-0.092**	-0.036**	-0.103**	-0.101**	1	
	Sig. (2-tailed)	0.000	0.000	0.000	0.000		
	N	28200	17172	17172	17172	31800	
Year	Pearson Corr.	0.001	0.068**	-0.102**	-0.038**	-0.051**	1
	Sig. (2-tailed)	0.813	0.000	0.000	0.000	0.000	
	N	28800	17496	17496	17496	31800	32400

**. Correlation is significant at the 0.01 level (2-tailed).

For the purpose of the combined exploitation of offshore wind and wave energy, the most favourable conditions occur when wind and wave temporal patterns are less correlated. Therefore, in order to identify cases where the variability of the produced wind and wave power would be reduced, the different meteo-climatic conditions were analysed by using a PCA/FA and then classified by means of K-means CA and HCA.

3.1.1 Classification of the meteo-climatic conditions

PCA/FA was applied to the horizontal (U) and vertical (V) wind components, v_w, wave direction, T_z and H_s. The resulting three components explains 89.9% of the original variance. The first component explain the 44.3% of the whole variance, while 28.6% and 17% of the variance is explained respectively by the second andthe third component. The factor loadings of the PCA/FA solution are shown in Table 3. The factor selection was evaluated on the basis of the scree plot (see Figure 6).

Table 3. Factor loadings of the PCA solutions. Higher correlations are highlighted in bold.

	Component		
	1	2	3
Wind Horizontal component at 10m (U, m/s)	0.355	**0.855**	-0.038
Wind Vertical component at 10m (V, m/s)	-0.018	-0.123	**0.989**
Wind speed (v_w, m/s)	**0.905**	0.084	-0.098
Mean Wave Direction (°)	0.044	**0.940**	-0.131
Mean Wave Period (T_z, s)	**0.881**	0.213	0.105
Mean Significant Wave Height (H_s, m)	**0.966**	0.184	-0.042

Extraction Method: Principal Component Analysis. Varimax rotation.

It can be observed that the first component accounts for the v_w, H_s and T_z and, consequently, it is the component that should be minimized to find wind and wave uncorrelated pattern. The second component accounts for wave direction and wind horizontal component and the third component accounts only for the wind vertical component.

A K-means CA was then applied to the factor scores obtained by the PCA/FA extraction at the time scale of year-month (e.g. 2008-1, 2009-4 etc.).

A five K-means clusters solution was chosen, where K-means cluster 1 and 2 show the most favourable meteo-climatic conditions for both wind and wave energy (see Figure 7):

- *K-means cluster 1*: shows v_w, T_z, H_s, wave direction and U wind component above the average and V wind component below the average;
- *K-means cluster 2:* shows all wind and wave characteristics highly above the average;
- *K-means cluster 3:* shows wave direction, U and V components below the average and v_w, T_z and H_s slightly above the average;
- *K-means cluster 4:* shows v_w, T_z, H_s and V wind component well below the average while wave direction and U wind component are above the average;
- *K-means cluster 5:* shows v_w, T_z, H_s, wave direction and U wind component below the average but V wind component above the average.

FIGURE 7

In Table 4 the different meteo-climatic characteristics of the five k-means clusters solution are summarized.

Table 4. Summary of the descriptive statistics of meteo-climatic parameters in the five selected clusters.

Cluster Number		v_w (m/s)	Wave Direction (°)	T_z (s)	H_s (m)
1	Mean	7.0189	244.1954	5.8513	1.4657
	Median	7.0236	245.9893	5.8261	1.4463
	Std. Deviation	0.97742	28.05989	0.53714	0.32199
	Minimum	3.53	151.28	4.13	0.48
	Maximum	9.72	327.53	7.82	2.36
	N	1791	1791	1791	1791
2	Mean	6.3096	236.0212	5.6843	1.2705
	Median	6.3126	236.5948	5.6279	1.2378
	Std. Deviation	1.14373	27.27497	0.47947	0.27122
	Minimum	2.35	113.86	4.39	0.49
	Maximum	9.19	323.53	7.88	2.13
	N	3143	3143	3143	3143
3	Mean	4.9634	151.2357	4.5885	0.7762
	Median	4.9505	152.7164	4.7436	0.7866
	Std. Deviation	1.14066	38.48107	0.80547	0.29004
	Minimum	1.20	2.65	2.30	0.16
	Maximum	9.73	245.43	7.11	2.03
	N	2807	2807	2807	2807
4	Mean	4.0967	256.2834	4.3092	0.5956
	Median	4.1109	255.7535	4.3721	0.5944
	Std. Deviation	0.86030	30.17478	0.62188	0.20302
	Minimum	1.23	147.67	2.59	0.15
	Maximum	6.71	357.31	6.38	1.35
	N	4083	4083	4083	4083
5	Mean	4.1508	188.4616	4.5601	0.6397
	Median	4.1976	191.6520	4.6464	0.6435
	Std. Deviation	1.13312	35.29018	0.69925	0.22378
	Minimum	1.21	23.50	2.46	0.15
	Maximum	8.09	311.69	7.08	1.88
	N	3728	3728	3728	3728
Total	Mean	5.0498	215.5785	4.8753	0.8754
	Median	4.9388	223.1816	4.9112	0.8060
	Std. Deviation	1.52051	50.82291	0.88329	0.41488
	Minimum	1.20	2.65	2.30	0.15
	Maximum	9.73	357.31	7.88	2.36
	N	15552	15552	15552	15552

It is interesting to compare the correlations between the wind and wave parameters obtained pooling all the data set (reported in Table 2) with the ones (shown in Table 5) obtained after splitting the dataset into the described meteo-climatic clusters. The clusters showing the lowest correlation between wind speed, wave period and significant wave heights are the K-means cluster 4 and 5 that refer the meteo-climatic conditions that should be dominant to maximize the advantage to combine wind and wave.

Table 5. Correlation analysis between wind and wave. Data splitted into the five meteo-climatic clusters.

Cluster Number of Case		v_w (m/s)	Wave Direction (°)	T_z (s)	H_s (m)
1	Wind speed v_w (m/s)	1	0.137^{**}	0.560^{**}	0.793^{**}
	Wave Direction (°)	0.137^{**}	1	0.307^{**}	0.274^{**}
	Wave Period T_z (s)	0.560^{**}	0.307^{**}	1	0.890^{**}
	Significant Wave Height H_s (m)	0.793^{**}	0.274^{**}	0.890^{**}	1
2	Wind speed v_w (m/s)	1	$0-.144^{**}$	0.229^{**}	0.718^{**}
	Wave Direction (°)	-0.144^{**}	1	0.355^{**}	0.132^{**}
	Wave Period T_z (s)	0.229^{**}	0.355^{**}	1	0.747^{**}
	Significant Wave Height H_s (m)	0.718^{**}	0.132^{**}	0.747^{**}	1
3	Wind speed v_w (m/s)	1	0.196^{**}	0.498^{**}	0.704^{**}
	Wave Direction (°)	0.196^{**}	1	0.425^{**}	0.313^{**}
	Wave Period T_z (s)	0.498^{**}	0.425^{**}	1	0.877^{**}
	Significant Wave Height H_s (m)	0.704^{**}	0.313^{**}	0.877^{**}	1
4	Wind speed v_w (m/s)	1	0.133^{**}	0.376^{**}	0.694^{**}
	Wave Direction (°)	0.133^{**}	1	0.063^{**}	0.130^{**}
	Wave Period T_z (s)	0.376^{**}	0.063^{**}	1	0.842^{**}
	Significant Wave Height H_s (m)	0.694^{**}	0.130^{**}	0.842^{**}	1
5	Wind speed v_w (m/s)	1	0.037^{*}	0.269^{**}	0.644^{**}
	Wave Direction (°)	0.037^{*}	1	0.215^{**}	0.106^{**}
	Wave Period T_z (s)	0.269^{**}	0.215^{**}	1	0.747^{**}
	Significant Wave Height H_s (m)	0.644^{**}	0.106^{**}	0.747^{**}	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

