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An Evaluation of Marine Renewable Energy Resources Complementarity in the Portuguese Nearshore

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Abstract: The Portuguese nearshore represents a suitable environment for the development of marine energy farms, with recent progress being related to the implementation of the first commercial wave farm or a large scale floating wind project. At the same time, there is also high solar power in this area that can be extracted; in the near future, the rapid development of floating solar projects all over the world is expected. In this context, the aim of the present work is to identify the complementarity between solar, wind and wave resources based on 10 years of ERA5 data (from 2012 to 2021). The results are provided mainly in terms of spatial maps. The analysis shows that solar and wind power are more significant in the southern part of this region, indicating for each resource an average value of 223 W/m^2 for solar and 660 W/m^2 for wind. On the other hand, the wave power gradually decreases from north to south, with an average value of 10 kW/m being expected at a distance of 50 km from the shoreline. In terms of complementarity, two scenarios were considered (mild and restrictive), the difference between them being estimated to be around 10%. Several dimensionless indices were defined in order to highlight the correlation between solar, wind and wave conditions, which may be considered as an element of novelty for the target area. In general, higher values (0.5) were noted in the case of the wind-wave and wave-solar combinations, excepting the southern part of Portugal (Algarve) where particular conditions were noted. Finally, the expected power outputs from some relevant technologies were also estimated, including a new concept of the wave energy generator designed for the WindFloat platform. Compared to the solar and wind systems, the performance of the selected wave generation system was quite low, suggesting that other types of wave energy converters would be more appropriate at this moment in the coastal area targeted. Finally, we need to mention that the idea of using multiple resources from a single marine site is an attractive one, while the methodology dedicated to this topic will continuously improve as new technological solutions emerge.

Keywords: Portuguese nearshore; marine renewable energy; solar; wind; waves; complementarity; ERA5; sustainability; hybrid projects

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1. Introduction

Regardless of the energy sources taken into account, there will always be controversy regarding the viability of a particular solution. Nevertheless, if we discuss the renewables sector, one of the biggest challenges is probably related to the intermittency of the natural sources that may significantly fluctuate over various time intervals and geographical areas. The coastal areas represent one of the best regions for the implementation of renewable projects, given the possibility of accessing multiple sources of energy. For example, they are suitable for the development of wave farms [1], provide the conditions for the implementation of large offshore wind projects [2] or the possibility of using solar power to support the tourism industry [3]. More than this, it is considered viable to develop mixed projects that combine conventional energy sources (such as oil, coal or natural gas) with renewable ones, or to capture two renewable sources from a single location. The combination of wind and solar seems to be the most frequent one; this being the case of Hassan et al. [4], who combined these two resources with a diesel power source for some rural areas in Iraq; or as in Santos et al. [5], where the impact of the two resources was evaluated for Brazil (onshore). As for the offshore areas, the wind and wave resources are strongly related, this aspect being reflected in Rusu and Onea [6] from a global perspective.

In the case of marine areas, it is expected to obtain more promising results from the development of the mixed wind-wave projects, taking into account that the offshore wind sector is a mature one, while the wave sector has the potential to obtain similar performance [7,8]. From this perspective, in the work of Perez-Collazo et al. [9] a comprehensive evaluation of the most relevant concepts was provided, highlighting at the same time the advantages emerging from a joint project, such as cost reductions, strong synergies, shared logistics, better predictability or coastal protection opportunities. Some other works are dedicated to the development of the wind-wave concepts, that are basically using the wind turbine supporting structure (monopile or semi-submersible platform) in order to add a wave energy converter (WEC). This is the case of Kamarlouei et al. [10], who developed and tested a 1:27 prototype model, or that of Hu et al. [11] which involved the numerical analysis of a large scale WindFloat system coupled to several WEC configurations. The WindFloat concept is designed around a floating triangular platform capable of supporting a wind turbine designed to operate in offshore areas. This project is operational [12], being implemented in several European sites, such as Kincardine (UK)—50 MW capacity; Erebus (UK)—96 MW; Golfe du Lion (FR)—30 MW; WindFloat Atlantic (PT)—25 MW; WindFloat1 (PT)—2 MW, decommissioned in 2016.

During recent years, the idea of using floating solar panels has gained attention. As mentioned in Hooper et al. [13], several marine designs were proposed, from which we can mention circular structures, hydro-elastic membranes, pontoons or light structures. It is important to mention that due to the natural cooling, a solar panel located at sea may increase its electricity production by 13% compared to a similar one located onshore. There are projects already being developed in shallow waters in the Maldives, North Sea or Abu Dhabi, that are expected to gradually expand to offshore areas [14].

More ambitious projects are targeting the developments of hybrid offshore renewable solutions that combine solar, wind and wave resources. This is the aim of the EU-SCORES (European Scalable Offshore Renewable Energy Sources) project [15], that involves several partners from Europe (for example TU Delft) and has a budget of EUR 45 million. According to the authors, the purpose of this proposal is to accelerate the energy transition in the EU (European Union) community and also to connect the academic and industrial partners involved in the renewable sector. The idea of using these three resources is not new, having already been discussed for some other coastal areas, such as in the US [16] or already tested by the start-up Sinn Power [17].

The target area considered in this work is related to the continental part of the Portuguese coastal environment facing the North Atlantic Ocean. By looking at the existing literature, we note that the previous works are in general dedicated to the assessment of a single marine resource (solar, wind or wave power). Nevertheless, a good starting point in the assessment of multiple sources is provided in Costoya et al. [18] that focused on the analysis of the offshore wind and solar energy for the entire Iberian Peninsula. Based on the data related to the CORDEX (Coordinated Regional Climate Downscaling Experiment) and ERA5 (ECMWF Reanalysis 5th Generation) projects, it was possible to provide a complete picture of the local resources for the time interval 2000–2040. In this case, it was found that wind power of 1200 W/m^2 may be expected in the northern part of this peninsula, while for the solar energy, more energetic resources are expected in the south-western part (≈210 W/m^2). The synergy between wind and solar resources was also evaluated, by defining various indicators such as the stability index, energy classification or risk index. At this point, we can mention that in the above work no restrictions were taken into account (e.g., water depth or Exclusive Economic Zone—EEZ) and the performance of a particular generator was not considered. In the work of Onea and Rusu [19], several scenarios that involve a hybrid wind-wave farm operating in the northern part of the Portuguese continental area (near Porto) were developed. Various aspects were taken into account, starting from the assessment of the natural resources, expected electricity production of some wind/wave generators and finally evaluating also the expected coastal protection induced by such a project. In terms of the capacity factor, the wind turbines present values in the range 26.7–46%, compared to a maximum capacity factor of 29% associated with the wave systems (Wave Dragon). In Fortes et al. [20], the possible benefits coming from the integration of multiple renewable sources into the Portuguese power sector were evaluated. This work involves several representative concentration pathway (RCP) scenarios that extend until the year 2050, with only the wind resources from the marine areas being considered. Based on these results, it was found that in the medium and long term the offshore wind will be positively affected, being capable of compensating for the expected decline of the Portuguese hydropower and solar photovoltaic (PV) sector. The increase in future wind energy is in line with recent studies that highlighted this tendency for some other European regions, such as the Baltic Sea, that may become a representative hot-spot for the offshore wind sector [21].

