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Offshore Wind and Wave Energy Assessment around Malè and Magoodhoo Island (Maldives)

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Abstract: The Maldives are situated in the remote equatorial Indian Ocean, covering 900 km from north to south. The 26 coral atolls forming the archipelago are composed of sand and coral with a maximum height of about 2.30 m above the mean sea level. Periodic flooding from storm surges and the frequent freshwater scarcity are perceived by the population and the economic operators as the major environmental stresses. Moreover, the strong dependence on imported fossil fuels increases, even more, the environmental concerns. Diesel, in fact, still represents the main source of power generation, typically through privately managed small diesel sets. The real challenge for this area is to promote the environmental quality with socioeconomic growth. The present study aims to evaluate the strategic effectiveness to face these issues by wave and offshore wind energy. Resources using a 10-year hindcast dataset are here examined. The annual offshore wave power was found to range between 8.46 kW/m and 12.75 kW/m, while the 10 m and 100 m mean wind power density is respectively 0.08 kW/m^2 and 0.16 kW/m^2. Based on these results, an environmentally and socio-economically sustainable best-case scenario is constructed and two atoll islands (Malè and Magoodhoo) are specifically investigated. As a result, multifunctional structures and multi-use systems, which combine power generation, desalinization and coastal defence, are strongly recommended.

Keywords: wave energy resource; offshore wind resource; Maldives; multi-use systems

1. Introduction

The Maldives, an island nation in the Indian Ocean, are largely recognized as one of the most beautiful countries in the world and an example of a natural paradise. However, a paradise with a particular issue: it is one of the most exposed countries in the world to the volatility and the rising of oil prices and it is extremely vulnerable to the effects of the climate change. The reason is twofold: country's strong dependency on fossil fuel, which is essentially the only exploitable source of energy, and the natural conformation of the Archipelago. The Maldives are composed exclusively of corals and sand, without surface bodies of fresh waters and with no point higher than 2.3 m above mean sea level. Moreover, much of the groundwater is polluted and cannot be used, which makes the Maldives an easy prey of emergency situations and speculations [1].

Several recent studies indicate a profound reorganization of the energy market and environmental policy in the Maldives, aiming to convert the island nation as the world's first carbon neutral country. Solar photovoltaic, wind energy and biomass represent the key renewable resources according to the *Scaling up Renewable Energy Program* (SREP) under the Climate Investment Funds [2]. Energy from waste is under consideration. As for tidal and marine currents, a study conducted by the Robert Gordon University of Scotland in 2011 concluded that current technologies are not yet relevant [3]. However, the SREP investment plan does not include in its study neither onshore/offshore wind source nor wave energy. Recently, the Government of the Maldives has recognized the need to improve the information available on solar and wind potential as it requested the support of the World Bank and ESMAP's Renewable Energy Mapping Initiative to help carry out a resource assessment and mapping [4], showing some preliminary results. With respect to traditional wind resource, offshore wind farms present benefits that include (a) lower visual and noise impact through distance from the shoreline and (b) higher wind resource (larger wind velocities) with lower turbulence levels than adjacent land sites. Furthermore, since industry is seeking economically viable devices for commercial deployment, the economic feasibility and regularity in the power output of offshore wind farms could be enhanced combining two forms of energy production, i.e., wind and wave, in one platform. Cases of integration of wave and wind power have been studied by [5–23], demonstrating as the joint exploitation of offshore wind and wave energy resources can have a number of advantages, including:

- higher quality of produced power when mixing the power from wind and wave energy;
- higher regularity of power delivered to the grid when swells continue after the wind declines;
- reducing risk and cost through sharing components, infrastructure, submarine electric cables and maintenance activities;
- less area and environmental impact for combined farms through the sharing of space.

Over the last two decades several efforts have been made to map the offshore wind and wave energy resource. Maps of the global offshore wind energy resources have earlier been published in [24], and wind resource assessment was analysed by, e.g., [25–42].

Considerable works have been undertaken on wave energy assessment in several areas worldwide (e.g., [43–67]). A global synthesis has been published in the review book by Cruz (2008), based on the WorldWaves data.

The present work analyses the blue energy resources along the Maldives coastline, using a 10-years data series provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) dataset [68]. The spatial distribution of both energy sources is analysed using data from 10 points along the coast. The approach used in the present study follows a widely validated methodology in literature for both the wind and the wave energy assessment undertaken for several locations worldwide [25–67], but the two assessments have been concurrently compared and innovative applications of hybrid technologies have been considered.

In particular, the objectives of this work are:

1. to characterize the wave climate around the study area, emphasizing wave power assessment and the involvement of different sea states (e.g., monthly variability and long period swell influence);
2. to provide a comprehensive study of offshore wind resource, provided at a height of 10, 25, 55, 80 and 100 m and referring to three practical utility-scale wind turbines;
3. to draw a preliminary discussion about the realistic perspectives of blue farm installations around the Maldives coastline, also through practical case studies of these innovative technologies.

For the last point, a special attention has been paid to enhance the environmental and socio-economical sustainability of blue energy technologies, identifying the possible "cost saving synergies" between wave energy and other sea uses. Two case scenarios will be presented to illustrate the approach: both of them include a hybrid platform of wave and wind and another (non-energy) sea use. Two representative islands are analyzed:

- Malé, the capital, one of the most densely populated cities in the world, with approximately 23,000 people per km^2 and an electricity demand of over 220 GWh/year in 2012 [69];
- Magoodhoo, a remote small island on the Faafu Atoll, at a distance of 134 km from the capital, with a population of 683 inhabitants distributed on a surface of less than 0.36 km^2.

The paper is structured as follows. Section 2 briefly describes the study area, presents the available data and introduces the methodology. In Section 3 the offshore wind energy and the wave energy resource along the Maldivian coasts are assessed. In Section 4 the results are discussed and the best-case scenarios for the two sites are specifically investigated, showing the combined maritime uses that can be more feasible. Conclusions are finally drawn in Section 5.

2. Materials and Methods

2.1. Wave and Wind Data for the Study Area

Since suitable buoy data and long-term historical wind record are not available off the coasts of the Maldives, the present work has been based on ERA-Interim dataset, freely available for downloading at the website (http://www.ecmwf.int/). This is a global atmospheric reanalysis provided by the European Centre for Medium-Range Weather (ECMWF), continuously updated in real time providing data from 1979. These operational numerical weather predictions are used to predict meteorological states, based on how the climate system evolves with time from an initial state. The ECMWF dataset is composed of a coupled ocean-atmosphere general circulation model, i.e., an atmospheric reanalysis coupled with a wave model integration where no wave parameters were assimilated, making the wave part a hindcast run. The Indian Ocean is covered by the base model grid with a resolution of 0.75° × 0.75°. Ten grid points have been selected in this study in order to cover the east and west side of the study area, covering a latitude from 1.5°N to 4.5°N (Figure 1). The five East grid points (on longitude 74.25°E) are here termed E1–E5, while W1–W5 (on longitude 72°E) are the West ones. These hindcast data provided by the ECMWF have been chosen for several reasons:

- ERA-Interim products are freely available on the ECMWF Data Server;
- due to the re-analysis nature, this dataset is free from a lack in the time series and the data should be considered as pre-processed from an error handling phase;
- for wave energy assessing purposes, this hindcast has been shown to be slightly conservative.

This conservative nature can be addressed to the peak attenuation due to the small sampling frequency (i.e., smaller than that of the traditional wave buoys). Moreover, in the characteristic meteorological spectrum of the model, the energy falls fairly rudely at about 125 miles, a dimension comparable to the model grid resolution. This approach makes results here presented reliable from an engineering point of view, albeit data validation is not possible since only limited measured wave time series are available for the analysed area. The main wind/wave parameters, such as the significant wave height (H_s), the mean wave period (T_m), mean wave direction (θ_m), the longitudinal component of 10 m wind speed (u) and a latitudinal component of 10 m wind speed (v) ranging from January/2005 to December/2014, were extracted from the ERA-Interim archive. For the wave energy computation, all the ten ECMWF points have been used. Because of the great depth around the archipelago, with rapid change in bathymetry just few tens of meters from the coral reef, effect of refraction along the exposed coast of the Archipelago can be considered negligible. Therefore, offshore energy density assessment could be considered valid also for nearshore conditions.