To highlight the areas where the most favourable meteo-climatic conditions are dominant, a new cluster analysis was performed aggregating the derived K-means clusters values by station over the whole 10-year series. The aggregation allowed to reduce the dataset from several thousands of records to a hundred and to run a second cluster analysis by using a hierarchical approach (HCA) with the Ward method to classify the station meteo-climatic dominant conditions.

Figure 8 shows the characteristics of this new six clusters solution: for the purpose of this study, the most interesting clusters are 1 and 4 and 5 which include the stations where the K-means cluster 4 and K-means cluster 5 (i.e. the ones showing the most favourable meteo-climatic conditions according to the K-means CA results over the time scale of the year-month) are dominant.

FIGURE 8

Finally, HCA clusters 1, 4 and 5 were mapped in order to identify stations showing the most favourable meteo-climatic conditions in terms of wind and wave energy availability (Figure 9).

FIGURE 9

3.2 Spatial analysis of vulnerabilities and human pressure

Due to the high complexity and the regional scale involved, the environmental background of the central Mediterranean Sea area, was considered through a set of multiple indicators, both of environmental vulnerability, and anthropic pressures. A matrix of 12 indicators of anthropogenic pressures and 4 indicators of environmental vulnerability was created for each of the 425 grid units.

For each indicator and every grid cell, two new variables have been calculated: the cell's presence/absence (1/0) and the frequency of occurrence (i.e. as the number of vulnerability elements or human activities per cell unit). Then, Vulnerability and Pressure Indexes were created of the kind presented by Azzellino and colleagues (2013b).

A Vulnerability Index (hereinafter VI) was defined for each grid cell by summing the presence of Marine Protected Areas, Posidonia and Cymodocea beds and the Mediterranean coralligenous communities. In this way, five classes of Vulnerability (from 1 to 5) were obtained and mapped (Figure 10).

FIGURE 10

Only 42% of the grid analysis cells had values higher than 1. The extension of the study area size and the existing data availability gaps both contribute to determine such condition. Grid cells falling in the lowest vulnerability classes (i.e. class 1 and 2) represent the 22 % of the total, reflecting the presence of MPA in offshore waters. The rest 19% of the grid cells are mostly concentrated in coastal areas and present the higher vulnerability classes (i.e. class > 2) due to the concurrent presence of protected areas, seagrass beds and coralligenous habitats (Figure 11).

FIGURE 11

So, in order to create a Cumulative Pressure Index (hereinafter CPI) avoiding any bias due to the variability in the unit of measurements, the frequency of the 12 different human pressures was normalized to 1 and the sum of the different anthropogenic activities within each cell unit was calculated and obtain a quantitative CPI (see Figure 12).

FIGURE 12

Finally, a cumulative impact index was drawn by multiplying the CPI by the VI. The obtained values of the Impact Index, specified on a logarithmic scale, were ranked into 4 classes of impact (< = 0.04 low impact; 0.05-0.33 moderate impact; 0.34-0.61 high impact; > 0.62 very high impact) based on the distribution of the data. As expected, areas showing the higher score (high and very high impact classes) are in general coastal areas and mostly concerns the northern Tyrrhenian Sea, the waters surrounding Sicily and the northern Adriatic Sea. On the other hand, the analysis allowed to identify sites characterised by a low and moderate potential impact, where future wind-wave energy installation could be developed such as the central and southern Tyrrhenian sea, the southern Adriatic sea and the Ionian sea (see Figure 13).

FIGURE 13

3.3 Optimal siting of wind-wave energy technology

The optimal locations for future wind-wave energy infrastructures can be identified by overlaying the areas showing the most favourable meteo-climatic conditions (i.e. stations classified as HCA Clusters 1, 4 and 5) with areas presenting medium and lower values of Impact Index (Figure 13). Based on this analysis (Figure 14) the optimal sites for future wind-wave energy installations can be identified for waters ranging between 50 - 350 m of depth (i.e. depth range suitable for floating offshore wind installations) and they appear mostly located along the Tyrrhenian coast south of Elba island, the northern-western Sardinian coast offshore Alghero, the southern Tyrrhenian off the Aeolian islands and along the southern Adriatic and Ionian coastal waters. Although the analysis been conducted at a coarse spatial scale, and is certainly affected by larger errors in those locations near the coast where hindcast models reveal their limits, still we believe it will be very useful as support for planning future wind-wave installations for the early minimization of potential impacts. Finer scale studies allowing a more accurate characterization of the local meteo-climatic conditions will be needed for the selection of the optimal wind turbine and wave energy converter combination that will leadto a less variable power output.

FIGURE 14

4 Conclusions

The present study highlights areas where a combined technology of wind and wave energy can be potentially developed in the perspective of energy availability and environmental impact minimization.

It is known that the diversification of wind and wave energies generates benefits in terms of produced power. The results of this study showed that despite the general strong correlation between wind and waves, local and temporary conditions of wind –wave weak correlation exist and may be exploited .. for effective combined production of marine renewable energy. The wind-wave meteo climatic analysis here presented showed that these conditions occur in the western and southern part of the study area, in both coastal and offshore deep waters. These results are in partial agreement with the ORECCA project outcomes that suggest only the Strait of Sicily and the French Blue Coast as potential development sites in the Mediterranean Sea area which corresponds to our study. However, their conclusions are mostly based on QuikSCAT[1] satellite offshore measurements of wind speed and direction (Furevik et al., 2010) which are known to have limitations. QuikSCAT data in fact make it possible to draw up homogeneous wind maps of large areas with 0.25° resolution, however measurements taken from satellites by means of scatterometers do have rather high uncertainties (up to 2 m/s) especially in closed basins such as the Mediterranean Sea and, even more, the Adriatic Sea or the Black Sea. So, the fact that our analysis, based on ECMWF data, outlines additional sites of potential developments, such as the Tyrrhenian coast south of Elba island, the southern Tyrrhenian off the Aeolian islands and the southern Adriatic and Ionian coastal waters complements and does not contradict ORECCA results.