Although the Portuguese environment seems to have significant solar, wind and wave conditions, little attention was given to the synergy between these three marine resources, more important studies being focused on the wind and solar combination for the onshore area. This is the case of Couto and Estanqueiro [22], that considered combining the existing wind power plants with PV systems, a higher complementarity being noted in the central and northern part of Portugal. According to these results, the onshore area of Portugal is suitable for the development of large-scale hybrid projects. In a similar way, Jerez et al. [23] performed an analysis for the entire Iberian Peninsula, concluding that the entire onshore area has strong potential for the development of hybrid solar-wind projects. The complementarity analysis of the natural resources represents a relatively new topic as we can see from Jurasz et al. [24], with more important progress being associated with the interval 2009–2018. From all the studies, only in Kies et al. [25] was the idea of using the solar, wind and wave power considered in order to cover the energy balance from the Iberian Peninsula. For this geographical area, a significant part of the complementarity analysis is dedicated to the analysis of the solar-wind resources associated with the onshore area of Spain. Definitely, there is interest in the Portuguese marine energy sector, considering that there are plans to develop hybrid wind-wave farms near the locations of Aguçadoura and Viana do Castelo (north of Porto) that may include wave capacities of 10 MW. These investments are made through the EU-SCORES project [26] that will also include an offshore solar-wind project near Belgium, from which 3 MW will be a PV system. Therefore, the present work aims to provide a better understanding of the correlation between these three marine resources, by using relevant thresholds for the performances of the converters.

In this context, the following research questions will be addressed:

(a) Provide a complete picture of the solar-wind-wave resource complementarity in the Portuguese nearshore;
(b) Identify some suitable hot-spots for the development of hybrid marine renewable projects;
(c) Establish the performances of some renewable generators (solar, wind and waves) operating in the Portuguese nearshore area.

2. Materials and Methods

2.1. Target Area

In Figure 1, the Portuguese coastal environment is presented. According to Bueno-Pardo et al. [27], this could be divided into three sectors (north, center and south). In addition to this, some other features were represented, such as the boundaries of [28], and the 50 km distance from the shoreline that seems to be the current operational limit of the WindFloat platform [12].

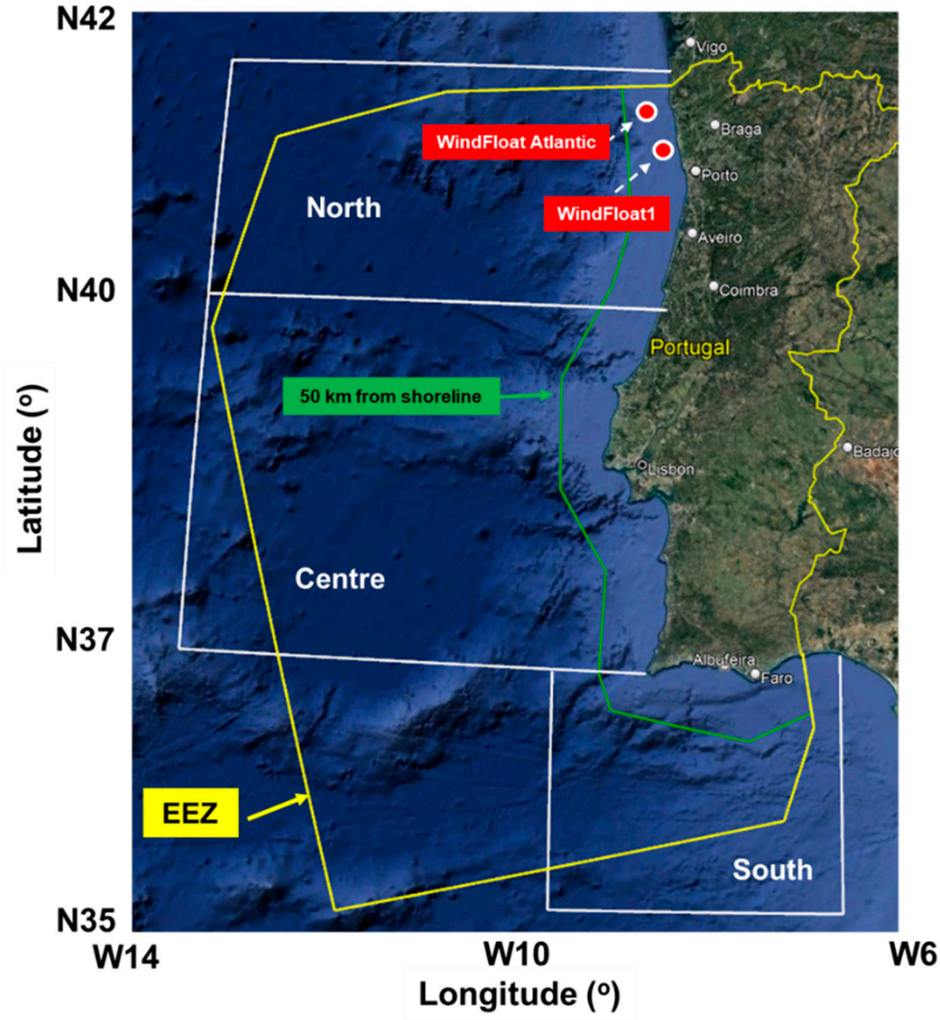

Figure 1. The Portuguese nearshore (target area). Figure processed from Google Earth 2022, including some additional information, such as the area covered by the Exclusive Economic Zone, the locations of the WindFloat projects and the separation between the coastal sectors (north, center and south).

The dynamics of the Portuguese electricity market are illustrated in Figure 2, considering the annual values reported between the years 1985 and 2022. It should be noted that the electricity consumption gradually increased over the years, starting from a minimum of 18.9 TWh (in 1985) and reaching a peak of 60.3 TWh (in 2016). Nevertheless, this evolution was not constant, with some periods when the consumption was constant (interval 2002–2004) or even decreased (2019–2022). In terms of the renewable share, only the wind and solar sectors were taken into account, the influence of the onshore market only being visible in recent years (after 2020), exceeding for the first time the share of 25%. For the interval 2015–2019, the wind market was less performant in the conditions where the electricity demand reached historical peaks. As for solar power, this started as a 0.3% (in 2010) share, gradually expanding to a 4.5% share in 2022, which means that there is enough space for development.

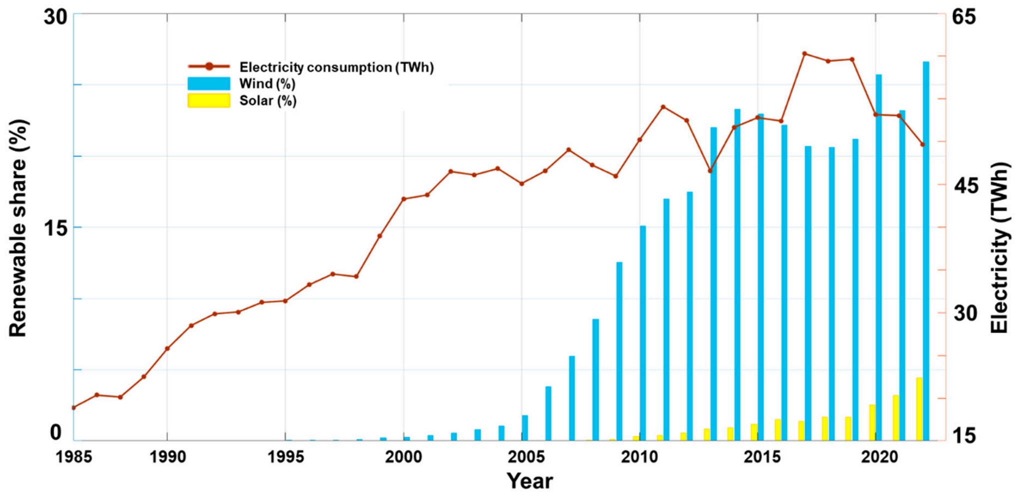

Figure 2. Portugal's electricity balance (1985–2020) distributed between electricity consumption and electricity generation from wind and solar sources. Information processed from [29].

