Marine renewables: Exploring the opportunity for combining wind and wave energy

Resource diversity is considered the key to manage the intrinsic variability of renewable energy sources and to lower their system integration costs. The expected development of Marine Renewable Energy Installations is likely to result in further transformation of coastal sea areas, already heavily impacted. In this perspective, the combination of different renewables and their potential impact on the environment must be evaluated in the context of the existing pressures. In this study the opportunity of co-locating offshore wind turbines and wave energy converters and their environmental sustainability is evaluated through a quantitative Marine Spatial Planning (MSP) approach.

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Introduction

Marine Renewable Energy Installations (MREIs) are likely to become a large part of the future energy mix worldwide. Some authors [1, 2] have recently suggested that resource diversity may be used to manage the variability of renewable energy sources and lower the system integration costs of renewables. The key benefit, deriving from the diversification of the mix of renewable technologies, lies in the possibility of reducing the variability of the produced power. When adopting a single variable source (for example wind) the only way to reduce variability is by geographical diversity and displacement of the farms. When considering different variable sources, if they are uncorrelated their combination is a powerful alternative in order to obtain a reduction of the overall variability of the produced power. On the other hand, the increasing awareness of the cumulative effects of human activities on the marine ecosystem and the rapid development of the offshore renewable energy sector has led to an increased requirement for Marine Spatial Planning (MSP) to fulfill the need of a holistic and integrated approach to management [3, 4]. The expected development of MREIs is likely to result in further transformation of our coastal sea areas, already heavily impacted by anthropic activities. 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. Spatial planning approaches to marine areas are increasingly required and a distinct field of study and practice is emerging as the result of this new awareness [5, 6, 7]. The spatial conflicts of sea uses and the demand for sea space are in fact increasingly growing. The development of the MRE sector in such a complex framework of existing uses, pressures and expected developments, makes the

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need for MSP even more urgent. Spatial decision support systems, through the efficient exchange of information between experts, stakeholders and decision makers offer the opportunity to guide the transition from the single sector management toward the integrated management of sea uses. The early prediction of the areas of potential conflicts creates 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 in the Italian seas is analyzed. The fact that waves are more constant than winds and the delay between both resources provide the background of the investigation. Although wind [8] and wave energy assessment off the Italian coasts have been recently developed [9, 10, 11, 12], this is the first time that the opportunity for combining wind and wave energy is investigated.

Materials and methods

Study area

The Mediterranean sea is known to be one of the most impacted marine environments [13] and, the Italian seas, according to the same study [13], are among the highest impacted waters, being about 80% of the Italian territorial waters subject to mid to high impacts. The development of the offshore renewable energy sector is likely to result in further transformation of our seas, already affected by significant pressures. Figure 1 shows the study area and the used ECMWF (European Center Medium Weather Forecast) data points.

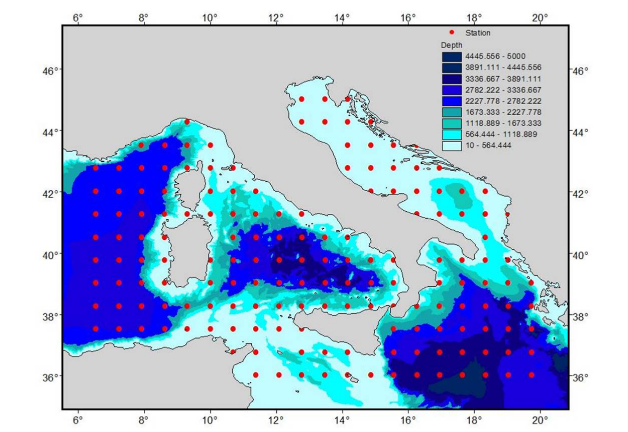

FIGURE 1 Study area

Used data

We used the ECMWF ERA-Interim Data Set (http://www.ecmwf.int/en/research/climate-reanalysis/era-interim). The fields used from this dataset were: horizontal and vertical components of wind speed at 10 m, mean wave direction, mean wave period, significant wave height. We used the ECMWF stations available at all the stations encompassed in the geographical range 36-46 degree of latitude and 6–20 degree of longitude. The data covered a 10-year period from 2005 to 2014. Moreover, a grid was created for the study area for the purpose of the spatial analysis, dividing the area into cells of 60 × 50 kilometers of grid size. As indicators of human pressure the ship traffic and the relevance of the area for the fisheries were taken into account considering their highest impact. Data on naval traffic was derived from the results of PASTA-MARE project which processed AIS (Automatic Identification of Ships) data into estimates of maritime traffic density, whereas the fishery productivity of the different areas were evaluated based on the statistics available from *Osservatorio Nazionale Pesca* (2011). Bathymetry data were obtained through the GEBCO (General Bathymetric Chart of the Oceans) One minute Digital Atlas.