Optimal water depth for the development of wind turbines ranges from 50- to 350 meters, so, even though the favourable meteo-climatic conditions appear to be widely available, in some areas (e.g. waters off Corsica, and Ligurian Sea) these resources cannot be easily exploited due to the unfavourable conditions, the low feasibility, and the costs outweighing the benefits.

The study also demonstrates how quantitative elements of impact and vulnerability could be used to better coordinate the different uses of marine space, and to address the need for protecting the common interests from the unsustainable exploitation of finite spatial resources. Vulnerable coastal habitats (i.e. protected species presence as *Posidonia oceanica*, Delile, 1813) should be considered to estimate the ecosystem vulnerability within the suitable depth range for offshore wind farms installations. The used methodological approach allowed to restrict the optimal siting for combined wind wave energy offshore installations to some areas of potential development: along the Tyrrhenian coast south of Elba island, the northern-western Sardinian coast off the town of Alghero, the southern Tyrrhenian Sea off the Aeolian islands and along the southern Adriatic and Ionian coastal waters, all characterized by a good energy potential and a low Cumulative Impact Index.

The cumulative impact indexes developed in this study, although based on a smaller set of human pressures, appear to be coherent with the cumulative human impact assessment presented by Stock and Micheli (2016) and Micheli (2013).

Environmental impact studies of this kind may feed quantitative spatial planning and support the selection of the sites of potential interest for co-locating wind and wave energy installations, providing support for the sustainable development of future wind-wave offshore parks.

5 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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[1] http://manati.orbit.nesdis.noaa.gov/datasets/QuikSCATData.php/

6 Author Contributions

Azzellino and Lanfredi conceived the study, analysed the data and wrote the paper; Riefolo and De Santis contributed to data analysis and to the revised paper writing; Pasquale Contestabile and Diego Vicinanza supervised the meteo climatic data assessment, revised the paper draft.

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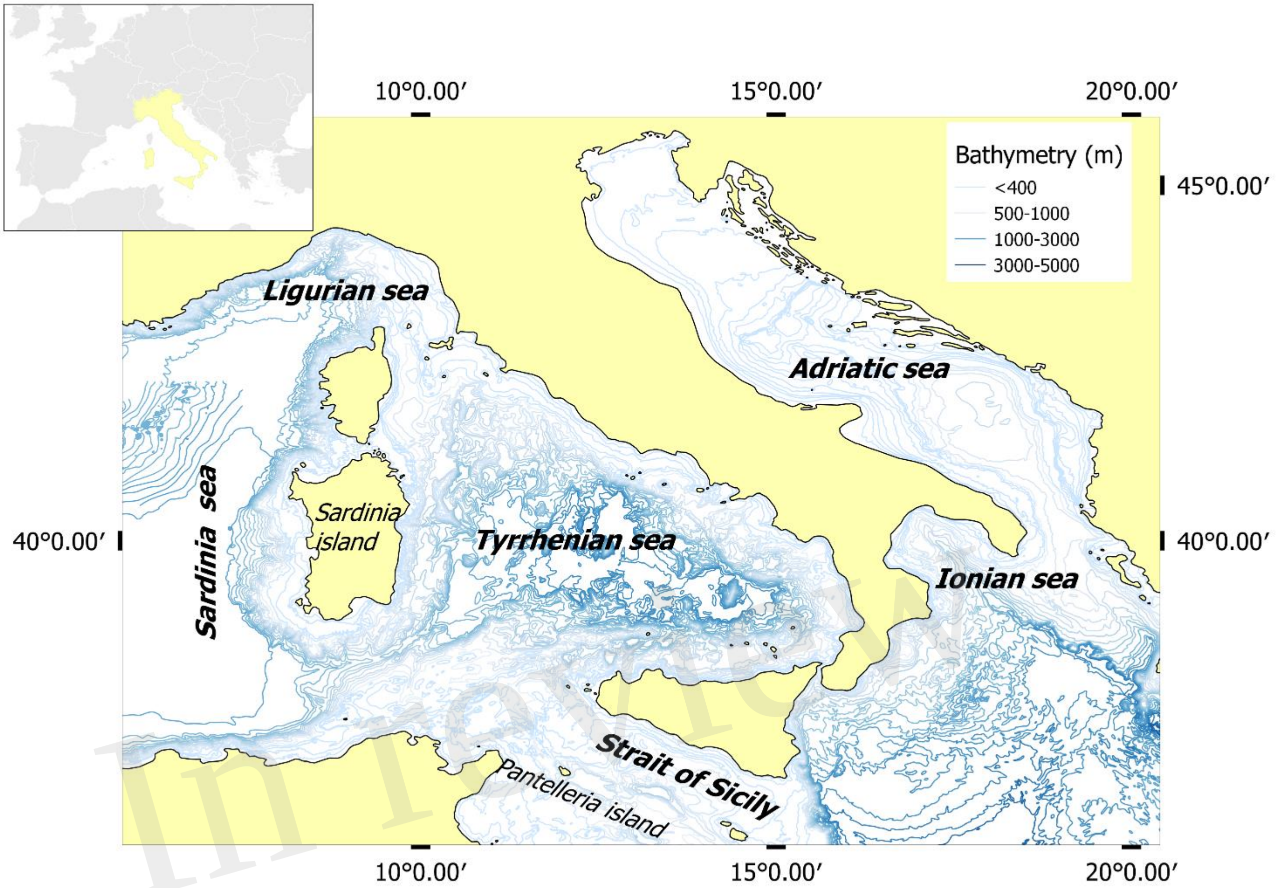

Figure 1. Map of the study area.

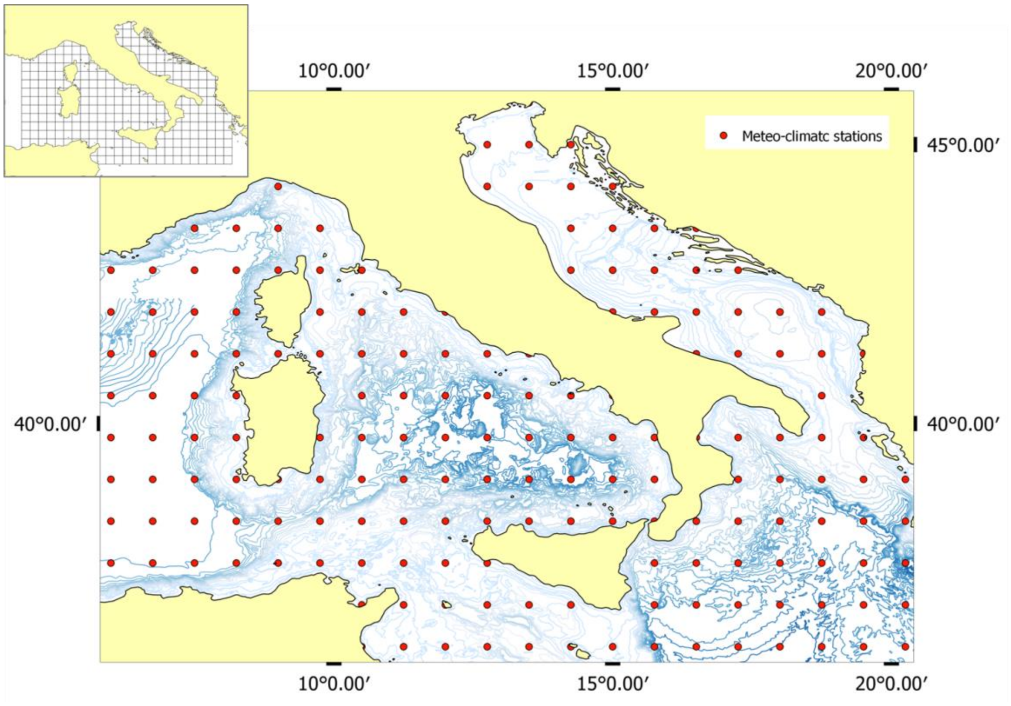

Figure 2. Meteo-climatic stations (n=164). The analysis grid is also shown.