2.2. Dataset

The reanalysis data (solar, wind and wave) used in the present work are related to the ERA5 project that is provided via the Copernicus Climate Change Service [30]. This is based on the previous ERA-Interim and ERA-40 datasets, being capable of combining numerical simulations with in situ observations in a consistent way. A time interval of 10 years (from January 2012 to December 2021) was selected for evaluation; the dataset includes hourly values (24 per day) for each type of parameter.

For the solar energy, the surface solar radiation downwards (or SSRD in J/m^2) was used, this being defined as the amount of the solar radiation that reached a horizontal plane. This includes the diffuse and direct solar radiation and is similar to the measurements provided by a pyranometer located at the surface of the Earth. As mentioned in the ERA5 documentation [31], all the parameters simulated are averaged over a model grid box and therefore significant differences may occur when compared to a particular in situ station that is linked to a particular location and time frame. In order to express this parameter in terms of watts per square meter (W/m^2), the values accumulated need to be adjusted to an accumulation period (3600 s in this case), which leads to [32]:

$$P_{solar} = \left(\frac{SSRD}{3600}\right) \quad (1)$$

The wind speed represents the next parameter, more precisely the one associated with a height of 100 m above the surface of the Earth (from u and v components), that will be further denoted as $U100$. This is a relatively new parameter, which avoids the uncertainties that were related to the adjustment of the initial $U10$ parameter to a particular hub height [8]. Moreover, at this moment, most of the operational onshore and offshore wind turbines are defined by hub heights of 100 m [33,34]. In order to obtain the wind power density (in W/m^2), the following expression will be used [8]:

$$P_{wind} = \frac{\rho_{air} \cdot U_{100}^3}{2} \quad (2)$$

where, ρ_{air}—air density (≈1.225 kg/m^3 at 15 °C and 1 atm).

The wave power (in kW/m^2) is defined by using the parameters mean wave period (*Te*) and the significant height of combined wind waves and swell (*Hs*), as follows [8]:

$$P_{wave} = \frac{\rho_{water} \cdot g^2}{64 \cdot \pi} \cdot T_e \cdot H_s^2 \quad (3)$$

where ρ_{water} is water density (1025 kg/m^3), g is gravitational acceleration (9.81 m/s^2). At this point, it is important to mention that the ERA5 project provides solar and wind datasets at a spatial resolution of 0.25° × 0.25°, while the wave parameters are associated with a grid of 0.5° × 0.5°. As a consequence, in the case of wave complementarity assessment only the solar/wind grid points associated with the wave model are considered in order to obtain a similar fit.

In general, the studies focused on the assessment of multiple natural resources using the complementarity analysis in order to identify the dependency of one resource on another. A higher value of the parameter rated above a particular threshold indicates a strong complementarity and therefore only a project based on that resource should be recommended. On a general level, this can be expressed as [35]:

$$xCy = \frac{Number\ of\ hours\ (x > threshold\ x\ and\ y < threshold\ y)}{Total\ numbers\ of\ hours} \quad (4)$$

$$yCx = \frac{Number\ of\ hours\ (y > threshold\ y\ and\ x < threshold\ x)}{Total\ numbers\ of\ hours} \quad (5)$$

where, xCy and yCx are the complementarity index of x to y parameter (and vice versa) rated between 0 and 1 (dimensionless index); threshold x and threshold y—particular thresholds mentioned in the literature review. For example, a higher value of xCy indicates that only a renewable project focused on the x resource should be developed.

In Table 1, the complementarity indices used in the present work including the thresholds used for evaluation are presented. Based on the existing literature, for the wind and wave conditions, two different case studies (CS1 and CS2) were considered for assessment, the second one being more restricted in terms of the energy level. In the case of the solar parameter, based on existing works [32], it is recommended to use the 5th percentile statistical value associated with the area taken into account.

Table 1. The case studies considered for the complementarity assessment of the solar-wind-wave resources.

Case Study	Renewable	Renewable	Ref.
CS1	Solar	Percentile of 5% related to the current target area	[32]
	Wind	80 W/m^2	[35]
	Wave	2.5 kW/m^2	
CS2	Solar	Percentile of 5% related to the current target area	[32]
	Wind	280 W/m^2	[36]
	Wave	5 kW/m^2	
	Complementarity indices		
SOCWI		Solar complements wind	
WICSO		Wind complements solar	
SOCWA		Solar complements wave	
WACSO		Wave complements solar	
WICWA		Wind complements wave	
WACWI		Wave complements wind	

By looking at the existing literature, we identified two case studies for the present work. The first one (denoted as CS1) is taken from Wen et al. [35] and is related to wind and wave complementarity. For example, in the case of the wind resources, a wind speed value of 5 m/s (or 80 W/m^2 in terms of wind power) was used as a threshold since these are the expected values at which most of the offshore wind turbines start to generate electricity. For the waves, the authors concluded that a wave power value of 2.5 kW/m (associated with $Hs > 1$ m and $Te > 5$ s) is relevant for the performances of various wave generators, after consulting the power matrix of different WECs. Another approach is to consider thresholds associated with the mean annual values related to the target area taken into account. The scenario CS2 is based on the work of Kardakaris et al. [36], where the wind and wave complementarity related to the Greek Seas were evaluated. The results were based on the ERA5 data and in situ measurements, concluding that a minimum threshold of 280 W/m^2 and 5 kW/m are relevant for the wind and wave power, respectively. For simplicity, the same values were considered for the evaluation, noting that these values were two times higher than in the case of CS1 (see, for example, the waves). As a consequence, the scenario CS2 can be related to CS1, as a more restrictive version.

2.3. Solar, Wind and Wave Energy Systems

In addition to the resource assessment, another objective of the present work is to identify the expected power output from a renewable system that may operate in the vicinity of the Portuguese coastal environment. The first presentation of these systems is provided in Table 2. The solar panel was previously considered in de Souza Nascimento et al. [32] for an offshore application involving the coastal environment of Brazil, while the expected power output can be simply defined as [32]:

$$P_{solar\ panel} = P_{solar} \cdot A_s \cdot \eta \quad (6)$$

where P_{solar} is solar power (in W/m^2), A_s is solar panel area, η is the efficiency of the panel (26.8% in this case).

Table 2. Technical specifications of the renewable systems considered.

(a) Solar Panel [32]		**(b) Wind—Vestas Offshore V164-9.5 MW [37]**		**(c) Wave—WWF SWEDE [38]**	
Type	Silicon crystalline	Power rating	9.5 MW	Rated power	2.4 MW
Efficiency	26.8%	Cut-in wind speed	3 m/s	Sphere radius	5 m
Output capacity	221.1 W	Nominal wind speed	14 m/s	Cut-in	1 m/1 s
		Cut-out wind speed	25 m/s	Cut-out	8 m/14 s
Panel area	2 m^2	Rotor diameter	164 m	Type	Single point absorber
		Hub height	100 m		

For the wind turbine, the WindFloat platform was considered as a reference since it is a successful project already implemented in several European offshore sites, as can be observed in Figure 1 [12]. The WindFloat 1 project was the first one in which a semi-submersible platform was connected to a floating wind turbine, capable of operating in wave heights of 17 m and wind speeds of 40 m/s. This was installed in 2011 at a distance of 5 km from the shore, and during the 5-year operating period has provided almost 17 GWh to the local grid throughout a single Vestas V80-2 MW generator. The WindFloat Atlantic project is located near the Portuguese city of Viana do Castelo (20 km from shore); it was connected to the grid in 2019 and has a capacity of 25 MW (3 × Vestas V164-8.4 MW) and initially cost almost EUR 60 million. Another interesting project is Erebus that will be initiated in 2027 in the coastal area of Pembrokeshire, Wales, at a distance of 44 km from the shore. The project will have an installed capacity of 96 MW and be expected to provide electricity for almost 90,000 homes.