Statistical methods

The potential delay between wind and wave resources provides the background of this study.

Wind and wave conditions

The correlation between wind and wave parameters at the different locations were quantified through the Pearson's correlation coefficient:

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

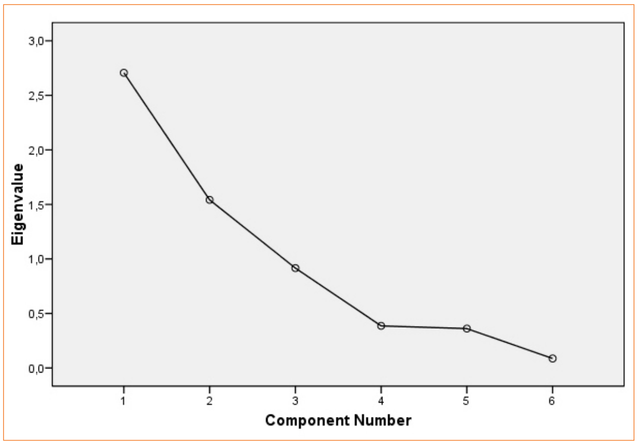

FIGURE 2 Scree plot showing the eigenvalues extracted from the covariance matrix of the original variances

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.

Classification of the meteo-climatic conditions

Two different multivariate techniques were used to analyze wind and wave energy data and the final multicriteria matrix: Principal Component Analysis and Cluster Analysis [14]:

1) **Principal Component Analysis**
   Principal Component Analysis (PCA) was 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. The number of factors to retain was chosen on the basis of the scree plot (see Fig. 2). That allowed to select few components to describe the whole data set with minimum loss of original information.
2) **Cluster Analysis**
   Cluster Analysis (CA), both hierarchical (HCA) and non-hierarchical K-means [14] were used to analyze the similarities of data groups. As distance measure, the Euclidean Distance was chosen:

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

K-means was used when the data set was constituted by several thousands of records whereas HCA was preferred when the data set accounted only some hundreds of records. When the hierarchical procedure was run, the Ward linkage method was selected as agglomeration criterion. K-means CA, on the other hand, was run twice: the final cluster centroids of the solution obtained after the first run were in fact used as initial centers in the second run. Only the second run results are showed here.

Spatial interpolation

AIS data on ship traffic were interpolated using an Inverse Weighted Distance interpolator (IWD).

		Wind speed ($m \cdot s^{-1}$)	Mean Wave Direction	Mean Wave Period (s)	Significant Wave Height (m asl)
N	Valid	332804	522612	522612	522612
Mean		5.0235	215.4373	4.8533	0.8701
Median		4.4740	236.3722	4.7288	0.6724
Std. Deviation		2.63165	95.77630	1.31472	0.67705
Minimum		0.35	0.39	1.66	0.06
Maximum		19.41	359.51	11.39	6.39
Percentiles	25	3.0076	141.6582	3.9487	0.4032
	50	4.4740	236.3722	4.7288	0.6724
	75	6.5166	298.3866	5.6686	1.1354