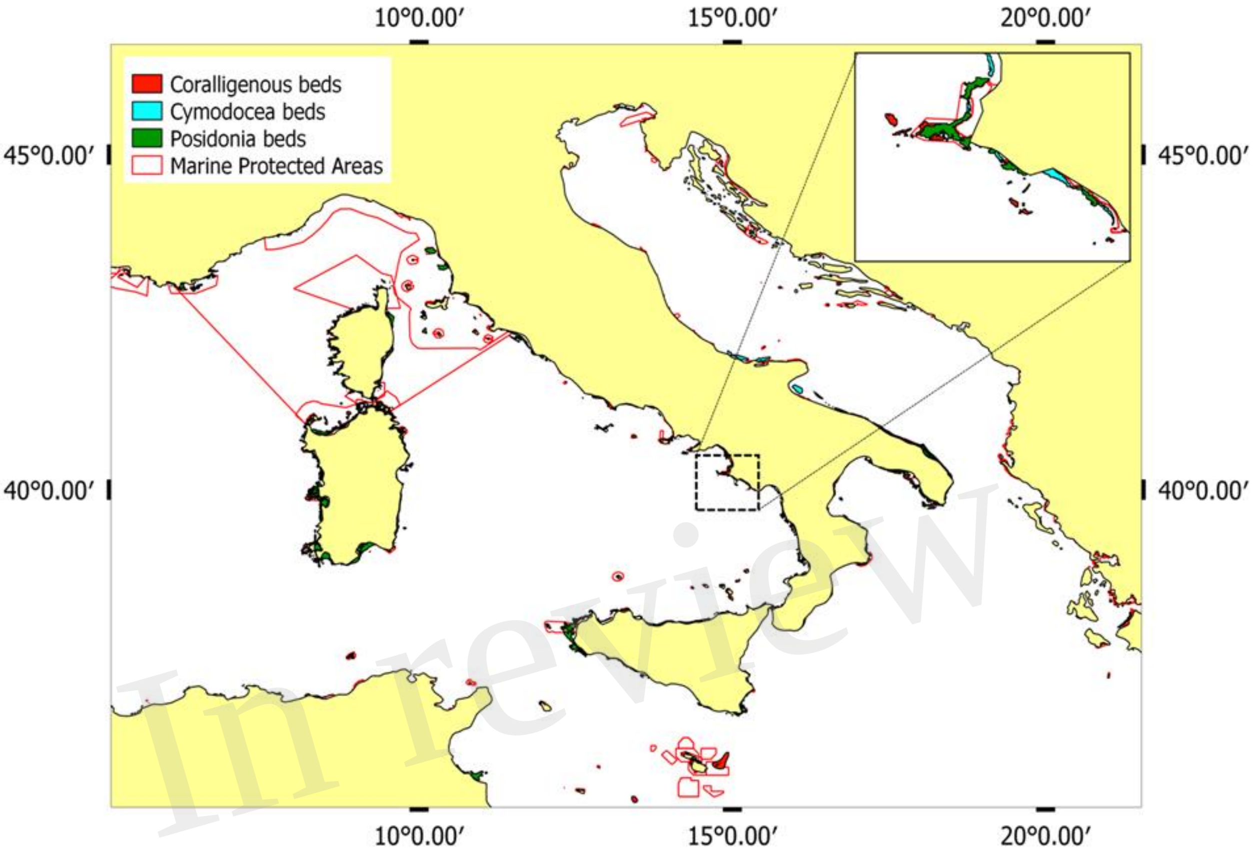

Figure 3. Maps of MPA and Habitats

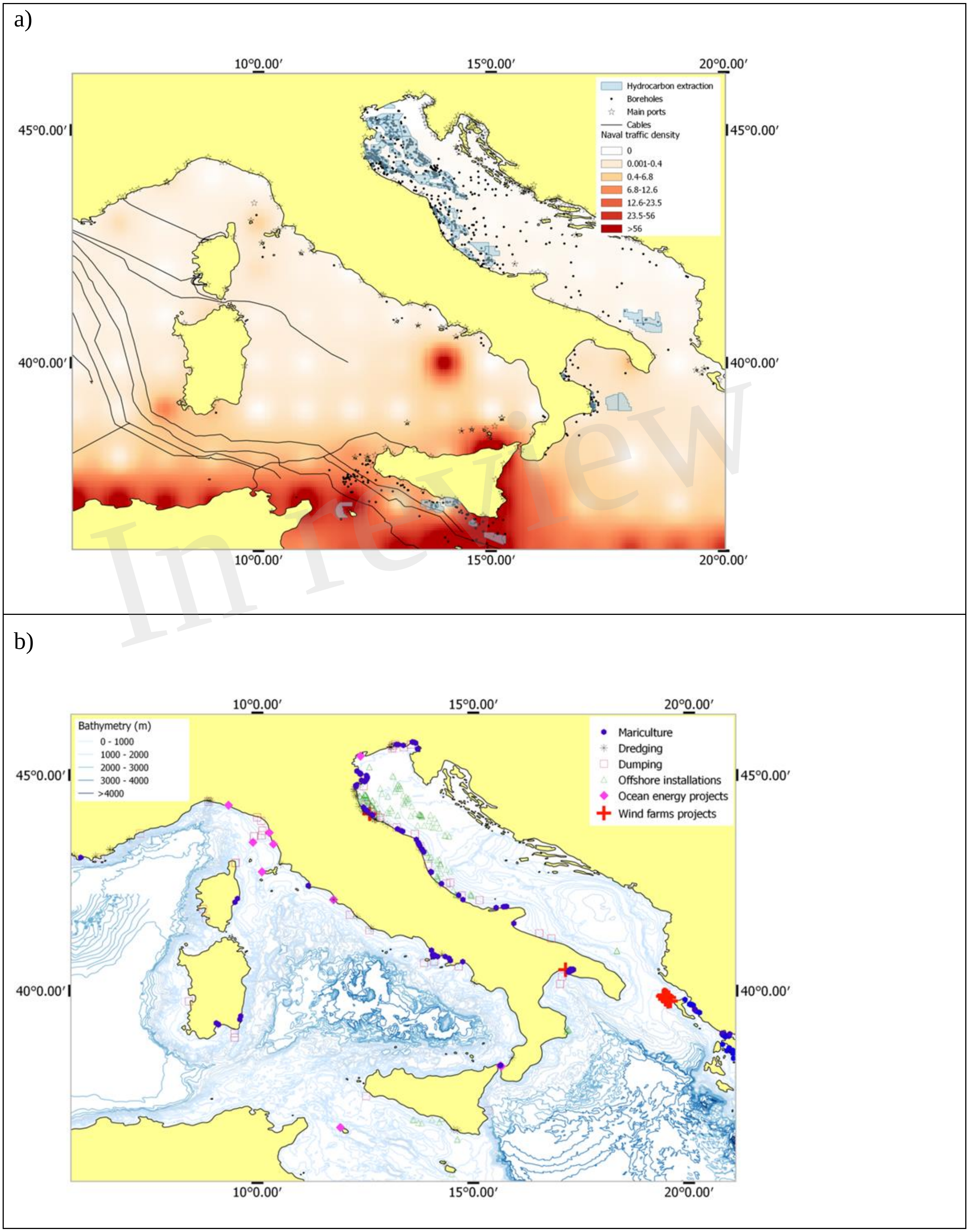

Figure 4. Maps of the pressures: a) hydrocarbon extraction and naval traffic; b) mariculture, dredging and dumping and other activities.

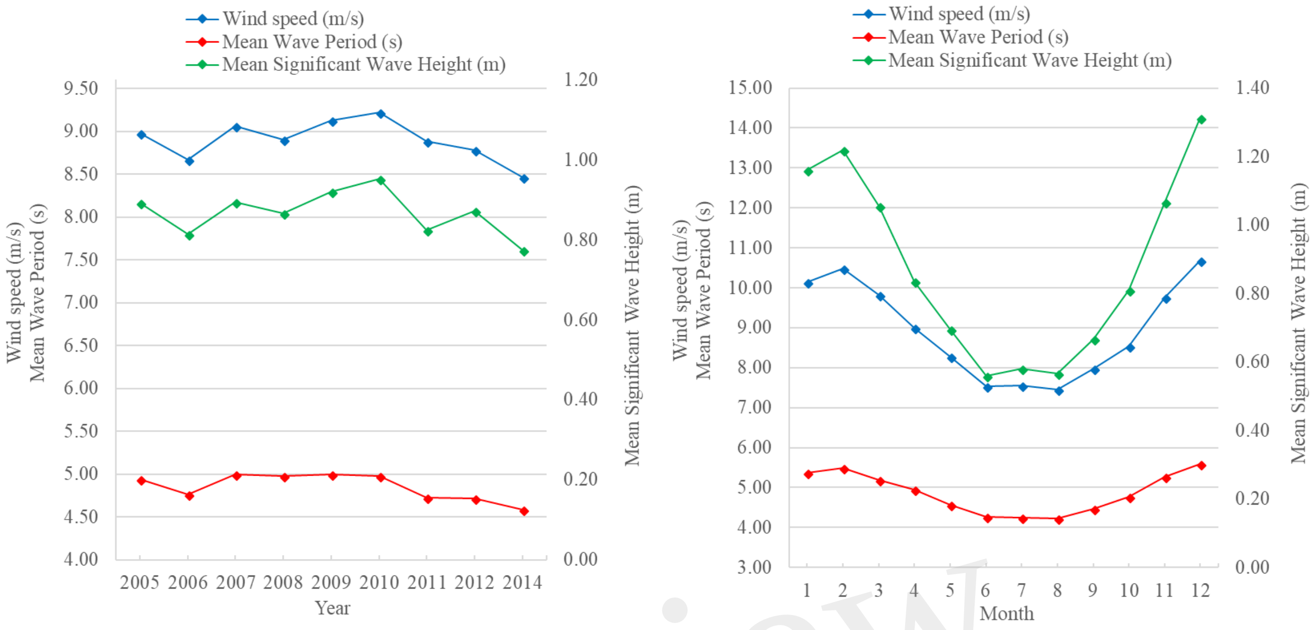

Figure 5. a) Inter-annual and **b)** monthly variability in wind and wave patterns

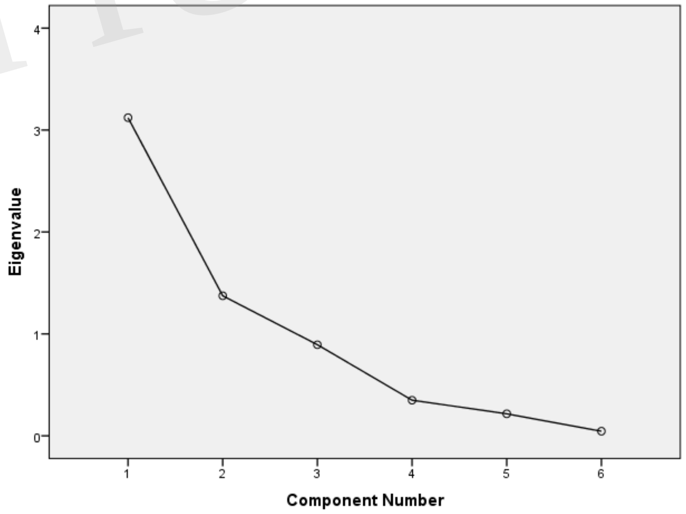