The Vestas V164-9.5 MW wind turbine [39] was used for assessment since it is suitable for installation on WindFloat platforms. According to the existing information, the operating hub height is in the range 105–140 m, but for the present work a hub height of 100 m was considered in order to use the $U100$ parameter related to the ERA5 dataset. Based on the information provided in Table 2 and on the characteristics of the power curve presented in Figure 3 the expected power production of these generators can be expressed as [40]:

$$P_{turbine} = \int_{cut-in}^{cut-out} f(u)P(u)du \quad (7)$$

where *cut-in*/*cut-out* are the characteristics of the considered turbine, $f(u)$ is the Weibull probability density function, $P(u)$ is the power curve of the Vestas V164-9.5 generator.

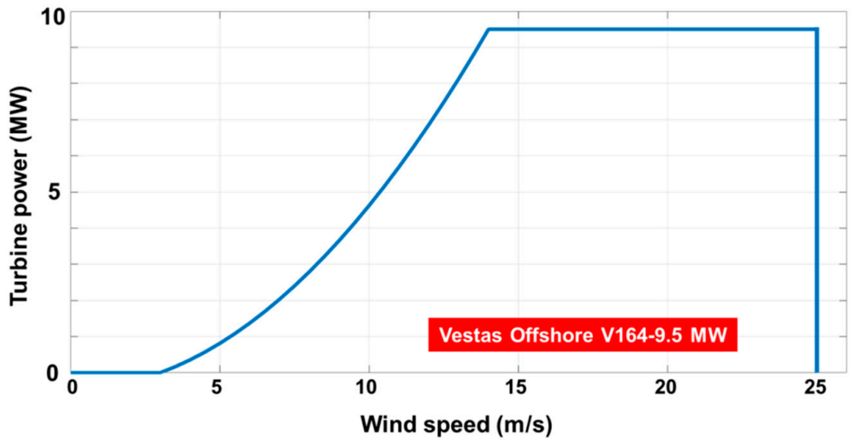

Figure 3. Power curve of the Vestas Offshore V164-9.5 MW wind turbine based on the information provided in Yue et al. [37].

The success of the WindFloat project inspired some other researchers to develop hybrid wind-wave projects in which a wave energy converter (WEC) was adjusted to the structural frame of this platform. This is the case of the WWF SWEDE (WindWaveFloat single point absorber) system that was proposed among some other solutions, such as oscillating water columns or oscillating plates [38]. The power matrix of this concept is presented in Figure 4, where the power output is indicated in terms of the bivariate distribution of the sea-state (wave height and period). It is important to mention that the authors provide this matrix in terms of the wave conditions reported for regular waves (*H* and *T*), while for the present work the wave characteristics were associated with the parameters *Hs* and *Te*, which may be considered a limitation of the present work.

H (m) \ *T* (s)	4	5	6	7	8	9	10	11	12	13	14
1	4	34	134	19	2	0	0	0	0	0	0
2	16	130	389	71	8	2	0	0	0	0	0
3	36	278	695	147	19	4	1	0	0	0	0
4	66	470	1044	244	33	6	2	1	0	0	0
5	107	701	1436	357	52	10	3	1	0	0	0
6	157	1002	1862	484	75	15	4	1	1	0	0
7	214	1590	2354	624	103	21	6	2	1	0	0
8	276	1586	2903	778	137	29	8	3	2	1	0

Figure 4. Power matrix associated with the WWF SWEDE wave generator. Information processed from [38], where the output power is in kW (green colour indicates zero or small values, yellow average and red high power values).

In order to identify the performances of a particular WEC system, the following equation can be applied [40]:

$$P_{WEC} = \frac{1}{100} \cdot \sum_{i=1}^{nHs} \sum_{j=1}^{nTe} PM_{ij} \cdot PW_{ij} \tag{8}$$

where PM_{ij} is the expected power output for a particular sea state (e.g., 2903 kW output related to H = 8 m and T = 6 s), PW_{ij} is the energy percentage related to the bivariate distribution (wave height and period) of a particular site, nHs and nTe are the number of particular bins (in this case: 8 for the wave height and 11 for wave period).

3. Results

Figure 5 presents the spatial distribution of the natural resources for the entire Portuguese EEZ. The first parameter taken into account is the solar power (Figure 5a), where the values oscillated between 165 and 220 W/m^2, higher resources being noted in the southern part of the Iberian Peninsula. For each coastal sector (north, center and south) indicated in Figure 1, some grid points where the energy level was higher are highlighted. These were located in the range of 0–50 km (see dashed line) distance from the shore. The point SO1 (solar 1) was associated with the northern sector and presented a value of 198.3 W/m^2. From this, the solar power increased to 217. 1 W/m^2 (SO2—center) and up to 223.4 W/m^2 in the case of SO3 (south). In the case of wind power (Figure 5b), the amount of energy was higher compared to solar, a maximum of 348 W/m^2 (north), 346.3 W/m^2 (center) and 660.9 W/m^2 (south) being expected. It is important to mention that the location of the maximum values for solar and wind power from the southern sector was identical (≈7.5° W/36.5° N).

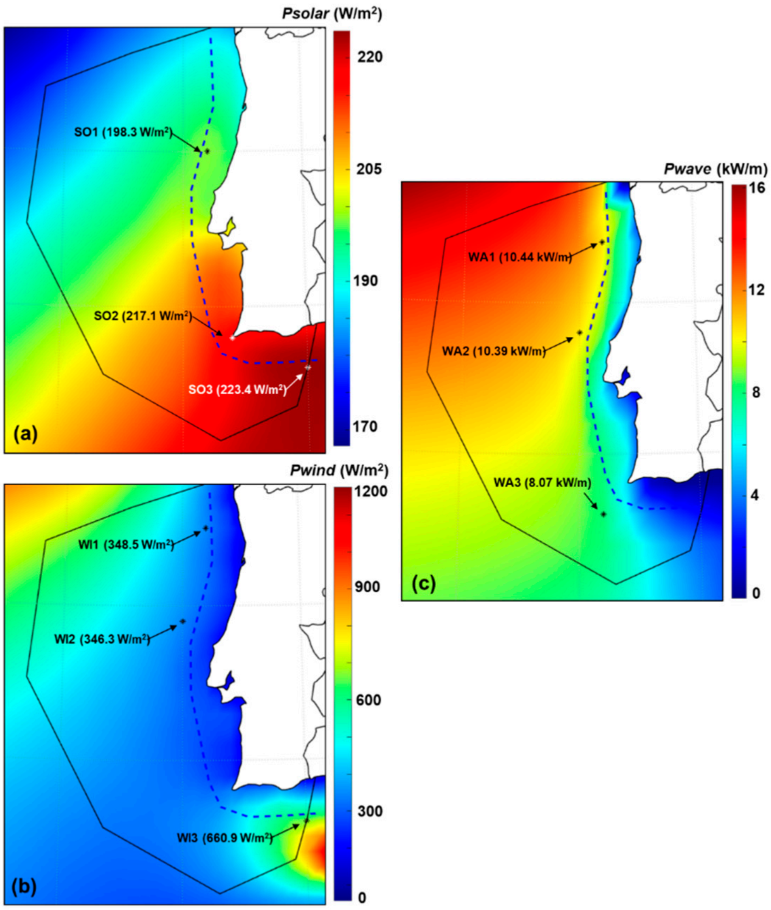

Figure 5. Spatial distribution of the marine resources (average values) near the Portuguese coastal area. Results based on 10 years of ERA5 data (from 2012 to 2021), where: (**a**) solar power; (**b**) wind power; (**c**) wave power. The local maximum values are also indicated for each sector (north–1; center–2; south–3).

For the wave power (Figure 5c), the northern and center sectors were defined by a significant decrease in energy near the 50 km isoline, while the southern sector may be associated with lower wave resources that can go up to 8.07 kW/m (WA3). A maximum value of 10.44 kW/m was related to the point WA1, although for the northern sector the average values can go up to 16 kW/m as we reach the western boundary of the EEZ. Near the 50 km isoline, the values associated with the northern and center sectors were quite similar, gradually decreasing as they enter the shallow water areas.