TABLE 1 Main Statistics of the wind and wave parameters

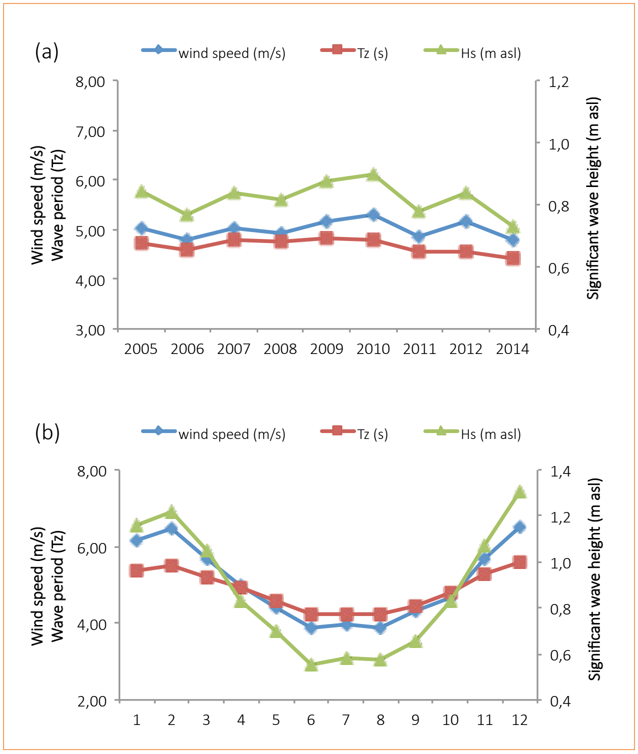

FIGURE 3 Interannual variability (a) and monthly variability (b) in wind and wave patterns

Results and discussion

Wind and wave conditions

Table 1 presents the main statistics of the wind and wave parameters throughout the study period (2005-2014).

As can be observed in Figure 3, the area is characterized by a certain degree of inter-annual and seasonal variability. Table 2 shows the correlations between the wind and wave parameters and their correlation with time.

Although wind and waves temporal patterns (i.e. annual and monthly) are generally well correlated, there might be conditions when the two are less correlated and these conditions are the most interesting in the perspective of reducing the overall variability of the produced power. So, in order to identify those patterns, the different meteo-climatic conditions were classified by means of the k-mean CA algorithm.

Classification of the meteo-climatic conditions

PCA was applied to the wind and wave data (i.e. U and V wind components, the resulting wind speed, the wave direction, period and significant height).

		Correlations wind speed (m/s)	MEAN WAVE DIRECTION	Tz (m asl)	Hs (m asl)	year
wind speed (m/s)	Pearson Correlation Sig. (2-tailed) N					
MEAN WAVE DIRECTION	Pearson Correlation Sig. (2-tailed) N	.058** .000 283239				
Tz (m asl)	Pearson Correlation Sig. (2-tailed) N	.634** .000 283239	.180** .000 522612			
Hs (m asl)	Pearson Correlation Sig. (2-tailed) N	.861** .000 283239	.157** .000 522612	.815** .000 522612		
year	Pearson Correlation Sig. (2-tailed) N	.008** .000 332804	.033** .000 319374	-.066** .000 319374	-.020** .000 319374	
month	Pearson Correlation Sig. (2-tailed) N	-.064** .000 331876	-.006** .000 522612	-.059** .000 522612	.065** .000 522612	-.006** .000 374216

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

TABLE 2 Wind and Wave Correlations

	Components		
	1	2	3
Wind Vertical component at 10 m (V, $m \cdot s^{-1}$)	-0.106	-0.449	**0.885**
Wind Horizontal component at 10 m (U, $m \cdot s^{-1}$)	0.499	**0.693**	0.271
Wind speed ($m \cdot s^{-1}$)	**0.872**	-0.225	-0.101
Mean wave direction	0.283	**0.832**	0.220
Mean wave period (Tz)	**0.850**	-0.240	0.008
Significant wave height (Hz, m asl)	**0.940**	-0.244	-0.024
Extraction Method: Principal Component Analysis			

TABLE 3 Factor loadings of the PCA solutions

Three components were extracted explaining 86.1% of the original variance, the first component explaining 45.1%, the second 25.7%, and the third 15.3% of the whole variance. Table 3 shows the factor loadings of the PCA solutions.

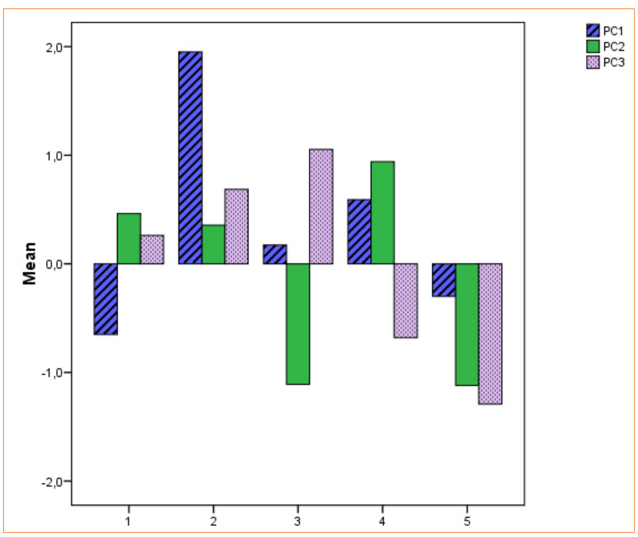

FIGURE 4 Standardised characteristics of the five clusters: *Cluster 1* wind and wave characteristics below the average, horizontal and vertical wind component and wave direction above the average; *Cluster 2* all wind and wave characteristics highly above the average; *Cluster 3* wind and wave characteristics slightly above the average, wave direction and horizontal wind component highly below the average, and vertical wind component well above the average; *Cluster 4* wind and wave characteristics, wave direction and horizontal wind component above the average, vertical wind component below the average; *Cluster 5* all wind and wave characteristics below the average