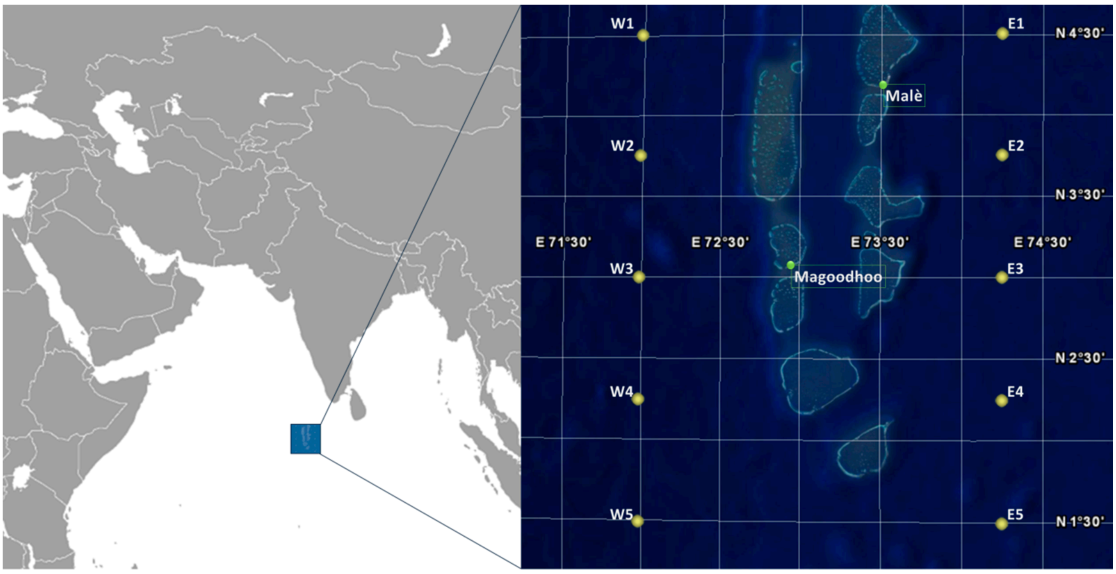


Figure 1. Map of Western Indian Ocean showing the location of ECMWF grid study points around the Maldives islands and the two focus sites (Malè ad Magoodhoo).

2.2. Method for Wave Energy Potential Computation

The methodology used to determine the offshore wave power follows that successfully applied to others deep waters regions (e.g., [60,65]. Regarding the calculation of the wave energy flux transmitted per unit width of waves, it is worth remarking that all reference points used in the present analysis are located in deep waters. For regular waves, the sum of kinetic and potential energy density per unit width can be computed according to the following well-known relationship:

$$E_{wave} = \rho g H^2/8 \tag{1}$$

where ρ is the sea water density, g is the gravity acceleration and H is the wave height. It this work an average value of ρ = 1025 Kg/m^3 has been adopted. The energy flux across a vertical section of unit width perpendicular to the wave propagation direction can be expressed as follows:

$$P_{wave} = E_{wave} \times C_g \tag{2}$$

in which C_g is the group velocity. In case of deep water, C_g can be expressed as follows:

$$C_g = \frac{g}{2\omega} \tag{3}$$

where the wave frequency, ω, is $2\pi/T$, being T the wave period.

In a real sea state, the power of irregular waves can be described by a superposition of an infinite number of regular waves with different amplitudes and frequencies. Therefore, the wave energy flux using spectral parameters can be defined as:

$$P = \rho g \int_0^{2\pi} \int_0^{\infty} C_g(f,h) \times S(f,\theta) df d\theta \tag{4}$$

in which $S(f,\theta)$ denotes the directional wave spectrum and $C_g(f,h)$ denotes the general expression of the wave group velocity, expressed as:

$$C_g(f,h) = \frac{1}{2}\left[1 + \frac{2kh}{\sinh(skh)}\right]\sqrt{\frac{g}{h}\tanh(kh)} \tag{5}$$

Wave height computation is based on the zero-order moment of the spectral function and readily estimated as:

$$H_{m0} = 4\sqrt{m_0} \tag{6}$$

As a period parameter, the present method uses the energy period, T_e, defined as the ratio between the minus-one and the zeroth spectral moments:

$$T_e = \frac{m_{-1}}{m_0} \tag{7}$$

Being known the mean period T_m from the hindcast dataset, it was assumed that $T_e = 1.14T_m$, according to the approach used in preparing the Atlas of UK Marine Renewable Energy Resources [70]. Hence, the wave power, under a wave crest 1 meter wide is given by:

$$P_{wave} = \frac{\rho g^2 H_{m0}^2 T_e}{64\pi} \tag{8}$$

For each six-hours triple (H_s, T_m, θ_m) provided at each hindcast point, the related power series using Equation (8) was computed. It is important to underline that the presence of atolls creates sheltered areas in their lee into which wave energy penetrates mainly through diffraction. Due to the high environmental value of the coral reef and internal waters of the archipelago, hypothesis of blue energy installations in the sheltered areas has not considered in this study. Therefore, analysis of wave energy density in the internal waters (therefore taking into account refraction, diffraction, etc.) is out of the scope of the present paper.

2.3. Method for Wind Energy Potential Computation

With regard to offshore wind power, the approach applied in this work follows previous studies (e.g., [6,40]). As known, the wind energy in an open air stream is proportional to the third power of the wind speed. In particular, the total amount of kinetic energy flowing through an area R during the time t is expressed as:

$$E_{wind} = \frac{1}{2}\rho_a t R w^3 \tag{9}$$

where ρ_a is the air density (a constant value of $\rho_a = 1.177\ \mathrm{Kg/m^3}$ was adopted in this study considering an average annual air temperature of 27°) and w is the wind speed computed from the horizontal North-East wind components ($\sqrt{u^2+v^2}$). The eastward (u) and the northward (v) wind components provided by the ERA-Interim refer to the wind at 10-m elevation above the mean sea surface. To calculate the actual wind speed at different heights, the logarithmic wind profile is used [71]:

$$U(z) = H(H) \times \left(1 + \frac{\ln\left(\frac{z}{H}\right)}{\ln\left(\frac{H}{z_0}\right)}\right) \tag{10}$$

where z is the general height above sea level, H is the reference height of 10 m, and z_0 is the terrain roughness parameter. The latter coefficient, in the case of offshore locations, varies between 0.01 in nearshore areas with onshore wind and 0.0001 in open sea without waves. For the study area, a conservative value of $z_0 = 0.001$ has been chosen. In this paper, the average annual offshore wave power has been calculated for 10 m and 100 m. The electric power collected at the terminals is given by the following relation:

$$P_{wind} = \frac{1}{2}C_p(w)\rho_a R_b w^3 \tag{11}$$

where C_p *(w)* is the power coefficient and R_b represents the area swept by the rotating blades. The maximum theoretical value of C_p, according to Betz's law, is 0.593; hence the maximum energy derived from a wind turbine is only the 59% of the available wind kinetic energy. Real values are lower, due to the losses in the turbine blades and PTO system. In this study, three practical utility-scale wind turbines have been analysed: a 100 kW, a 1.0 MW and a 2.3 MW wind turbine generator (WTG). For each of the three class, the computation of estimated production curves are obtained averaging the performance curves provided by well-known wind turbine manufacturers (i.e., Northern Power System, Polaris America and Wind Energy Solutions for the 100 kW turbine; WinWind and Nordic Windpower for the 1.0 MW turbine; General Electric and Siemens for the 2.3 MW generator). The resulting power curves are reported in Appendix A. Moreover, the hub height (z) is 80 m for the 2.3 MW turbine, 55 m for 1 MW generator and 25 m in 100 kW nacelle. Operatively, from 6-h pairs of wind component for 10 m height (u_{10}, v_{10}), the wind speeds w_{10} at the three hub heights have been computed and then, the Equation (10) has been applied to each swept areas to compute the electric power collected at the terminals of each model.

3. Results

3.1. Wave Power Assessment

In Tables 1 and 2 the geographical information of the grid points, such as the water depth and coordinates, and the main wave parameters, such as maximum, mean and standard deviation of the H_s, T_m and θ_m, have been calculated for each ECMWF grid point. The average significant wave height, $H_{s,mean}$, ranges between 1.3 m (E1) to 1.5 m (E5 and W5), while the average spectral mean period, $T_{m,mean}$, increases with the increasing of the mean wave height, varying between 7.81 s (E1) to 9.12 s (W5). It can be noted that the selected statistic wave parameters increase moving from North to South, but also a longitude influence can be noticed. The enhancing in wave characteristics is much more evident for extreme events. Indeed, the maximum significant wave height, $H_{s,max}$, for western and eastern EMCWF points are respectively 3.59 m (W1) and 3.05 (E1). Also, the maximum mean period, $T_{m,max}$, is smaller for eastern grid points (in average about 2.5 s). The main reason for these reductions in wave parameters is the prevailing S-SW wave direction, which implies less wave energy per unit length of coastline relative to the east part of the archipelago. In this vein, the change from 195° to 165° in averaged mean direction, $\theta_{m,mean}$, moving from western to eastern reference points can also be explained.