The complementarity distribution between the solar, wind and wave resources is presented in Figures 6–8, considering the thresholds associated with the case studies CS1 and CS2, respectively. For solar power, the 5th percentile value related to the Portuguese EEZ was considered to be close to 134 W/m^2. Figure 6 presents the distribution of the

SOCWI/WICSO indicators for the entire Portuguese EEZ, including the 50 km isoline. In the case of the SOCWI index, a maximum of 0.3 (CS1) was associated with the center of the target area, while the southern part of the Iberian Peninsula (Algarve region) was defined by values that could go down to 0.15 (CS1) or 0.22 (CS2), respectively. From the distribution of the WICSO values, we noted that a solar project combined to a wind farm could be successfully implemented up to 50 km from the coastline, especially in the coastal areas facing the North Atlantic (west side). In this case, the values were close to 0.15/0.20 depending on the scenario taken into account, reaching a maximum of 0.4 near the north-western and south-eastern corners of the EEZ.

Figure 7 illustrates the solar-wave complementarity. Based on the distribution of the SOCWA index (Figure 7a,b), it was observed that a successful hybrid project could be implemented outside the 50 km isoline (values << 0.20), preferably in the northern sector, an aspect that was better highlighted by case study CS2. For the Algarve region, maximums of 0.4 were observed in both case studies, suggesting that only a floating solar project would be more competitive. In the case of WACSO values, only a wave farm project is recommended outside the 50 km isoline (values $\geq$ 0.40), while a joint wave-solar project may present some interest for the southern sector (values $\leq$ 0.10).

Maybe, the most interesting results are related to the WICWA index (Figure 8a,b), highlighting that a wind-wave project built around the wind sector, could be successfully implemented for most of the Portuguese EEZ (values $\leq$ 0.15), excepting the Algarve region (south) where the wind component alone would be more promising. The WACWI values (Figure 8c,d) are in general above 0.30, lower values (>0.10) being expected in the eastern part of the Algarve region.

Based on the information provided in the previous spatial maps, the locations of the highest values associated with the natural resources and solar-wind-wave complementarity are identified in Figure 9.

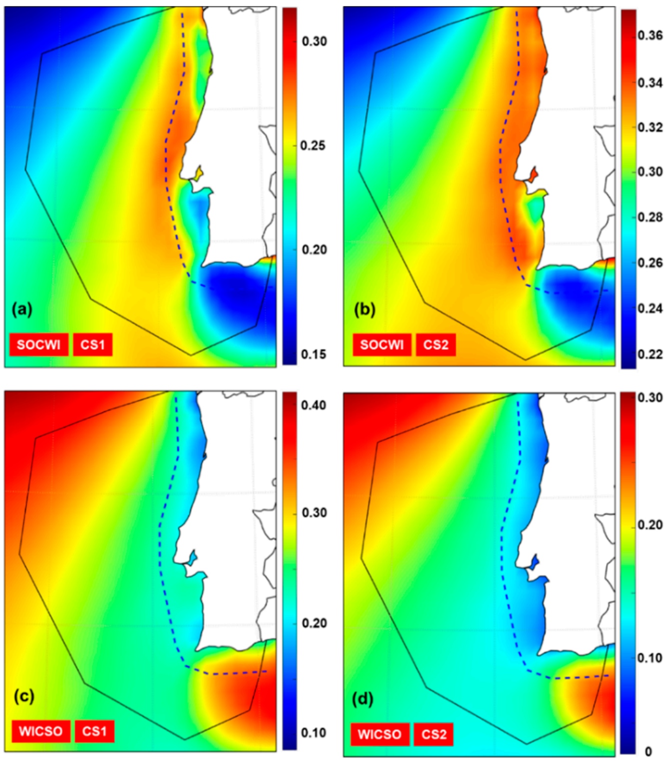

Figure 6. Spatial maps illustrating: (**a**,**b**) solar-wind power complementarity (SOCWI)—case studies 1 and 2, respectively; (**c**,**d**) wind-solar complementarity (WICSO)—case studies 1 and 2, respectively (where the dotted line indicates the 50 km izoline).

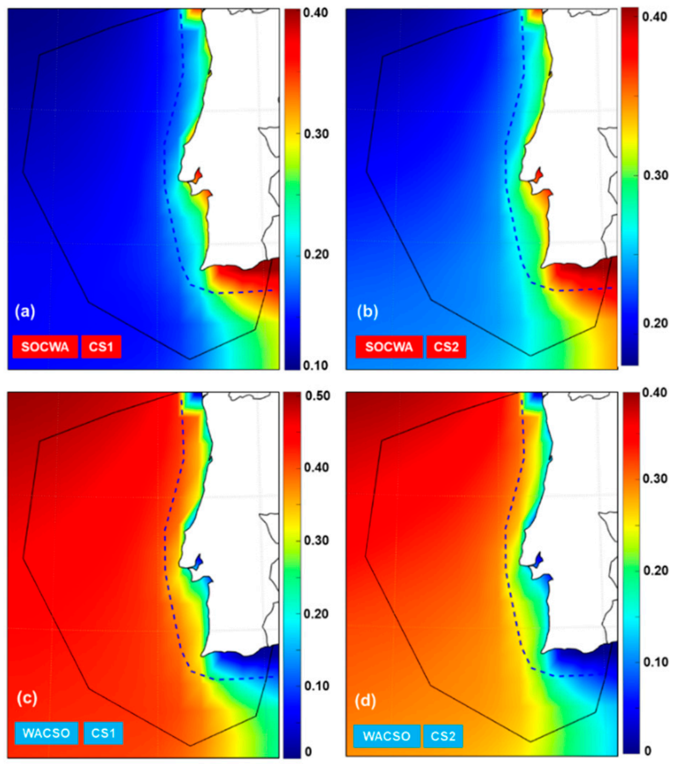

Figure 7. Spatial maps illustrating: (**a**,**b**) solar-wave power complementarity (SOCWA)—case studies 1 and 2, respectively; (**c**,**d**) wave-solar complementarity (WACSO)—case studies 1 and 2, respectively.

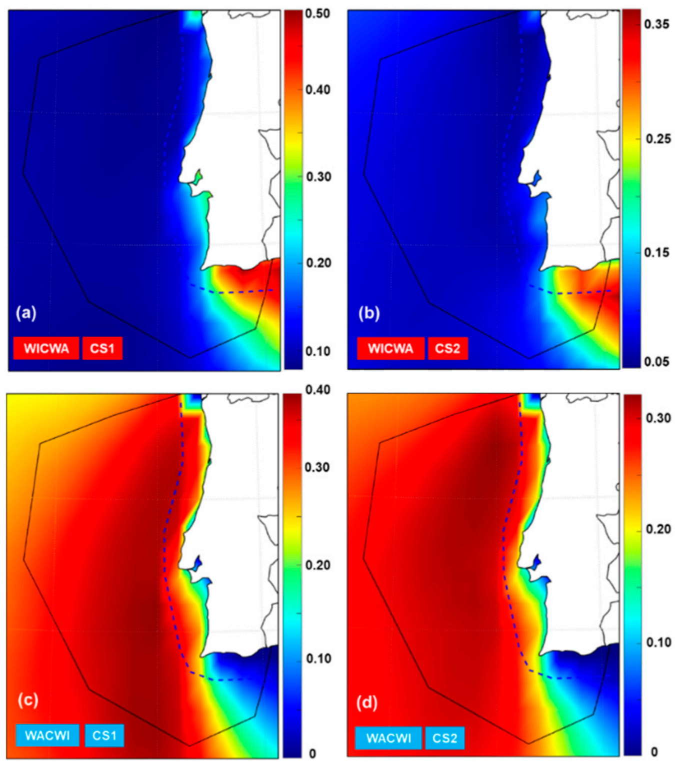

Figure 8. Spatial maps illustrating: (**a**,**b**) wind-wave power complementarity (WICWA)—case studies 1 and 2, respectively; (**c**,**d**) wave-wind complementarity (WAWI)—case studies 1 and 2, respectively.