As can be observed, the first component accounts for wind speed, significant wave height and wave period and, for this reason, it is the component that should be minimized to find wind and wave patterns uncorrelated, whereas the second (accounting for wave direction and wind horizontal component) and the third component (accounting for the only wind vertical component) represent the uncorrelated variability of both wind and wave energy sources.

A K-means Cluster Analysis was then applied to the component scores obtained by the principal component extraction. And a five-cluster solution was chosen. Figure 4 shows the characteristics of the five clusters in terms of principal component scores, and Table 4 summarises the different meteo-climatic characteristics of the five clusters.

Figure 4 shows the characteristics of the five clusters and particularly the following:

- *K-means Cluster 1* wind and wave characteristics below the average, horizontal and vertical wind component and wave direction above the average;
- *K-means Cluster 2* all wind and wave characteristics highly above the average;
- *K-means Cluster 3* wind and wave characteristics slightly above the average, wave direction and horizontal wind component highly below the average, and vertical wind component well above the average;
- *K-means Cluster 4* wind and wave characteristics, wave direction and horizontal wind component above the average, vertical wind component below the average;

Cluster Number		wind speed ($m \cdot s^{-1}$)	mean wave direction	Tz (s)	Hs (m asl)
1	Mean	3.07	242.55	3.92	.40
	Median	2.98	256.22	3.91	.37
	Std. Deviation	1.10	69.59	.95	.21
	Minimum	.35	4.47	1.66	.06
	Maximum	8.97	359.30	8.93	1.74
	N	110626	110626	110626	110626
2	Mean	9.22	269.32	6.44	1.94
	Median	9.04	271.08	6.36	1.80
	Std. Deviation	2.32	27.04	.91	.69
	Minimum	1.12	78.20	4.15	.58
	Maximum	18.20	353.27	10.36	6.07
	N	24492	24492	24492	24492
3	Mean	6.30	172.70	5.15	1.06
	Median	5.99	169.39	5.06	.95
	Std. Deviation	2.17	38.36	.99	.52
	Minimum	.75	4.18	2.66	.14
	Maximum	16.34	327.98	10.19	5.20
	N	48673	48673	48673	48673
4	Mean	6.42	308.80	5.04	1.01
	Median	6.04	315.78	4.98	.90
	Std. Deviation	1.86	35.04	.91	.47
	Minimum	1.82	84.38	2.54	.15
	Maximum	18.37	359.36	10.02	4.49
	N	51240	51240	51240	51240
5	Mean	5.40	72.09	4.69	.82
	Median	4.87	64.25	4.56	.67
	Std. Deviation	2.53	46.47	1.12	.57
	Minimum	.62	0.57	1.76	.06
	Maximum	19.41	308.37	9.39	4.71
	N	48208	48208	48208	48208
Total	Mean	5.16	215.83	4.68	0.83
	Median	4.62	234.98	4.59	0.65
	Std. Deviation	2.67	93.40	1.23	0.63
	Minimum	0.35	0.57	1.66	0.06
	Maximum	19.41	359.36	10.36	6.07
	N	283239	283239	283239	283239

TABLE 4 Summary statistics of the five meteo-climatic clusters

- *K-means Cluster 5* all wind and wave characteristics below the average.

It is interesting to compare the correlations between the wind and wave parameters obtained pooling all the data set (Tab. 2) with the ones obtained by splitting the data set into the described meteo-climatic clusters (Tab. 5). As expected, the cluster showing the lowest correlation between wind speed, wave period and significant wave heights is the first, which refers the meteo-climatic conditions that should be dominant to maximize the advantage to combine wind and wave.