The results of the yearly average wave power and wave energy, based on 10-year average at the 10 ECMWF grid points, are synthetized in Table 3. The annual average wave power was found to range between 8.46 kW/m (E1) and 12.75 kW/m (W5), while the annual average wave energy ranges between 99.23 MWh/m (W1) and 111.72 MWh/m (W5). Results of the analysis are graphically represented for each site with polar diagrams and scatter diagrams characterizing the energy source for different classes of significant wave height (H_{m0}) and energy period (T_e), assembled in Figures 2 and 3.

Regarding the seasonal variability of the wave resource, small standard deviations of significant wave height $\sigma(H_s)$ and mean period $\sigma(T_m)$ indicate a low variability around a mean wave climate (Tables 1 and 2). Conversely, as confirmed by the average monthly power at each point in Tables 4 and 5, a relatively high seasonal variability can be highlighted with mean values of the ratio between the minimum and mean average monthly wave power ranging from 0.53 for western to 0.60 for eastern points. In order to better visualize the wave energy resource, an offshore energy flux density contour line along the two vertical lines of the ECMWF points was computed and shown in Figure 4. For all grid points, waves with periods greater than 11 s cover a consistent amount of energy (>20%), in accordance with the long fetch facing the archipelago. The Maldives, therefore, are extremely subjected to direct approach of swells from distant storms of the most perturbed region of the Indian Ocean (e.g., offshore of northern Madagascar).

Table 1. Geographical information and main wave climate parameters (based on 10-year average) at points W1–W5.

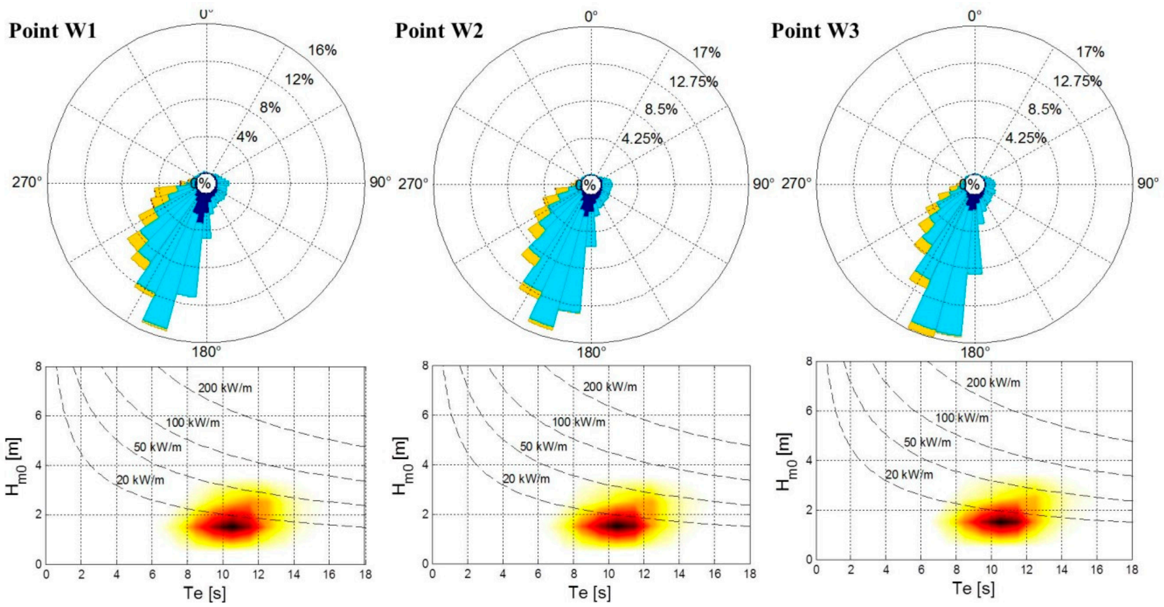
Point	*Lat*	*Lon*	*Depth* (*m*)	$H_{s,mean}$ (*m*)	$H_{s,max}$ (*m*)	σ_{Hs} (*m*)	$T_{m,mean}$ (*s*)	$T_{m,max}$ (*s*)	σ_{Tm} (*s*)	$T_{e,mean}$ (*s*)	Θ_m (°)
W1	4°30′N	72°00′E	>500	1.41	3.59	0.18	8.92	15.06	1.90	8.91	202.54
W2	3°45′N	72°00′E	>500	1.42	3.56	0.16	8.96	15.19	1.91	9.14	199.29
W3	3°00′N	72°00′E	>500	1.45	3.45	0.14	9.01	15.19	1.87	9.48	194.87
W4	2°15′N	72°00′E	>500	1.48	3.24	0.14	9.08	15.08	1.78	9.77	191.07
W5	1°30′N	72°00′E	>500	1.51	3.07	0.13	9.12	14.96	1.68	10.00	187.39
	Mean			1.45	3.38	0.15	9.02	15.09	1.83	10.28	195.03

Table 2. Geographical information and main wave climate parameters (based on 10-year average) at points E1–E5.

Point	*Lat*	*Lon*	*Depth* (*m*)	$H_{s,mean}$ (*m*)	$H_{s,max}$ (*m*)	σ_{Hs} (*m*)	$T_{m,mean}$ (*s*)	$T_{m,max}$ (*s*)	σ_{Tm} (*s*)	$T_{e,mean}$ (*s*)	Θ_m (°)
E1	4°30′N	74°15′E	>500	1.33	3.05	0.11	7.81	11.95	1.11	8.91	165.36
E2	3°45′N	74°15′E	>500	1.37	2.96	0.11	8.02	12.20	1.18	9.14	163.34
E3	3°00′N	74°15′E	>500	1.42	2.87	0.11	8.32	12.72	1.29	9.48	163.15
E4	2°15′N	74°15′E	>500	1.47	2.82	0.12	8.57	13.07	1.32	9.77	164.67
E5	1°30′N	74°15′E	>500	1.53	2.80	0.12	8.77	13.35	1.33	10.00	166.48
	Mean			1.42	2.90	0.11	8.30	12.66	1.25	9.46	164.60

Table 3. Yearly average wave power and wave energy (based on 10-year average) at ECMWF grid points.

Point	Average Power (kW/m)	Yearly Energy (MWh/m)	Point	Average Power (kW/m)	Yearly Energy (MWh/m)
W1	11.33	99.23	**E1**	8.46	74.11
W2	11.42	100.02	**E2**	9.11	79.81
W3	11.72	102.68	**E3**	10.18	89.22
W4	12.21	106.99	**E4**	11.31	99.03
W5	12.75	111.72	**E5**	12.45	109.07
Mean	11.89	104.13	Mean	10.30	90.25