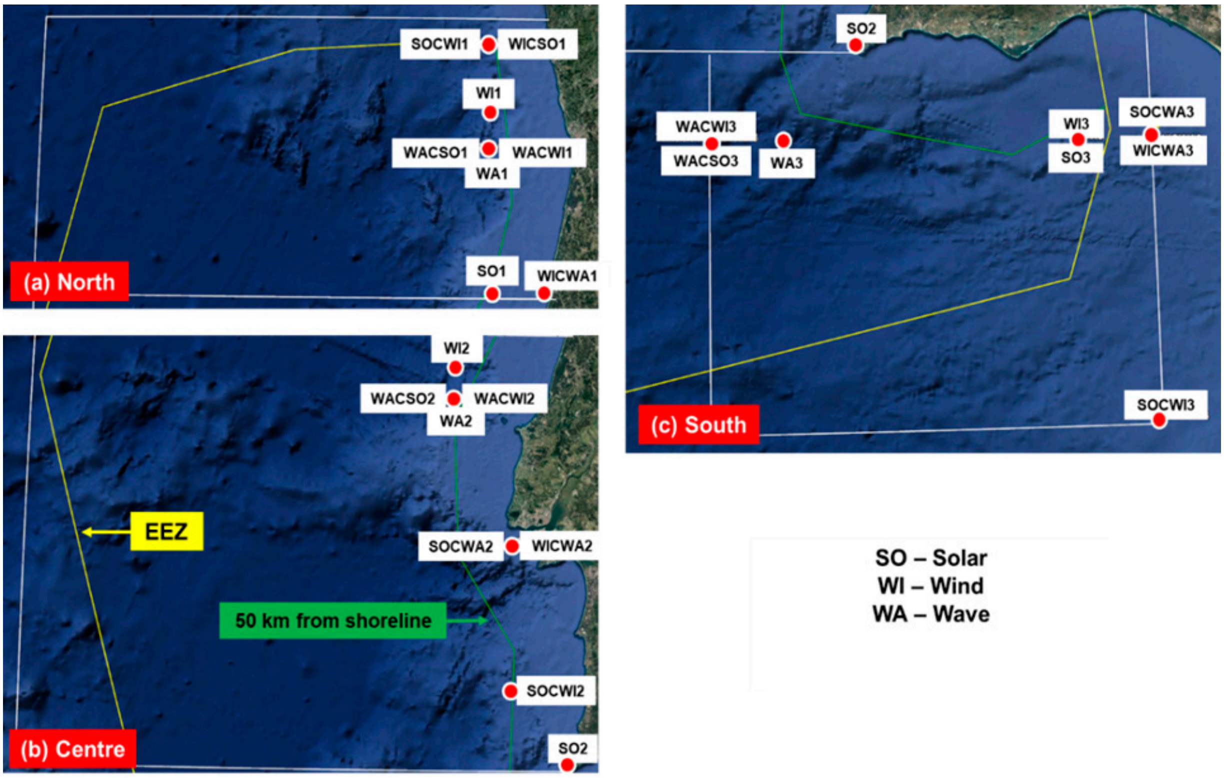

Figure 9. Identification of the most promising sites in terms of solar, wind or wave power, also including the location of the best sites related to the solar-wind-wave complementarity. (**a**) Northern area; (**b**) Central; (**c**) Southern Portuguese nearshore.

Most of the points are grouped along the 50 km isoline; it should be noted that several indicators share the same location. For example, in the case of the north sector the SOCWI/WICSO share the same locations, a similar situation being expected for the WACSO/WACWI/WA indicators. As for the central sector, these indicators are grouped as WACSO/WACWI/WA or SOCWA/WICWA, respectively. The best sites, in terms of wind and solar power, are located in opposite areas (north and south extremities). For the southern sector, only a wave farm is recommended for the site marked by WACWI/WACSO values, while a wind-solar project may be successfully implemented on the eastern part of the EEZ, close to the 50 km isoline.

As a next step, the expected power output related to each system (solar, wind and wave) was computed. The performance of a single unit rated at 221.1 Watt and covering a surface area (2 m^2) is provided in Figure 10a, while the legend associated with Figure 10b is related to the expected performances of a 1 MW project (≈4523 panels/0.009 km^2). Taking into account that the inter-turbine spacing between offshore turbines may vary from 5 to 20 rotor diameters [41], it appears that the proposed scenario is feasible. As expected, better performances were associated with the southern sector where a maximum power output of 120 W (*single unit)/0.54 MW (**1 MW project) may be expected. These values gradually decreased as we went to the northern sector (offshore), reaching minimums of 90 W* and 0.42 MW**, respectively.

Based on the information associated with the power curve of the Vestas Offshore V164-9.5 MW (described in Figure 3), Figure 11 provides the expected power output of this system, by considering a reference hub height of 100 m. Maximum values of 3.5–4 MW are indicated for the northwestern and southeastern regions, while close to the 50 km isoline, the values are close to 1.5 MW, associated with an average capacity factor of 16%. For the southern area (Algarve region), the capacity factor may increase up to 31% near the 50 km isoline.

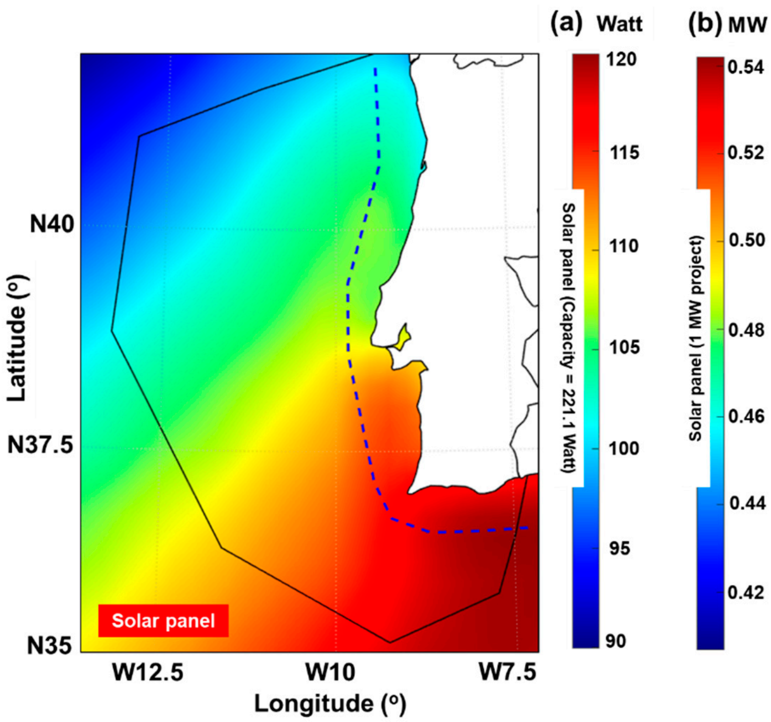

Figure 10. Expected power output from a solar panel operating in the Portuguese coastal area, where: (**a**) performance related to a single panel (221.1 Watt); (**b**) equivalent output of a 1 MW solar project.