In order to highlight the areas where the most favorable meteo-climatic conditions are dominant a new cluster analysis was performed, aggregating the data by station. This aggregation shrinked the data set from several thousands of records to a hundred. This allowed to use a hierarchical approach (HCA) when running this second cluster analysis. Figure 5 shows the characteristics of this new solution of five clusters: the clusters of highest interest in this case are clusters 4 and 5 which include the stations where the favorable meteo-climatic conditions (i.e. K-means Cluster 1) are dominant.

Cluster Number		wind speed ($m\cdot s^{-1}$)	mean wave direction	Tz (s)	Hs (m asl)	Year
1	Wind speed ($m\cdot s^{-1}$)					
	Mean wave direction	0.238(**)				
	Tz (s)	0.139(**)	0.112(**)			
	Hs (m asl)	0.570(**)	0.144(**)	0.646(**)		
	Year	0.045(**)	-0.002	-0.111(**)	-0.034(**)	
	Month	-0.015(**)	0.018(**)	-0.061(**)	-0.050(**)	-0.021(**)
2	Wind speed (m/s)					
	Mean wave direction	0.207(**)				
	Tz (s)	0.531(**)	0.131(**)			
	Hs (m asl)	0.766(**)	0.202(**)	0.785(**)		
	Year	0.048(**)	0.040(**)	0.037(**)	0.049(**)	
	Month	-0.090(**)	0.026(**)	-0.028(**)	-0.088(**)	-0.035(**)
3	Wind speed (m/s)					
	Mean wave direction	0.041(**)				
	Tz (s)	0.382(**)	0.098(**)			
	Hs (m asl)	0.723(**)	0.037(**)	0.726(**)		
	Year	0.063(**)	0.055(**)	-0.022(**)	0.041(**)	
	Month	-0.039(**)	-0.064(**)	-0.030(**)	-0.041(**)	-0.043(**)
4	Wind speed (m/s)					
	Mean wave direction	0.085(**)				
	Tz (s)	0.474(**)	-0.159(**)			
	Hs (m asl)	0.776(**)	-0.025(**)	0.763(**)		
	Year	0.029(**)	0.018(**)	-0.050(**)	-0.019(**)	
	Month	-0.059(**)	0.005	-0.102(**)	-0.111(**)	0.024(**)
5	Wind speed (m/s)					
	Mean wave direction	0.038(**)				
	Tz (s)	0.471(**)	0.223(**)			
	Hs (m asl)	0.794(**)	0.109(**)	0.778(**)		
	Year	-0.012(*)	-0.016(**)	-0.083(**)	-0.054(**)	
	Month	-0.023(**)	-0.027(**)	-0.042(**)	-0.038(**)	0.031(**)

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

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

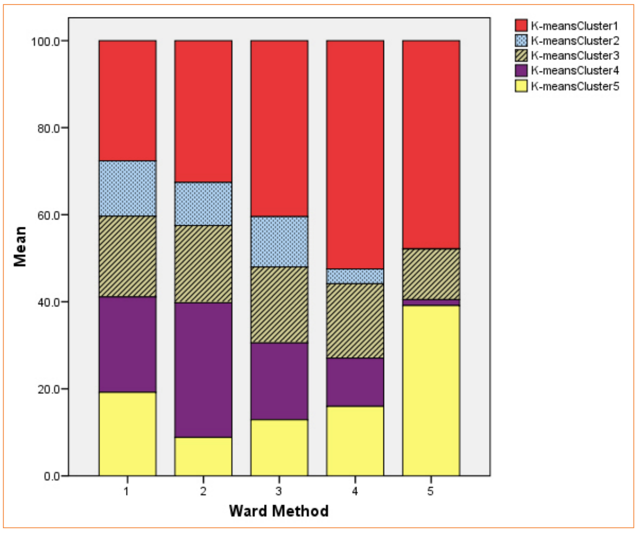

FIGURE 5 Bar charts show the characteristics of the five clusters obtained from performing the hierarchical CA based on the data aggregated by stations: the clusters of highest interest in this case are clusters 4 and 5 which include the stations where the favourable meteo-climatic conditions (i.e. K-means Cluster 1, see Fig. 4) are dominant

It must be observed that Cluster 4 should be preferred to Cluster 5 since it presents also a higher frequency of the K-means Cluster 5 conditions which are less favorable in terms of net potential energy (see Tab. 4 and Fig. 4).

Spatial Analysis

At this point the spatial position of the most favorable meteo-climatic conditions for combining wind and wave are analyzed and overlaid with the most significant anthropic pressures (i.e. naval traffic and fishery). Figure 6 shows the position of the HCA Cluster 4 and the situation in terms of naval traffic density and the relevance of the different areas for fishery.