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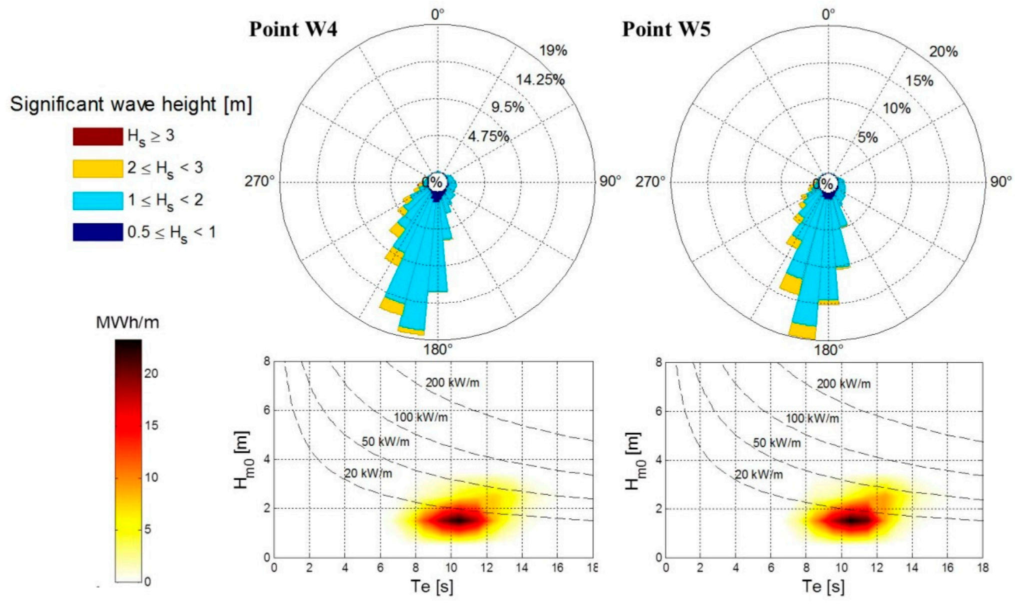
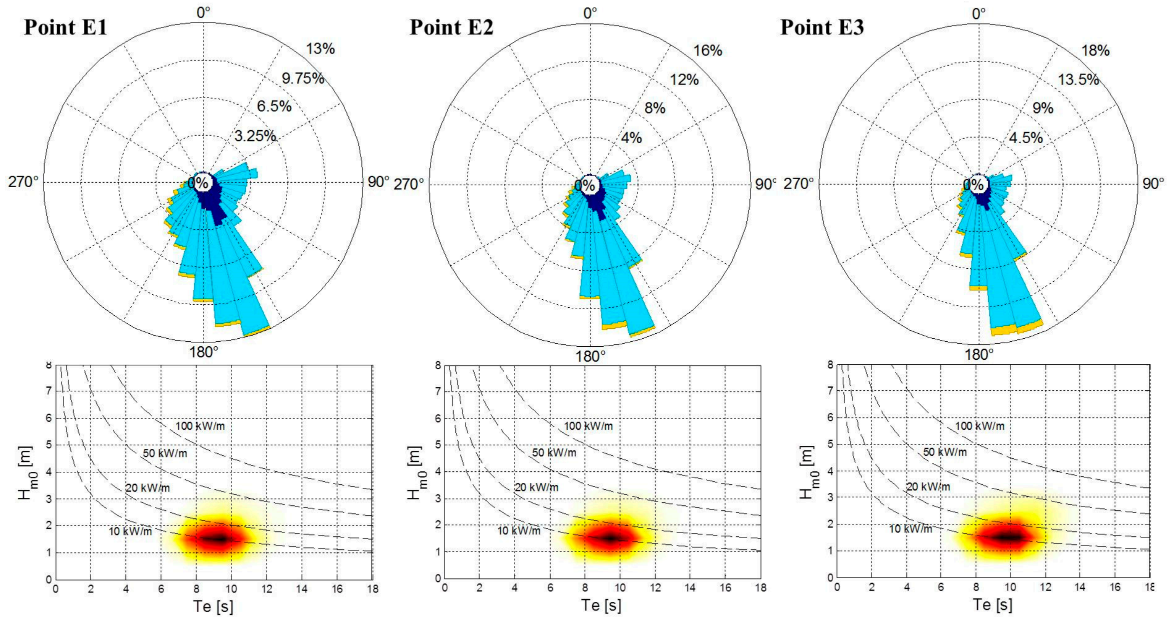


Figure 2. Characterization of the yearly average wave energy points E1–E5 in terms of significant wave height (H_{m0}) and energy period (T_e). The colors scale represents annual energy per meter of wave front (in MWh/m) and the isolines refer to wave power.



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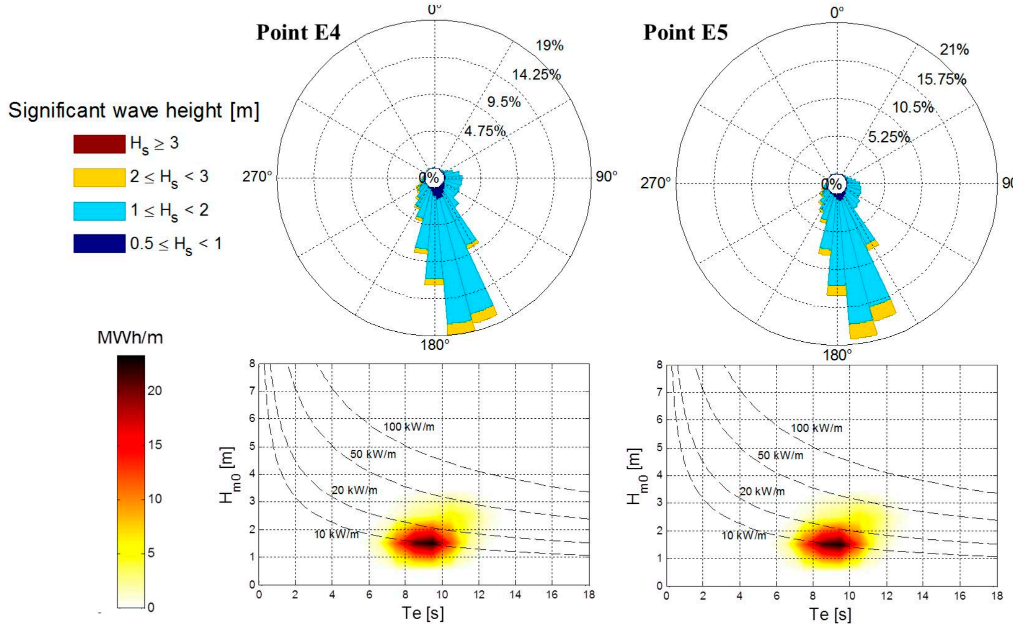

Figure 3. Characterization of the yearly average wave energy points E1–E5 in terms of significant wave height (H_{m0}) and energy period (T_e). The colors scale represents annual energy per meter of wave front (in MWh/m) and the isolines refer to wave power.

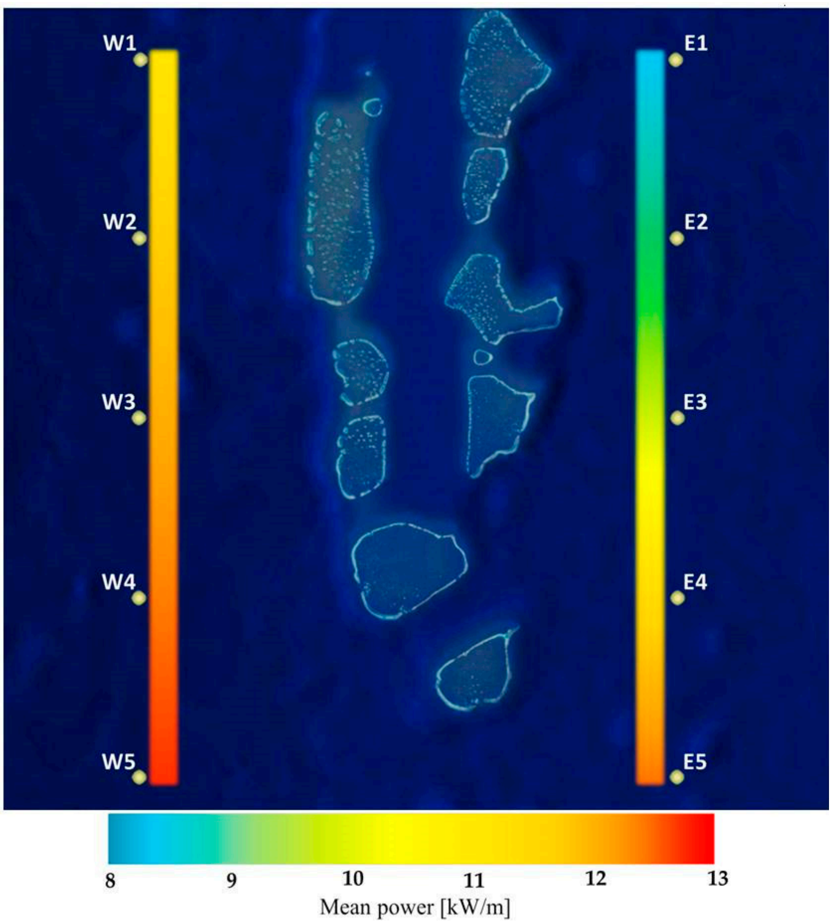

Figure 4. Mean wave power flux per unit crest along the 10 ECMWF offshore points.

Table 4. Monthly wave power (based on 10-year average) at ECMWF grid points W1–W5.