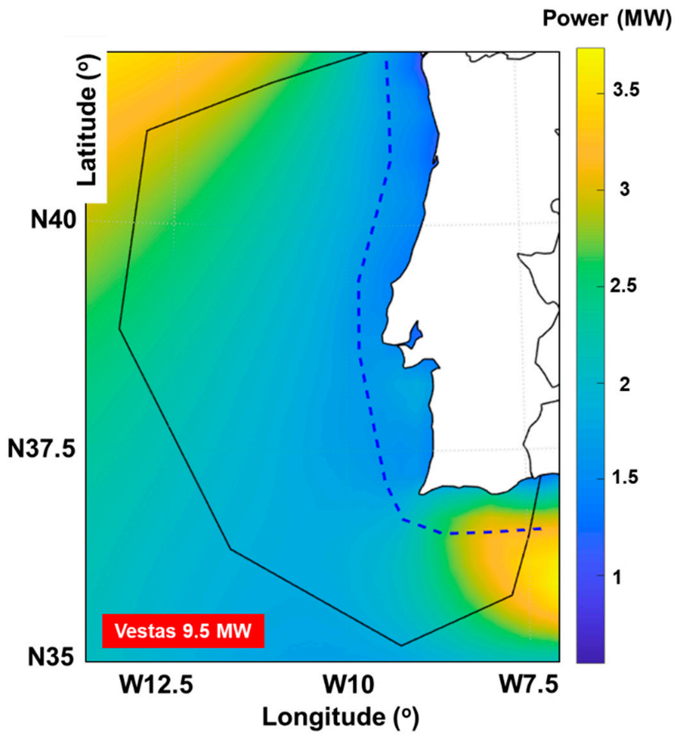

Figure 11. Expected power output (average) from the offshore wind turbine Vestas V164-9.5 MW (*U*100 values).

The expected power output of the SWEDE wave generator is indicated in Figure 12a, considering, this time, the reference sites SO, WI and WA, as indicated in Figure 9. We can see that better results are expected during the summertime, when a maximum of 107 W is related to July. In this case, the maximum capacity factor of this system is close to 4%, which is quite small for a renewable system.

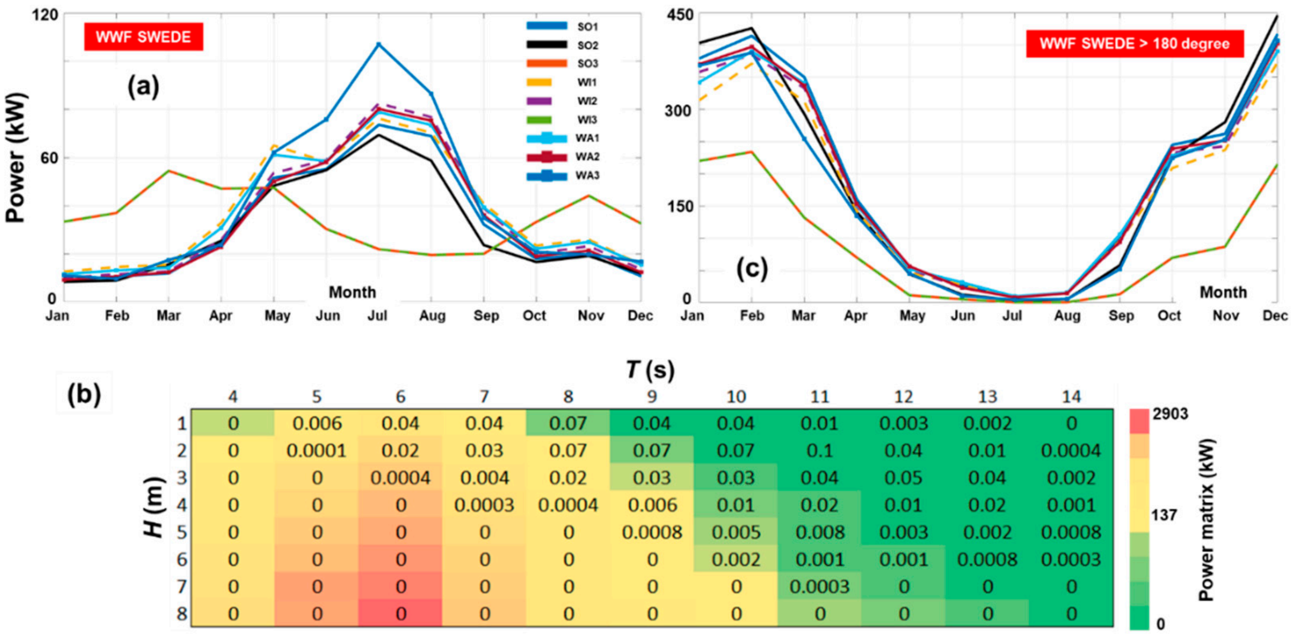

Figure 12. Performance of the WWF SWEDE generator indicated in terms of: (**a**) power output in kW; (**b**) bivariate distribution of the wave height and period (December month—as a percentage), overlapped to the power matrix of the SWEDE generator; (**c**) power output after the adjustment of the original power matrix (rotated 180° clockwise).

Figure 12b provides a possible explanation of this performance, by considering a winter month (December, in this case). By looking at the power matrix of the SWEDE system (colored scale) and at the bivariate distribution of the *Hs* and *Te* values (as percentages) we notice that the proposed WEC never generates power from the area where the rated power output (2903 kW) is located. In the case of the wave conditions, a distribution of 10% was noted for the bin 2 m/11 s, that would have no contribution to the total power output.

A characteristic of a WEC system is that it can be adjusted for a particular wave climate in order to obtain better performance [42,43]. Since no optimization studies were proposed for the SWEDE system, we considered flipping the power matrix of this WEC around its main diagonal, in order to provide a better fit with the local sea state distribution. The results obtained are presented in Figure 12c, where we noted that the general pattern changed, with better performances being noted during the wintertime (e.g., 446 kW in December). Even after the flipping of the power matrix, the increase in power was not very high, being associated this time with a maximum capacity factor of 15.3% which looked more promising compared to other WECs [44]. During the interval July–August, the modified WEC is expected to have no power output, which would make it less attractive for the implementation of a wave farm.

4. Discussion

The reanalysis data represent one way to assess the distribution of the natural resources over large geographical regions. In this connection, the ERA5 data is frequently used to assess the marine conditions from the vicinity of the Iberian Peninsula. In Costoya et al. [18], a total of 27 years of ERA5 solar/wind data were used to validate the data related to the CORDEX project that were further used to assess the near-future expectations for the interval 2000–2040. By looking at the distribution of the annual solar power (mean values), similar values were noted with the present work, with a maximum of 210 W/m^2 near the Algarve region. In terms of the wind power, a similar spatial pattern was observed with a maximum of 1200 W/m^2, the authors highlighting the northern part of the Iberian Peninsula as presenting more consistent resources. Nevertheless, the work of Costoya et al. [18] was dedicated only to the western part of the Iberian Peninsula, and missed the southern part (Algarve sector) that seems to present important solar and wind resources. Some other works based on the ERA5 data, where complementarity between multiple sources of marine data can be found, are: Kardakaris et al. [36]—wind and wave (Greek Seas) or de Souza Nascimento [32]—wind and solar (Brazil offshore). If we are discussing the Iberian Peninsula, it is worth mentioning the work of Lopez et al. [45], where a combined analysis of solar and wind power was made for the Asturias region (Spain). Along with the assessment of the natural resources, the performances of some PV panels were considered, the rated power being in the range 280–325 W. In Campos and Guedes Soares [46], a detailed investigation of the Portuguese offshore wind resources was performed for the time interval 2009–2013, based on a mesoscale atmospheric model that had a better grid resolution (0.081° × 0.097°) than in the present work. For that study, the wind power (*U*80 values) rose to 900 W/m^2 in the northern part, compared to a maximum of 800 W/m^2 noted in the present work (for the same region). Another important difference is related to the southern area (Algarve), where the compared study indicated this region as being less energetic (compared to the north) with values that did not exceed 500 W/m^2. In this work, in the southern extremity, a hot-spot was observed in terms of wind power that affects the local distribution (P_{wind} = 1200 W/m^2); in the absence of this extreme value the expected wind power field was located in the range 300–500 W/m^2. In future work, this aspect needs to be investigated in order to highlight the seasonal and inter-annual fluctuations of the wind conditions.