Figure 6. Scree plot showing the extracted components and their corresponding eigenvalues. Three components present eigenvalue higher than 1. Only these were considered in the analysis.

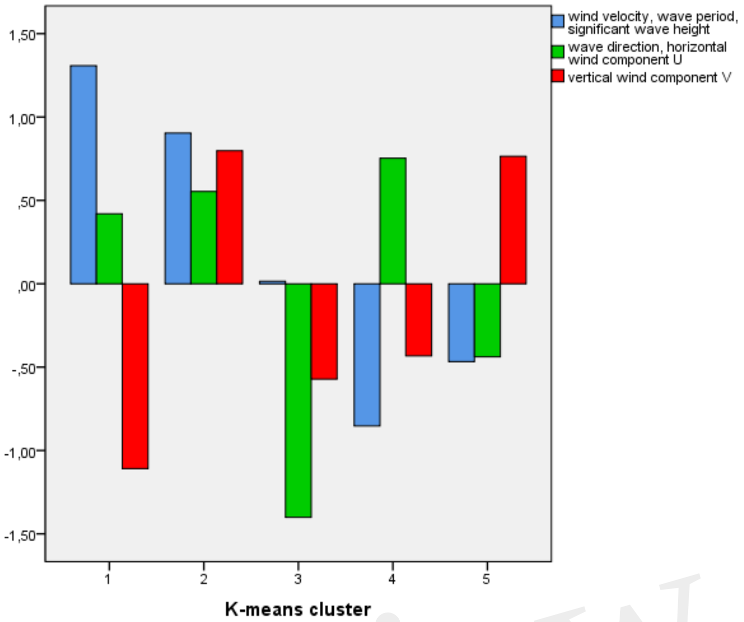

Figure 7. Standardised characteristics of the five K-means clusters. K- means cluster 4 and 5 shows the most favourable meteo-climatic conditions for combined offshore wind and wave energy technologies.