Point	Average Monthly Power (kW/m)												
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**Min/Mean**
W1	6.1	5.6	5.7	7.4	11.7	21.3	21.6	16.4	14.6	11.3	7.4	6.4	0.49
W2	6.4	5.8	6.0	7.8	12.1	20.5	20.8	16.3	14.8	11.8	7.7	6.7	0.51
W3	7.0	6.2	6.4	8.4	12.6	20.0	20.5	16.6	15.2	12.4	8.3	7.1	0.53
W4	7.0	6.6	6.8	9.0	13.2	19.9	20.8	17.3	16.0	13.0	8.9	7.5	0.54
W5	7.4	7.0	7.3	9.7	13.8	20.0	21.3	18.1	16.9	13.7	9.4	8.0	0.55
Mean	6.8	6.2	6.4	8.5	12.7	20.3	21.0	16.9	15.5	12.4	8.3	7.2	0.53

Table 5. Monthly wave power (based on 10-year average) at ECMWF grid points E1–E5.

Point	Average Monthly Power (kW/m)												
	January	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**Min/Mean**
E1	6.0	5.3	5.0	5.7	8.5	12.4	14.5	12.7	11.6	8.2	5.6	5.9	0.59
E2	6.3	5.6	5.5	6.4	9.4	13.0	15.3	13.7	12.5	9.0	6.2	6.2	0.60
E3	6.7	6.2	6.2	7.4	10.7	14.4	16.9	15.4	14.0	10.3	7.0	6.6	0.61
E4	7.2	6.7	6.9	8.4	12.0	16.0	18.7	17.0	15.6	11.6	8.0	7.2	0.59
E5	7.7	7.3	7.7	9.5	13.3	17.7	20.5	18.7	17.1	12.9	8.9	7.8	0.58
Mean	6.8	6.2	6.2	7.5	10.8	14.7	17.2	15.5	14.1	10.4	7.1	6.7	0.60

3.2. Wind Power Assessment

The results show that windiness increases in the northeastern area. For point E1, in fact, the average annual wind power density, $P_{wind,mean}$, raises from 104 W/m^2 to 204 W/m^2 at a height of 10 m and 100 m respectively, as shown in Tables 6 and 7, in which the wind power at the reference heights of 25, 55 and 80 m are also compared.

Table 6. The average annual wind power density at points W1–W5.

Point	P_{wind_MEAN} (W/m^2)				
	10 m	**25 m**	**55 m**	**80 m**	**100 m**
W1	88.0	117.0	146.5	162.1	171.9
W2	84.6	112.4	140.7	155.5	165.2
W3	79.9	106.2	133.0	147.2	156.1
W4	75.5	100.4	125.7	139.2	147.6
W5	71.8	95.4	119.4	132.2	140.1
Mean	80.0	106.3	133.1	147.3	156.2

Table 7. The average annual wind power density at points E1–E5.

Point	P_{wind_MEAN} (W/m^2)				
	10 m	**25 m**	**55 m**	**80 m**	**100 m**
E1	104.4	138.6	173.7	192.3	203.9
E2	97.0	129.0	161.5	178.7	189.4
E3	89.2	118.6	148.5	164.2	174.3
E4	81.7	108.5	136.0	150.5	159.6
E5	75.6	100.6	126.0	139.4	147.8
Mean	89.6	119.1	149.1	165.0	175.0

For all of these reference heights, wind parameters, such as minimum, maximum, mean and standard deviation of wind speed (W_{min}, W_{max}, W_{mean} and $\sigma(W)$ respectively), have been calculated and reported in Tables 7 and 8.

In order to quantify the energy fluctuations and the inactivity periods of the wind plants, a working time parameter, T_w, is reported, calculated as the fraction of a year in which a wind plant could yield energy, i.e., the wind speed is within the cut-in (w_{in}) and cut-off (w_{off}) speed. In the present study, these two working limits have been assumed to be equal to 3 m/s and 18 m/s respectively. In this vein, to provide information about the temporal distribution of the collected energy, the exploitable power fraction, X_w, is also shown (Tables 8 and 9). The latter parameter represents the fraction of the total wind power which may be exploited by a wind generator during operation conditions (i.e., when $w_{in} < w < w_{off}$). All the ECMWF points are characterized by a windiness that would allow a wind turbine to supply energy quite continuously over time. Referring to the standard height of 10 m, with the above-mentioned values of the cut-in and cut-off speed, the working time varies from 73.7% at W5 to 76.8% at W1. It is highlighted the very high value of exploitable power fraction ($X_w > 97\%$) for all sites at every reference height. It is worth noting also that maximum hindcast wind speed is 16.46 m/s (W5 at 100 m). Albeit this is not the true maximum wind speed measurable in the area, since smaller sampling frequency for the hindcast data involves peak attenuation, it demonstrates as the area experiences great windiness regularity.

Table 8. Main wind climate parameters (based on 10-year average) at points W1–W5.

Reference Height	Point	W_{min} (m/s)	W_{max} (m/s)	W_{mean} (m/s)	σ_W (m/s)	T_w (%)	X_w (%)
10 m	**W1**	0.06	13.06	4.55	1.99	76.79	98.46
	W2	0.03	12.95	4.50	1.95	76.46	98.22
	W3	0.03	12.58	4.44	1.92	75.53	97.89
	W4	0.05	12.73	4.37	1.91	74.75	97.64
	W5	0.03	13.17	4.31	1.89	73.72	97.32
25 m	**W1**	0.07	14.36	5.01	2.19	81.04	99.06
	W2	0.03	14.24	4.95	2.15	80.64	98.93
	W3	0.04	13.83	4.88	2.11	80.06	98.67
	W4	0.06	14.00	4.81	2.10	79.05	98.52
	W5	0.03	14.48	4.74	2.08	78.09	98.27
55 m	**W1**	0.07	15.48	5.39	2.36	83.76	99.39
	W2	0.03	15.35	5.34	2.32	83.35	99.24
	W3	0.04	14.91	5.26	2.28	83.08	99.14
	W4	0.06	15.09	5.18	2.26	81.98	98.99
	W5	0.03	15.61	5.11	2.24	81.41	98.83
80 m	**W1**	0.08	16.01	5.58	2.44	84.84	99.48
	W2	0.03	15.88	5.52	2.39	84.36	99.35
	W3	0.04	15.42	5.44	2.36	84.08	99.26
	W4	0.06	15.61	5.36	2.34	83.19	99.13
	W5	0.04	16.14	5.28	2.32	82.68	99.04
100 m	**W1**	0.08	16.33	5.69	2.49	85.32	99.53
	W2	0.03	16.19	5.63	2.44	84.97	99.41
	W3	0.04	15.72	5.55	2.40	84.62	99.34
	W4	0.07	15.92	5.47	2.38	83.92	99.21
	W5	0.04	16.46	5.39	2.37	83.52	99.13

Table 9. Main wind climate parameters (based on 10-year average) at points E1–E5.

Reference Height	Point	W_{min} (m/s)	W_{max} (m/s)	W_{mean} (m/s)	σ_W (m/s)	T_w (%)	X_w (%)
10 m	**E1**	0.04	12.96	4.97	2.04	81.32	98.81
	E2	0.07	13.37	4.86	1.99	80.97	98.65
	E3	0.06	12.80	4.75	1.96	79.83	98.37
	E4	0.05	12.57	4.62	1.93	78.38	98.09
	E5	0.05	12.21	4.50	1.91	77.20	97.70
25 m	**E1**	0.04	14.25	5.46	2.24	84.89	99.32
	E2	0.07	14.70	5.35	2.19	84.39	99.20
	E3	0.07	14.07	5.22	2.15	83.54	99.00
	E4	0.05	13.82	5.08	2.12	82.47	98.84
	E5	0.05	13.43	4.95	2.10	81.43	98.57
55 m	**E1**	0.05	15.36	5.89	2.41	87.03	99.56
	E2	0.08	15.85	5.76	2.36	86.66	99.46
	E3	0.07	15.17	5.63	2.32	85.97	99.34
	E4	0.06	14.90	5.48	2.29	85.29	99.21
	E5	0.06	14.47	5.34	2.27	84.23	99.07
80 m	**E1**	0.05	15.89	6.09	2.50	87.88	99.60
	E2	0.08	16.39	5.96	2.44	87.69	99.57
	E3	0.08	15.69	5.82	2.40	86.95	99.45
	E4	0.06	15.41	5.66	2.37	86.29	99.33
	E5	0.06	14.97	5.52	2.34	85.46	99.23
100 m	**E1**	0.05	16.21	6.21	2.55	88.44	99.64
	E2	0.08	16.72	6.08	2.49	88.24	99.62
	E3	0.08	16.00	5.94	2.45	87.54	99.51
	E4	0.06	15.72	5.78	2.41	86.71	99.38
	E5	0.06	15.27	5.63	2.39	86.01	99.32

This result is confirmed in Tables 10 and 11, where the monthly mean speeds at 10 m, $U_{10,mean}$, have been summarized. For all the selected points, the ratio between the minimum and mean average monthly wind speed $U_{10,mean}$ shows very high values, hence the area is characterized by very low seasonal wind speed variability. These outcomes seem in contrasts with some preliminary information described in [1], in which the Authors pointed out for the selected area long periods of the year with almost no useable wind.