The complementarity analysis represents an important objective of the present work and therefore for the wind and wave conditions, several thresholds were considered based on some previous published studies [35,36]. By looking at the Greek Seas (the CS1 scenario), the WACWI index may reach a maximum value of 0.5, compared to only 0.1 that is associated with the WICWA. Compared to these values, the two indices are rated above 0.3 for the current work, regardless of the scenarios taken into account. In the work of Wen et al. [35] associated with scenario CS2, the WICWA index processed for the southern coast of China could go up to 0.6, while for the more dominant WACWI index, the values were located below 0.2.

Regarding the performance of the solar-wind-wave generator, probably the most interesting results are related to the SWEDE wave generator, which can be considered to be very low. Probably, this should be expected from a WEC system that was only tested in the wave tank (regular waves). More than this, even the authors of the provided study [38] admitted that the proposed WEC solution would not make a great contribution to the reduction of the levelized cost of energy (LCOE), since the wave generators would generate a lower amount of energy compared to a wind turbine. Per total, it can be considered that the SWEDE system has poor performance, regardless of the scenario taken into account (original and flipped matrix). According to the information provided in Figure 12b, we note that the peak values of this WEC need to be located in the range 8–11 s (for *Te*) and more important in the interval 1–3 m (for *Hs*). The SWEDE concept is defined by a single peak value, which could be considered a drawback compared to other wave generators. For example, by looking at the power matrices of some other WECs [40], we find that the peak value is distributed over a range of *Hs*/*Te* bins, this being the case of Pelamis, AquaBuoy or Wave Dragon. Since the points SO, WI and WA are located relatively close to the shoreline area, the wave power will be significantly reduced, which brings into discussion their viability for a wave project, especially for the center and southern sectors. By carrying out a simple optimization study, it was noted that it is possible to slightly increase the power output, but during the summertime there would be no significant power output. Therefore, a combination of the initial power matrix and the optimized one should be considered, or eventually to develop more sophisticated systems in which SWEDE could adjust its performance in a dynamic way [47]. At this moment, in order to accelerate the implementation of a hybrid wind-wave project, it would probably be much better to consider an existing wave generator, around which can be developed a wave farm.

5. Conclusions

The Iberian Peninsula represents an important coastal area that can be used for the development of marine renewable projects, especially in the case of the Portuguese EEZ. Coincidence (or not), the Portuguese nearshore area was selected for the development of the first commercial wave farm (Aguçadoura project—Pelamis device) and also the testing of the WindFloat demonstration project in 2011. Motivated by these aspects and by the fact that Portugal has important solar resources, the aim of the present work was to provide an overview of the expected benefits coming from the implementation of the solar, wind and wave energy for this coastal environment. Only 10 years of ERA5 data (from 2012 to 2021) were considered for the assessment, but nevertheless, we need to take into account that these are related to hourly values (24 data per day) and cover several parameters, such as surface solar radiation downwards, wind speed (assembled from u and v components), wave height and period.

In terms of the natural resources, the results indicate that the southern part of the Portuguese EEZ (Algarve) represent the first option for the implementation of a floating solar project, especially in the areas that do not exceed the 50 km isoline. In terms of the wind power, better resources were noted in the northwestern part of the EEZ, with a local hot-spot also in the southern part of the Iberian Peninsula, but outside the Portuguese EEZ. Nevertheless, in future works, a more detailed investigation needs to be carried out in order to confirm this pattern, eventually by using a wind dataset defined by higher spatial resolution. The wave power gradually decays from north to south, and also from the 50 km isoline to the nearshore, which was expected due to the decrease in water depth. Several complementarity indices were considered in order to highlight the connection between the solar-wind-wave resources, and the expected opportunities for the implementation of hybrid projects. Based on these results, some important sites were identified in the vicinity of the 50 km isoline, which represent a viable distance from the shore at which a marine project can be developed.

From the performances of the renewable generators, it was found that the proposed SWEDE wave converter related to the WindFloat platform would not be recommended for the Portuguese coastal area since the power output would be quite low. At this point, the Vestas V164 wind system would make a significant contribution with an annual output of 2–2.5 MW expected for most of the Portuguese environment. Compared to the rated power of this system (9.5 MW), the capacity factor can be considered to be quite low (e.g., 26%). A floating solar farm could be easily integrated into an existing offshore wind farm layout, with a 1 MW capacity facility expected to cover at least 0.009 km^2 (according to this work). A maximum power output of 0.54 MW may be expected for the southern sector, that could be translated to an electricity production of 1188 MWh/year, assuming that the PV system will operate for at least 6 h per day.

The complementarity of marine resources is a relatively new topic and various approaches have been considered. The thresholds associated with the solar, wind and wave parameters are defined in different ways, involving either the annual average values of a particular resource or a general cut-in limit related to various wind and wave generators. The use of local statistical information can be considered to be quite limited, since the energy level significantly varies on different coastal and geographical areas, and therefore a direct comparison would be pointless. Since the aim of these studies is to see how a renewable project would perform in this coastal environment, probably the best approach is to consider the characteristics of the marine generators, by also including some performance thresholds related to the rated power of a particular generator. Nevertheless, the work is ongoing and future improvements may occur as the marine systems become more competitive. A significant issue that should be further considered in selecting the location of a marine energy project is related to the extreme events expected in that coastal environment. This is because, in many cases, the coastal areas with high waves and wind resources are very often subjected to extreme environmental conditions that can put the systems in danger. Furthermore, in the context of climate change, the intensity and frequency of extreme events is expected to increase and the marine energy farms should be prepared to face such harsh conditions.

Finally, we need to mention that the idea of developing mixed solar, wind and wave projects in marine areas is starting to gain momentum, going even further to proposals that involve projects capturing all three resources in a consistent way. Based on the know-how already accumulated, the Portuguese nearshore area may be recommended for the developments of such complex projects.

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Abbreviations

As	solar panel area
CORDEX	Coordinated Regional Climate Downscaling Experiment
CS	study case
EEZ	Exclusive Economic Zone
ERA5	ECMWF Reanalysis 5th Generation
EU	European Union
EU-SCORES	European Scalable Offshore Renewable Energy Sources
$f(u)$	Weibull probability density function
FR	France
g	gravitational acceleration
Hs	significant height of combined wind waves and swell
LCOE	levelized cost of energy
nHs, *nTe*	number of particular bins
P(u)	power curve of a wind turbine
P_{Mij}	WEC power output related to a particular sea state
P_{solar}	solar power
Psolar panel	expected power output from a solar panel
PT	Portugal
Pturbine	expected power output of a wind turbine
PV	Photovoltaic
PWEC	expected power output of a wave energy converter
P_{Wij}	energy percentage related to the bivariate distribution
P_{wind}	wind power
P_{wave}	wave power
RCP	Representative Concentration Pathway
SOCWA	solar complements wave
SOCWI	solar complements wind
SSRD	surface solar radiation downwards
Te	mean wave period
u,*v*	eastward and northward wind vectors
$U10$, $U100$	wind speed reported for a 10 and 100 m height above sea level
UK	United Kingdom
US	United States

WACSO	wave complements solar
WACWI	wave complements wind
WEC	wave energy converter
WICSO	wind complements solar
WICWA	wind complements wave
WWF SWEDE	WindWaveFloat single point absorber
xCy, yCx	complementarity of x to y parameter (or y to x)
η	efficiency of a solar panel
ρ_{air}	air density
ρ_{water}	water density

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