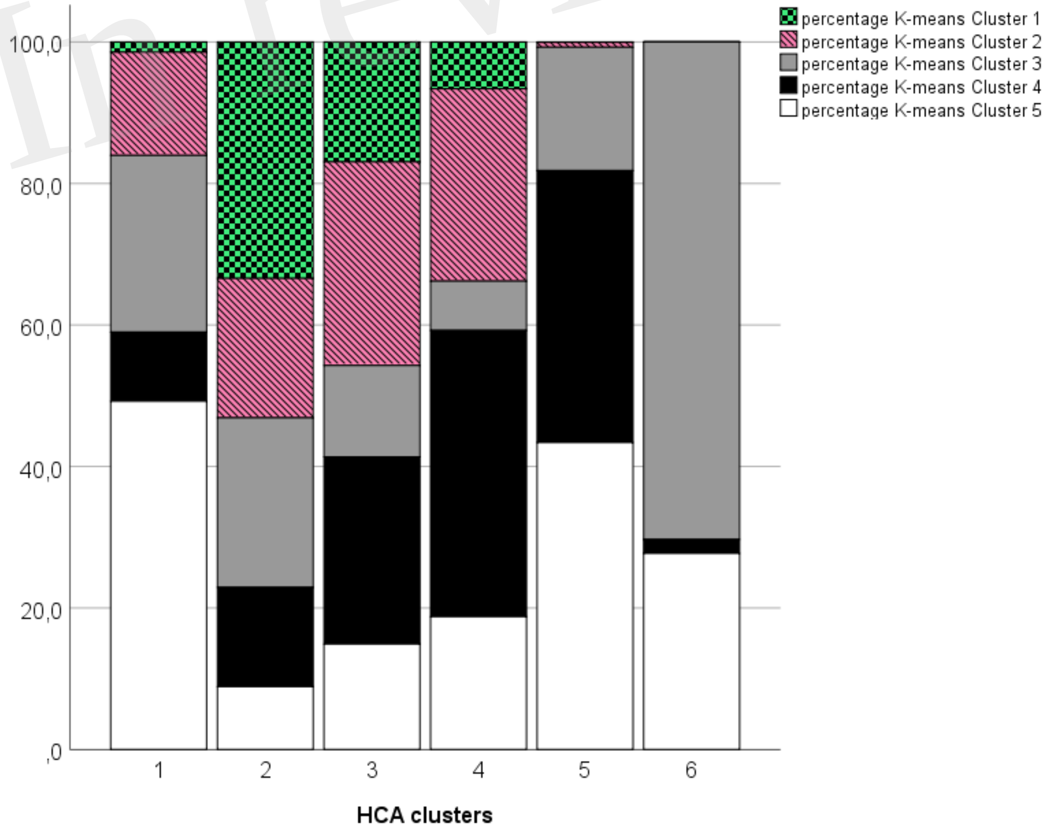

Figure 8. HCA analysis aggregated by stations over the 10-year time series: each bar represents a cluster identified through HCA and colours represent the percentage of K-means Clusters present on each cluster. The HCA clusters of highest interest are 1, 4 and 5 which include the stations where the most favourable meteo-climatic conditions (i.e. K-means cluster 4 and 5) are dominant.

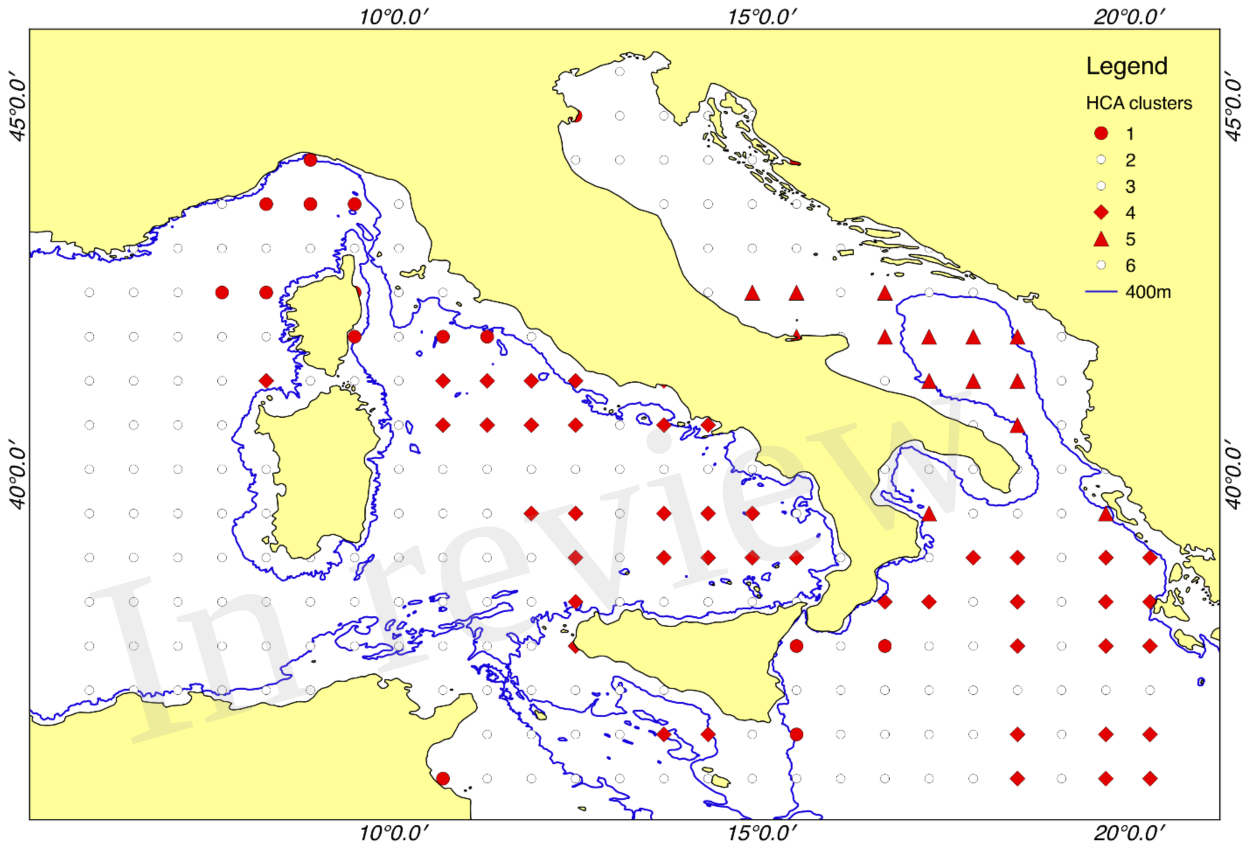

Figure 9. Map of the HCA clusters. The 400m bathymetry is also shown.