Figures 5 and 6 report the wind rose with both the annual frequency distribution of the wind direction and the annual mean wind speed. It is clearly shown as the wind mostly blows from the West, with a secondary sector from E-NE. In order to better visualize the wind climate, an offshore energy flux density plot was computed and shown in Figure 7.

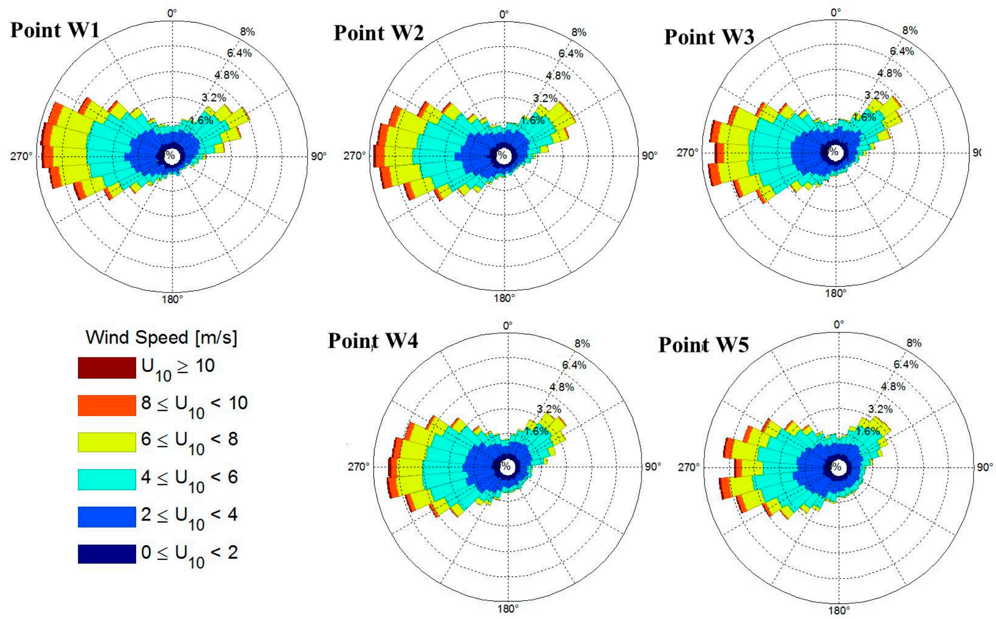

Figure 5. Wind rose at points W1–W5 with directional bins of 10°.

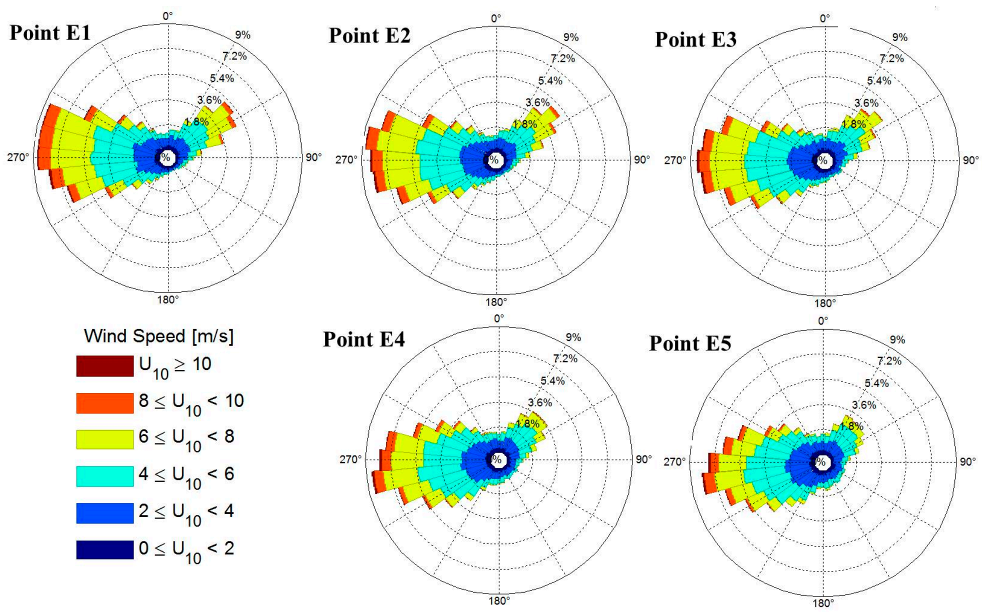

Figure 6. Wind rose at points E1–E5 with directional bins of 10°.

Table 10. Monthly mean speeds $U_{10,mean}$ at points W1–W5.

Point	$U_{10,mean}$ (m/s)												
	January	February	March	April	May	June	July	August	September	October	November	December	Min/Mean
W1	5.0	4.5	3.6	3.4	5.1	5.5	5.2	4.8	5.1	4.6	3.8	4.0	0.74
W2	5.1	4.6	3.6	3.5	5.1	5.2	4.8	4.5	4.9	4.7	4.0	4.1	0.78
W3	4.2	4.7	3.6	3.6	5.1	4.8	4.4	4.2	4.8	4.8	4.1	4.1	0.82
W4	4.9	4.6	3.6	3.8	5.0	4.5	4.1	3.9	4.6	4.9	4.4	4.2	0.82
W5	4.8	4.5	3.6	3.9	4.9	4.2	3.9	3.7	4.4	4.9	4.6	4.3	0.83
Mean	6.8	6.2	6.2	7.5	10.8	14.7	17.2	15.5	14.1	10.4	7.1	6.7	0.80

Table 11. Monthly mean speeds $U_{10,mean}$ at points E1–E5.

Points	January	February	March	April	May	June	July	August	September	October	November	December	Min/Mean
E1	5.5	4.8	3.7	3.8	5.8	6.0	5.7	5.5	5.5	4.8	4.1	4.5	0.74
E2	5.5	4.9	3.7	3.9	5.8	5.6	5.2	5.1	5.2	4.9	4.2	4.5	0.75
E3	4.4	4.8	3.6	4.0	5.7	5.2	4.8	4.8	5.1	5.0	4.3	4.4	0.78
E4	5.1	4.6	3.6	4.1	5.5	4.9	4.5	4.6	4.9	5.0	4.5	4.3	0.78
E5	4.8	4.5	3.6	4.2	5.3	4.6	4.2	4.3	4.7	4.9	4.6	4.4	0.79
Mean	6.8	6.2	6.2	7.5	10.8	14.7	17.2	15.5	14.1	10.4	7.1	6.7	0.77

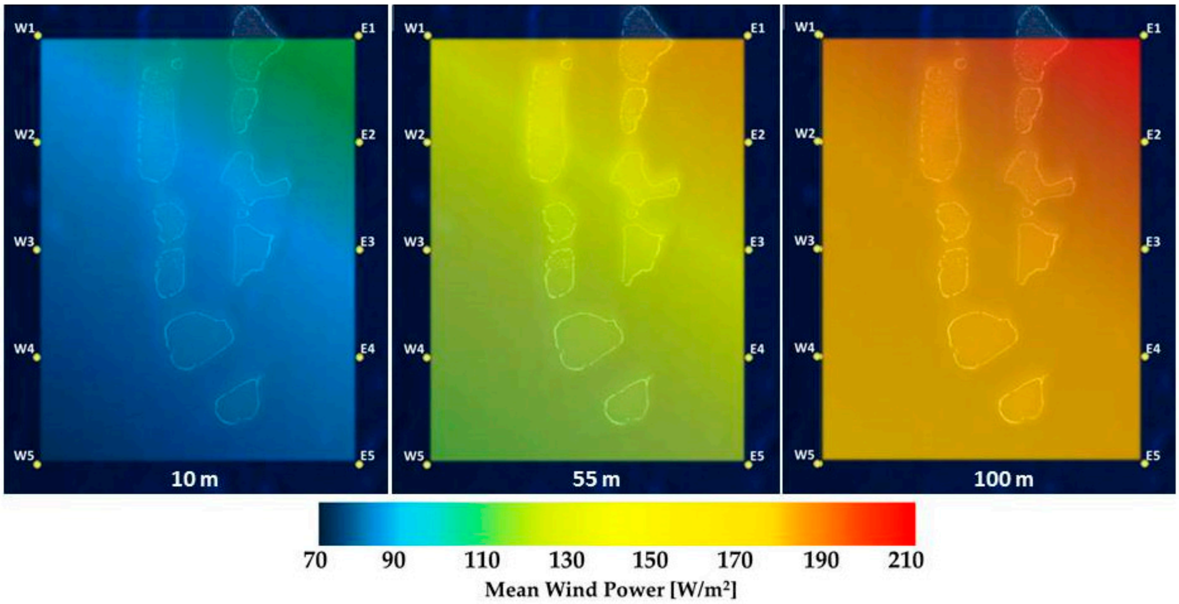

Figure 7. Mean wind power plot along the studied area.