It can be observed that the most interesting areas for combining wind and wave are the southern Adriatic sea, the coastal areas of the central and southern Tyrrhenian sea, and some spot coastal areas in the Ionian sea. As shown in Figure 6, these areas, are also relevant for fishery (e.g., the Adriatic sea) and naval traffic (e.g., central Tyrrhenian sea and the coastal areas surrounding the Strait of Messina). This highlights the potential conflictual use of the marine space by these different human activities. It is also worthwhile to remind that the Italian seas are among the most impacted marine environments [13] and, particularly, the areas outlined in this study as of potential interest for the MREI area, characterized by mid to high cumulative impacts (Fig. 7).

In these situations quantitative criteria are needed to implement Marine Spatial Planning (MSP) to better coordinate the different uses of space, and to address the need for protecting the common interests from the unsustainable exploitation of finite spatial resources.

The spatial conflicts of sea uses and the demand for sea space are in fact increasingly growing. The development of the MRE sector in such a complex framework of existing uses, pressures and foresees developments, makes the need for quantitative MSP even more urgent.

In this study examples are given on how spatial planning methods should support the optimal siting of new marine infrastructures in the perspective of the mitigation of conflicts between competitive uses and their environmental sustainability.

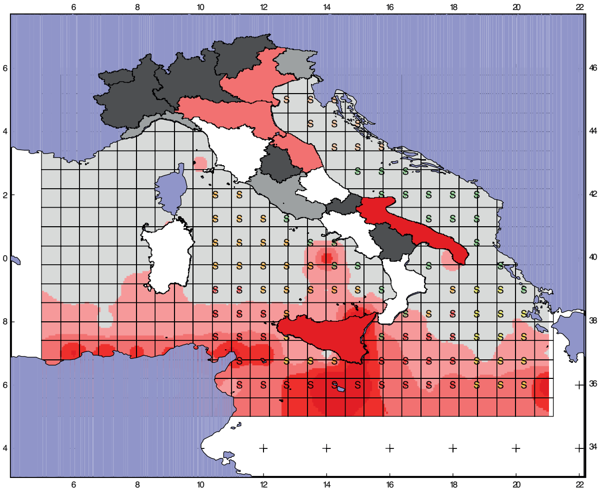

FIGURE 6 Map of the meteo-climatic clusters overlaid with naval traffic and fishery pressure

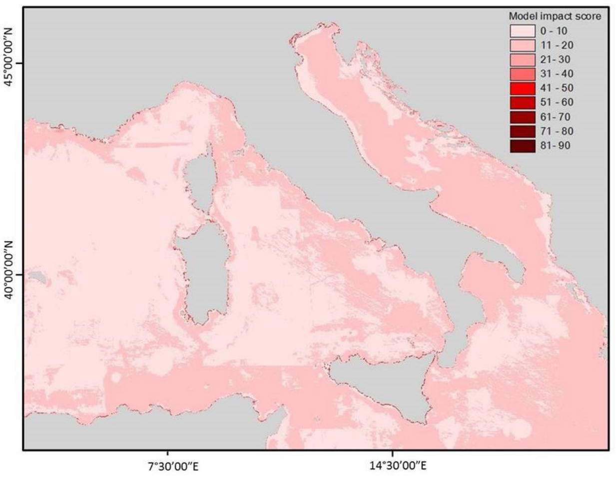

FIGURE 7 Map of the cumulative anthropic impact of the Italian seas
Source: [13]

Conclusions

This study highlights the potential benefits of combining wave and wind power in the Italian seas. The hypothesis of the diversification of renewable energies is grounded on two key benefits: 1) the variability of the produced power can be decreased; 2) power availability can be increased. These benefits are greater when un-correlated resources are combined. This study showed that, although waves and winds are strongly correlated, in some conditions their correlation may be lower. In these situations the combined production would be less variable and more available.

This pattern in the Italian portion of the Mediterranean Sea occurs more frequently in the southern Adriatic Sea closer to the Tyrrhenian and Ionian Sea coasts. Moreover, this study demonstrates how quantitative spatial planning methods may support the selection of the sites of potential interest in the perspective of co-locating wind and wave energy installations, allowing an early identification of the potentially conflictual uses (i.e., ship traffic and fisheries) and providing support for the optimal siting of the wind-wave parks in the light of the environmental sustainability.

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