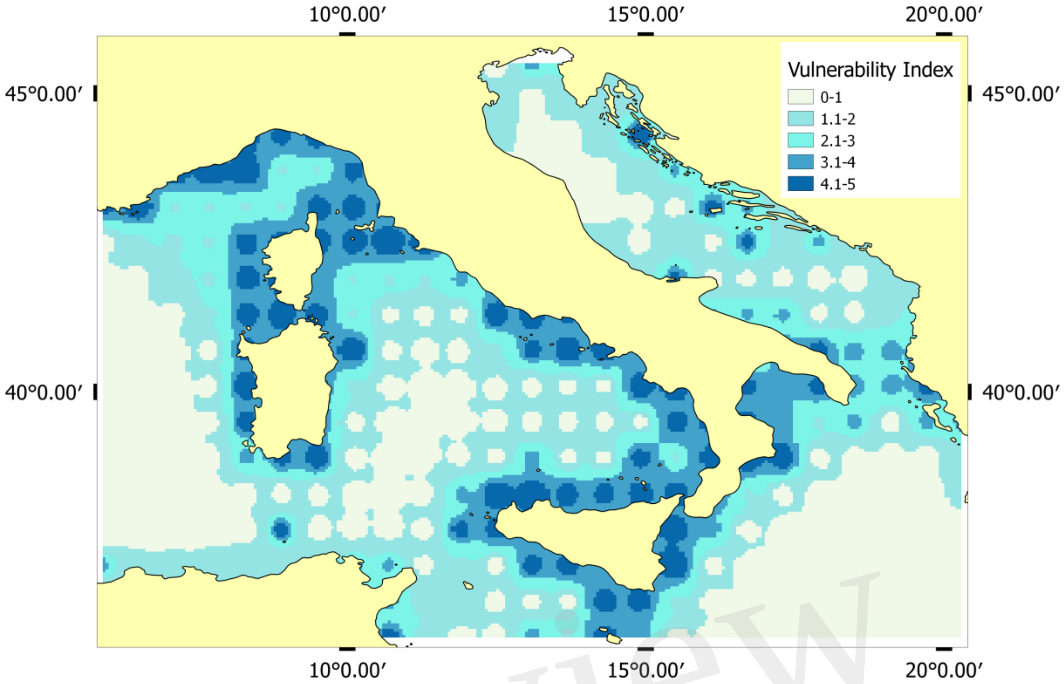

Figure 10. Map of the Vulnerability Index (VI).

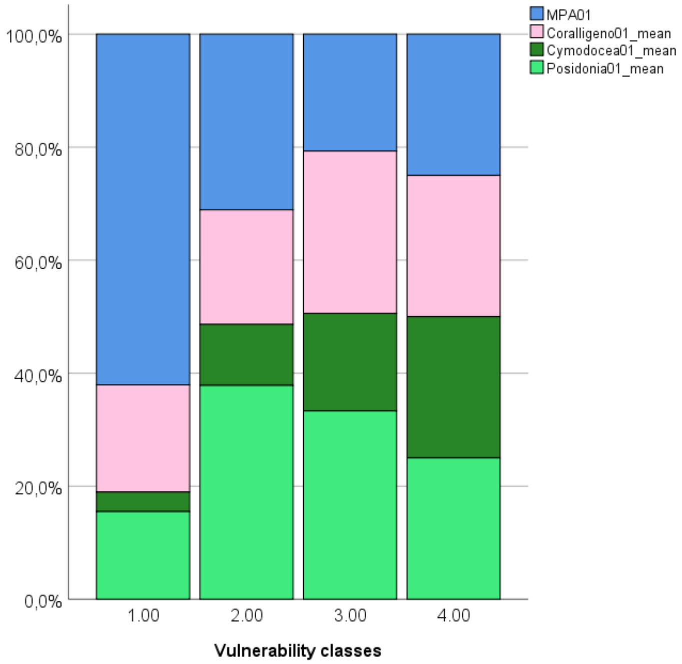

Figure 11. Vulnerability classes description. Only the 4 classes with vulnerability higher than zero are shown.

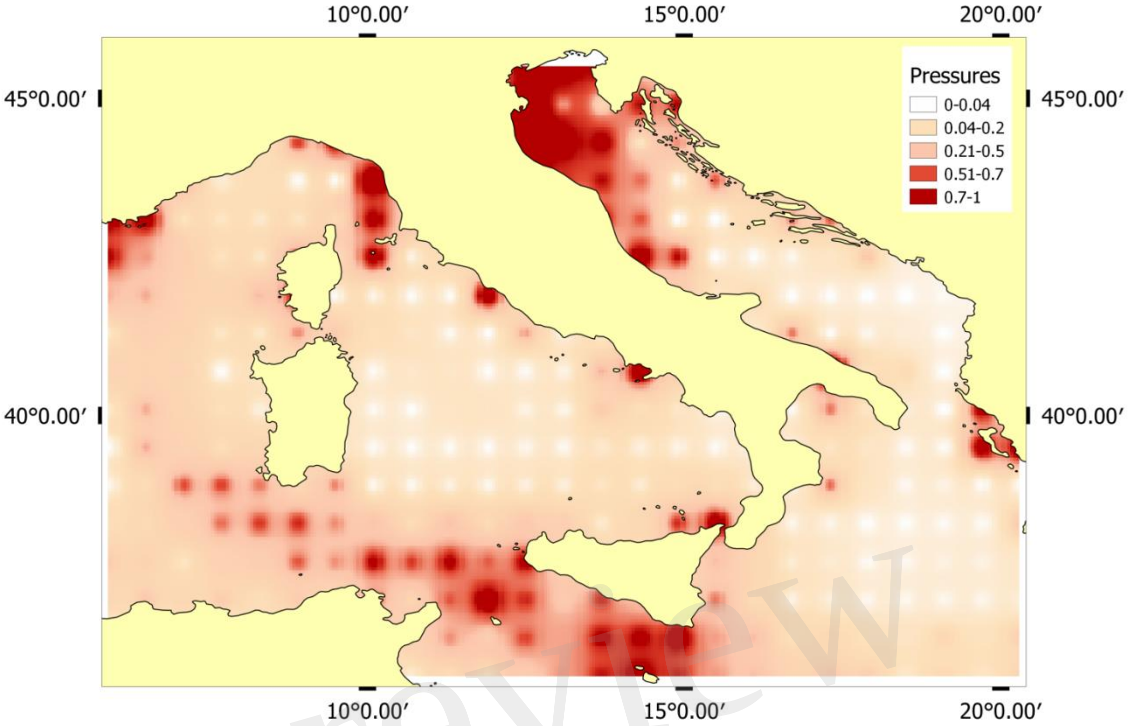

Figure 12. Map of the Cumulative Pressure Index (CPI).