4. Additional Considerations and Discussion

As showed in previous chapter, the area is characterized by a significant seasonality of wave regimes and a poor monthly variability of wind conditions. An heuristic explanation could be provided considering that the Maldives wave sea state is comprised of multiple wave fields, i.e., sea waves generated by local winds plus very long-period swells approaching from several distant sources and different directions. In support of this argument, it is possible to note as the highest values of wave power are measured from May to October, which correspond to the period when the southwest monsoon is in full swing [72]. On the basis of the above considerations, it is reasonable to also explain the poor relationship between the main directions of waves and local winds. As demonstrate by [73], the time scale of the directional response appears to be equal to the time scale of wave energy growth only for young sea states, hence in absence of swell. Therefore, the energy patterns suggest that wind and waves are generally uncorrelated, especially during the period of southwest monsoon. These conditions are very interesting in the perspective of reducing the overall variability of the produced power. Indeed, the correlation of ocean waves to wind is a very important aspect for both forecasting models of energy production and for design of mooring/substructure/structure of wind/wave energy devices.

In order to boost blue growth and make wind and wave energies environmentally and socio-economically sustainable, a role of preference could be addressed bringing together the energy demand with other local issues. Indeed, the need for fresh water is at the top of the Government agenda for critical problems. Malé, the capital of the Maldives, declared a state of emergency in 2014 due to the lack of potable water, when the majority of the inhabitants were left without access to potable water. Today, rainwater is more widely used than groundwater for drinking purpose and about 88% of the population in Malè intercepts rainwater via tanks [1]. Furthermore, it is expected that population growth and the increase of the number of tourists will result in ever-increasing demands for clean water. Generally, the potable water demand in coastal areas is met by means of large-scale desalination systems. However, also the modern systems require very high energy consumption, which still represents a crucial drawback for this technology. Furthermore, numerous low-density population islands lack not only fresh water availability, but also the electrical grid connection or any other energy source. The real challenge, consequently, is to ensure adequate fresh water supplies at the minimum possible cost. For these reasons, wind and wave energy coupled with desalination systems appear as a promising opportunity for small islands and developing countries to meet their water supply needs. Providing for these crucial needs via renewable natural resources, resulting in a broad social acceptance.

The water supply is not the only problem for Maldivian islands: the result of a study [74] shows that around 64% of all the islands reported severe beach erosion. Beach replenishment may only be a temporary remedy and traditional hard solutions, such as groynes, revetments or breakwaters, are often unpopular for aesthetic reasons and they reduce the recreational values. An interesting alternative may be represented by the beach drainage system, which has the great advantage to eliminate the visual impact. Additionally, its installation is not as costly as the traditional hard coastal structures and it does not suffer from wear rates as beach nourishments. This innovative system has been proven to stabilize the beachface when low incident wave energy conditions are ensured [75–77], like the ones inside a coral reef. In the context of the promotion of hybrid systems, it is remarkable that the drained water flows may be considered as a water pre-treatment for desalination, with both drainage and desalination plants powered by inshore/offshore blue energy technologies, pursuing a very high ethics perspective.

In order to boost blue growth, the paper investigates the uses of multifunctional structures combining power generation, desalinization and coastal defence. As aforementioned, two representative islands are analysed: Malé, and Magoodhoo. The selection of these sites provides two good case studies for different reasons. The first one is the opposite demographic conditions between the two islands. Then, the difference in the waterfront and coastal line, since Magoodhoo is a natural environment without any sign of significant human activity, while the Male Island is almost entirely protected by six-kilometers circumference of sea walls. Furthermore, the electricity demand in the capital island increases at a yearly rate of 11% [69] but, at the same time, there is not enough land to expand power plants. Therefore, it is crucial to find alternative options to supply electricity. Finally, Magoodhoo hosts the Marine Research and High Education Center born by the collaboration of Maldivian Government and the University of Milan-Bicocca. In particular, within the program "*Benefits of using renewable energy for Maldivian communities and marine ecosystems*" promoted with the support of the Italian Caritas, a photovoltaic system has been donated to the people of Magoodhoo [78]. This system feeds power to the island grid, and it is helping to reset the electricity production, moving from a small diesel sets configuration. Moreover, the cooperative agreement between Italy and the Maldives has also supported a new project termed "*Installation of a water desalination plant on the island of Magoodhoo—Faafu Atoll*" [79]. The desalination plant, through the use of solar thermal and photovoltaic panels, will provide clean water to the island's population, who currently does not have drinking water, and so to the MaRHE Center.

Nowadays, over 1000 wave energy converters (WECs) [80] have been patented over the last twenty years in order to transform wave energy into electrical energy. Several of these technologies are still in an early stage of technical development, and only few of them are ready for a pre-commercial stage (e.g., Aquabuoy, Aws II, Dexa wave, Limpet, Mutriku, OBREC, Oyster, Rewec III, Seabased, Pelamis, PowerBuoy, Wave Dragon, Wavestar, etc.) The selection of the best leading technologies or the tuning study of a specific WEC is out of the scope of this paper. Regarding the wave-to-wire efficiency of these technologies, from previous extensive literature [81–95] it is possible to assume, for a generic WEC, an overall averaged efficiency of 16.5%. In order to cover the Malé electricity demand of 300 GWh/year, a theoretical wave harvester over 20 km long should be required (8.8 kW/m are considered). Hence, wave energy seems more promising in supply energy in conjunction with other renewable sources. In particular, WECs have specific advantage for smaller islands, in order to maximize diesel savings in the short term and minimize the energy storage costs in the longer term. For instance, for Magoodhoo (where about 11.6 kW/m are computed), just a ten meters wide WEC is able to supply the whole island electricity demand (approximately 150 MWh).

Wind resource in the Maldives is high in comparison to the energy demand. Tables 12 and 13 compare the theoretical wind power, P_{wind}, the wind-to-wire power, P_{tur}, and the annual averaged energy, $E_{yearly,mean}$, produced by the three aforementioned idealized WTGs at each Western and Eastern grid points. From an economic point of view, results show that larger turbines are more efficient. In fact, regarding the energy production, for one 2.3 MW WTG, three 1.0 MW WTGs and about 21 small 100 kW WTGs are needed. For a large turbine, the yearly energy could arise in average 4.33 GWh on the west side and 5.11 GWh on the eastern part of the archipelago. This represents an important result because about 100 wind generator of 2.3 MW could provide the approximately 480 GWh of the whole electricity sector, moving the Maldives towards energy self-sufficiency using offshore wind power.

However, such a high level of wind energy potential does not come without difficulties. First of all, the use of a single source of energy does not fit with energy security strategies, addressed to ensure the uninterrupted physical availability of energy products and to balance and diversify the various sources of supply. Secondly, visual impacts of onshore and nearshore wind facilities represent one on the major concern considering the high value of Maldive's natural seascapes. The environmental and socio-economic impact visual assets at highest risk from coastal and marine landscape change are directly linked to the height of wind towers and to the distance from the coastline [96]. Both the social acceptance of an offshore WTG and the economic appeal for investors and utility providers remain heavily dependent on costs vs. payback analysis, that means competitively priced electricity supplies and reliability.