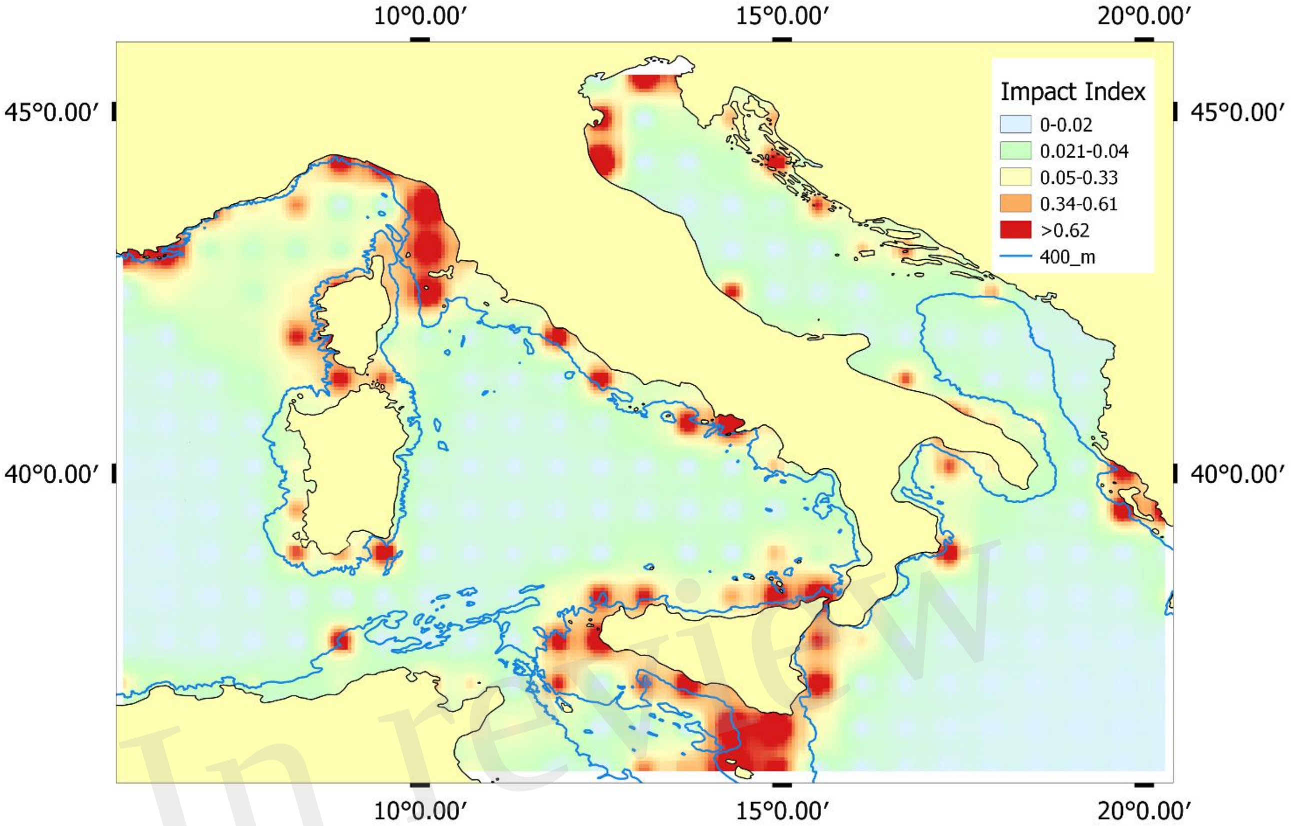

Figure 13. Map showing the Impact Index, ranked into 4 classes of impact (< = 0.04 low impact; 0.05-0.33 moderate impact; 0.34-0.61 high impact; > 0.62 very high impact) based on the distribution of the data.

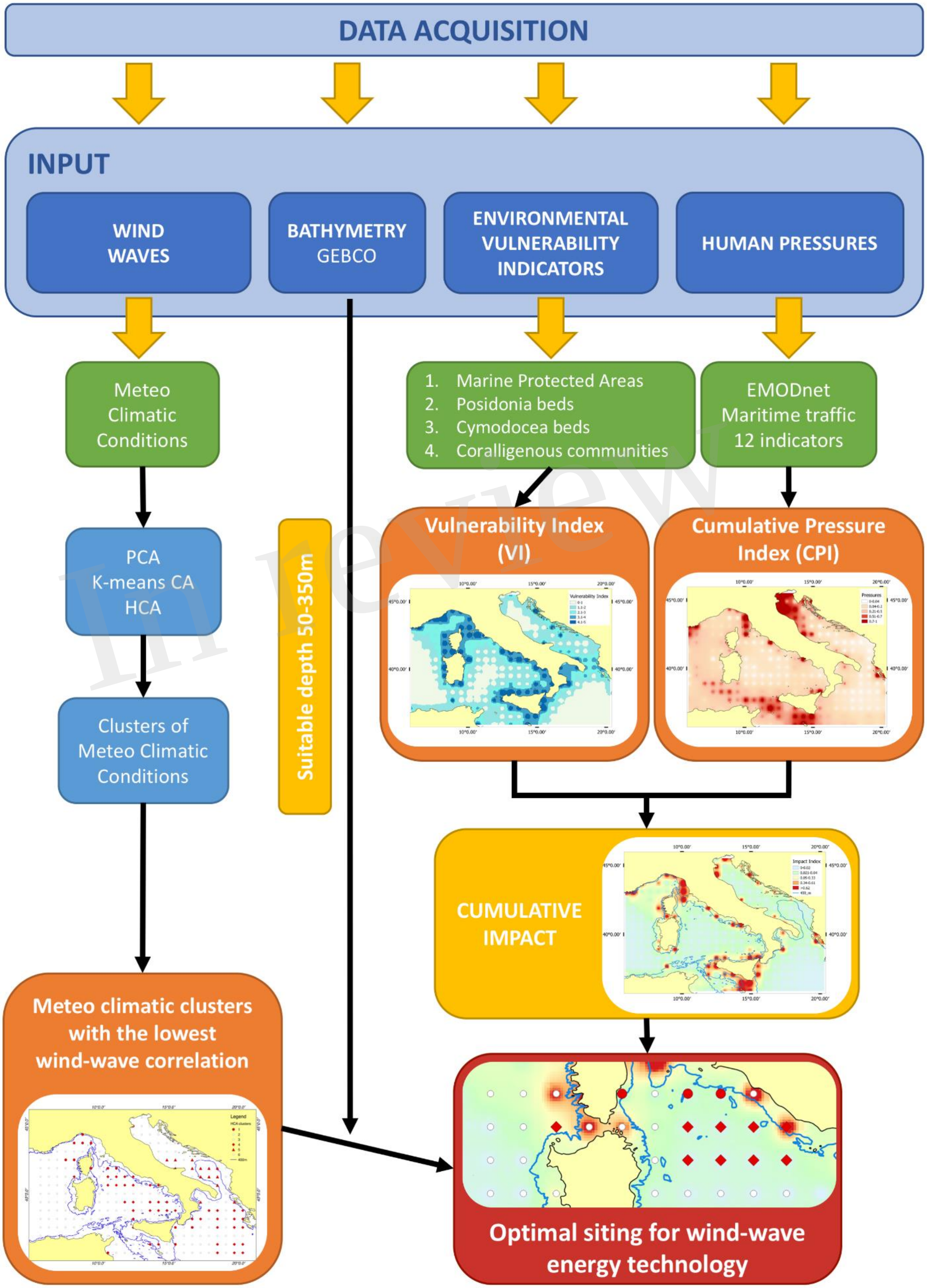

Figure 14. Flow chart showing the optimal siting proposed methodology