A solution to significantly decrease the production costs of blue energies would be to develop hybrid technologies, i.e., co-locating floating/fixed WTGs and WECs at offshore locations, possibly by promoting multi-use platforms [13–23]. The combination of wind and wave energy resources reduce the overall dimensions per unit of power, the operational requirement for reserve and regulating power [97–101] as well as the requirement for generation capacity to maintain the power system reliability [102–104]. By the co-location of wind and wave generators, also the nearshore or shoreline devices are further promoted. Especially for the last case, devices embedded within coastal [93,105–109] or offshore infrastructures could be also combined with desalination plants. That solution has been recently considered in depth from many Authors (e.g., [110–113]). Numerous low-density population areas lack not only fresh water availability, but in most of the cases electrical grid connection or any other energy source as well [114]. Most of the countries experiencing "water stress" have enough water, but lack the means to provide it in an accessible manner [115]. For Magoodhoo, based on a specific energy consumption of 2.0 kWh/m^3 [116] and water requirements of 1100 m^3 per person per year (included domestic, drinking and food production purposes according to [117]), a 90 m wide WEC could ensure the total freshwater demand.

Moreover, this island has been recognized as one of the 86 islands that have reported severe beach erosion since 1990 [118]. In order to provide stabilization to the 2.3 km of Magoodhoo coastline with a beach drainage system (considered a low impact soft-engineering solution by coastal managers), a preliminary configuration has been assessed. For such a configuration, constituted by 4 parallel pipelines surrounding the island and pumping stations characterized by 12 pumps of 6.5 kW (adapted from [75] and [119]), an average annual electricity demand of about 200 MWh €/year can be computed. Hence, a WEC 115 m wide could provide the total requests of energy, freshwater and beach stabilization purposes of the whole island. This proves the high benefits provided by WECs for small islands, according to [56,120].

On the other hands, due to the lower wave resource in the eastern region, the about 114 million m^3/year of potable water for Malè requires large wind farms. A preliminary analysis using data for the 2.3 MW WTG, indicates as a number of 42 turbines are needed. Obviously, that number can reasonably be reduced if wind and wave harvesters are co-located.

Table 12. Theoretical wind power, P_{wind}, wind-to-wire power, P_{turb}, and the annual averaged energy produced, $E_{yearly,mean}$, by the three idealized WTGs at points W1–W5.

	100 kW Turbine			1.0 MW Turbine			2.3 MW Turbine		
Point	P_{wind_mean} (kW)	P_{turb_mean} (kW)	$E_{yearly,mean}$ (GWh/y)	P_{wind_mean} (kW)	P_{turb_mean} (kW)	$E_{yearly,mean}$ (GWh/y)	P_{wind_mean} (kW)	P_{turb_mean} (kW)	$E_{yearly,mean}$ (GWh/y)
W1	56.74	23.82	0.22	360.87	164.95	1.52	1298.97	505.60	4.66
W2	54.51	23.06	0.21	360.87	164.95	1.52	1247.81	485.50	4.52
W3	51.50	21.92	0.21	327.54	149.29	1.40	1179.00	459.01	4.32
W4	48.71	20.83	0.20	309.79	141.72	1.35	1115.08	435.09	4.16
W5	46.26	18.36	0.18	294.20	134.39	1.30	1058.97	414.20	4.01
Mean	51.54	21.60	0.20	330.66	151.06	1.41	1179.96	459.88	4.33

Table 13. Theoretical wind power, P_{wind}, wind-to-wire power, P_{turb}, and the annual averaged energy produced, $E_{yearly,mean}$, by the three idealized WTGs at points E1–E5.

	100 kW Turbine			1.0 MW Turbine			2.3 MW Turbine		
Point	P_{wind_mean} (kW)	P_{turb_mean} (kW)	$E_{yearly,mean}$ (GWh/y)	P_{wind_mean} (kW)	P_{turb_mean} (kW)	$E_{yearly,mean}$ (GWh/y)	P_{wind_mean} (kW)	P_{turb_mean} (kW)	$E_{yearly,mean}$ (GWh/y)
E1	67.29	28.56	0.27	427.93	196.74	1.87	1540.33	610.55	5.77
E2	62.55	26.72	0.26	427.93	196.74	1.87	1432.00	571.09	5.45
E3	57.51	24.90	0.24	365.76	169.66	1.65	1316.56	525.39	5.11
E4	52.67	22.94	0.23	334.97	154.45	1.54	1205.73	482.29	4.76
E5	48.79	20.09	0.20	310.27	143.43	1.44	1116.82	447.11	4.48
Mean	57.76	24.64	0.24	373.37	172.20	1.67	1322.29	527.29	5.11

5. Conclusions

The present paper provides a preliminary assessment of the electric power generation of offshore wind turbines and wave energy converters along the Archipelago of the Maldives coasts. Wind and wave climate has been analysed and characterized using a 10-year period ECMWF wave forecasting data for 10 grid points. Both resources are relatively abundant, albeit opposite trends for energy potential have been recognized. While the wind power increases in the N-NE direction (moving from 72 W/m^2 to 104 W/m^2 in the study area), the average wave power density in deep waters ranges between 8.5 kW/m in the north-eastern area to about 12.7 kW/m in the south-west region. Furthermore, wind resource seems characterized by lower seasonal variability than wave energy. The energy patterns suggest that wind and waves are generally uncorrelated, especially during the period of southwest monsoon. These conditions are very interesting in the perspective of reducing the overall variability of the produced power.

This coastal area, therefore, shows to be an important candidate for the next optimal study site for several kinds of combined wind turbines and wave energy converters. Promising configuration of multi-use device is investigated through two case studies at Malè and Magoodhoo Island, in particular to face two main problems: water scarcity and beach erosion. Introducing additional considerations for environmental impact assessment, the high-density power provided by wave energy harvesters results as a good compromise for low-density population areas, lacking of not only fresh water availability, but in most of the cases also the electrical grid connection or any other energy source. However, very large offshore wind farms or co-located wind and wave farms are strongly recommended for higher energy demand areas. It has been demonstrated that renewable energy resources of offshore wind and wave can move the Maldives towards energy self-sufficiency. These combined farms would best be located near points along the coast where regions of high wind and wave resources overlap. The combined use of this resource, together with solar and biomass, has been shown to produce important benefits for the electric power system especially in the perspective of an energy diversification strategy.

Author Contributions: Pasquale Contestabile and Paolo Galli conceived and wrote the paper draft. Enrico Di Lauro performed the analysis for wave and wind energy assessment. Diego Vicinanza and Cesare Corselli revised the paper draft and Pasquale Contestabile updated the paper according to their review.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ECMWF	European Centre for Medium-Range Weather
N-NE	North-NorthEast
S-SW	South-SouthWest
WEC	wave energy converter
WTG	wind turbine generator

Appendix A

This appendix contains details about power production curves of the three practical utility-scale wind turbines analysed in this study.

As aforementioned the production curves are obtained averaging the ones provided by the following wind turbine manufacturers:

- for the 100 kW WTG, with hub height of 25 m, the power curves of Northern Power System, Polaris America and Wind Energy Solutions are averaged;
- for the 1.0 MW WTG, with nacelle height of 55 m, the power curves of WTG proposed by WinWind and Nordic Windpower are considered;
- finally, for the 2.3 MW WTG, with hub posed ad 80 m, the production curves of the correspondent WTG size measured by General Electric and Siemens are averaged.

The resulting power curves are reported in Figure A1.

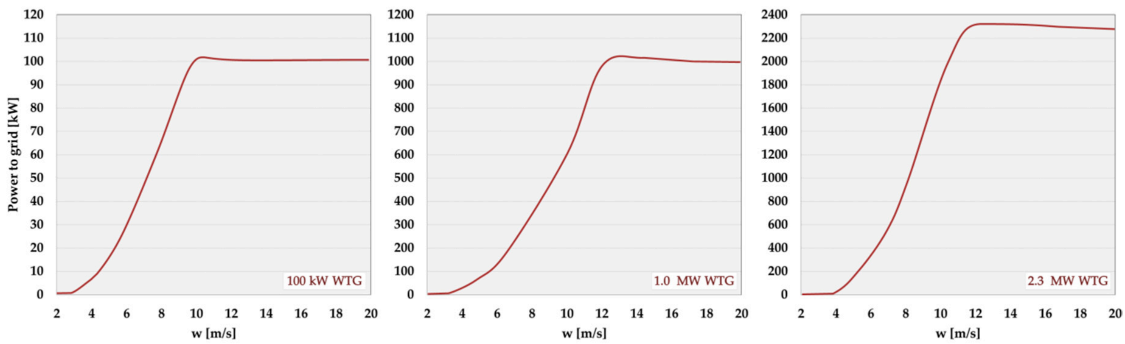

Figure A1. Power to grid vs. wind velocity at hub height (power curve) for the three wind turbines analysed.

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