Wave electricity production in Italian offshore: A preliminary investigation

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1. Introduction

Among renewable energy resources wave energy represents a large and viable source of power supply, which deserves serious attention [1]. Although it represents only a small portion of wind energy, which in turn is only a small fraction of solar energy, the energy of the surface ocean waves is more predictable, persistent and spatially concentrated [2]. The enormous wave power potential together with the technical advantages of wave energy conversion has stimulated the interest of governments and energy companies since the oil crisis of 1973. Nowadays, a number of full scale wave energy devices have been deployed in real sea conditions and several others are at the end of their development phase [3]. However, the technology is still far from the maturity and significant efforts are required to make it economically convenient with respect to other renewables such as wind and solar energy. At present, harnessing wave energy is a big challenge for the scientific community, which could play a significant role in the reduction of the world dependence on fossil fuels and in the mitigation of climate change problems.

Wave energy exploitation starts with the characterization of the wave energy resource. The resource assessments allow to select the most promising locations for wave farms, to design the wave energy converters and to estimate the energy production and the possible cost of energy. Wave energy assessments are typically based on wave buoy records, satellite measurements and/or hindcast data by ocean wave prediction models. Energy atlas provides

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information on the wave energy potential, expressed as power per unit of wavefront length, and sometimes also on the composition of the resource in terms of sea states and seasonality.

At the global scale, maps of the wave energy resource have been recently published by Cruz [4], Cornett [5], Gunn and Stock-Williams [6] and Arinaga and Cheung [7]. These atlas show that the most energetic areas of the global oceans are found in moderate to high latitudes and are located off the western coasts of the continents due to the Coriolis effect. It is also evident that the southern hemisphere presents lower seasonal variability of the wave power potential and so it is advantaged in the exploitation of the ocean wave energy.

In Europe, a wave energy atlas [8] has been developed in 1998 by six different countries and provides detailed wave climate and wave energy statistics at 85 points off the European coasts. Moreover, different European countries have assessed and characterized their offshore wave energy resource to investigate the feasibility of wave energy conversion along their coasts. In the Iberian Peninsula, the average annual wave power is about 30 kW/m–40 kW/m off the northern Portugal coast [9] and varies from 15 kW/m to 50 kW/m in the northwest of Spain [10]. The British Islands have the highest wave energy resource in Europe with annual power levels up to 75 kW/m off the Irish coasts [11] and between 60 kW/m and 70 kW/m in the most attractive sites of the United Kingdom [12]. Moving to the northern Europe the available wave power decreases to 30 kW/m off the northern part of the Norwegian coast [3] and to 5 kW/m off the Swedish west coast [13]. In the Mediterranean basin, the average annual wave power varies between 3 and 12 kW/m and the most energetic areas are located in the western Mediterranean between the Balearic Islands and the western coast of Sardinia and in the Sicily channel [14].

A number of studies have recently assessed and characterized the wave energy resource in island environments. Because of their geographic isolation, islands are extremely dependent on fossil fuels and suffer for high electricity rates. Moreover, they have typically abundant renewable resources and are especially vulnerable to the impacts of climate change. These features make island environments particularly suitable for renewable energy technologies. Wave energy potential has been evaluated for the Archipelago of Azores [15], the Madeira Islands [16], and two islands in the Canary Archipelago [17,18]. These works have shown that wave energy is abundant in these islands and that significant concentration of wave energy may occur in the proximity of the coasts, due rapid bathymetric changes.

Referring to the Italian scenario, a recent survey [19] reports that renewable energies in Italy covers more than 20% of the state energy demand. The largest contribution comes from hydropower systems, while wind energy ranges close to 3% and photovoltaic conversion as well. Even if wind energy installations are still increasing, photovoltaic experienced a real boom between 2010 and 2011 passing from 1906 GWh to 19,796 GWh. In terms of power, the importance of renewable resources is even bigger since hydroelectric plants add up to 21,737 MW (18.4%), wind turbines to 6918 MW (5.8%) and photovoltaic stations to 12,773 MW (10.8%).

Apart from short term power oscillation for wind generators which requires both mechanical and electromagnetic damping [20], the main problem of renewable resources is the natural intermittency at larger time scale. Attempts to cast the problem in a more general energy strategy framework can be found in the literature ten years ago, already [21].

Interesting considerations about the costs of intermittency in energy production are presented by Leijon et al. [22] and Skoglund et al. [23] with general reference to renewable electric energy sources. Different technical alternatives for energy storage are compared by Connolly et al. [24] with reference to hydroelectric systems and by Azcarate et al. [25] for what about the hydrogen cycle is concerned. At a local scale, an interesting solution could be to co-locate offshore wind turbines and wave energy converters, as proposed by Stoutenburg et al. [26], due to the different time scales of the devices.

The first assessment of the wave energy resource in the Italian offshore has been carried out by Filianoti [27] analysing 11-year wave buoy records for 8 locations off the Tyrrhenian, Adriatic and Ionic coasts. Recently, this study has been updated considering a longer wave measurement period and further offshore locations [28], and an Italian Wave Energy Atlas has been published and is available on the web (www.italywaveenergy.it). According to the atlas in the Italian seas the average annual wave power is very low – around 2 kW/m off the Adriatic coasts and between 3 kW/m and 4 kW/m in the Tyrrhenian and Ionian seas – but in the north-west of the island of Sardinia it exceeds 9 kW/m.

During the last two decades a great number of technologies has been designed to extract energy from ocean waves but only few full-scale prototypes have been deployed in real sea conditions. Moreover, there is still no consensus on which type of device is ideal for which circumstances [1]. Recent reviews on the existing wave energy converters (WECs) can be found for example in Clément et al. [3], Cruz [4] and Falcão [29]. The different technologies may be classified by either the principle of operation or the geometry of the device or the primary location (onshore, nearshore or offshore). A widely used classification is based on the horizontal size and orientation of the device. If the horizontal physical dimension is much smaller than the wavelength of the incident waves, the WEC is called point absorber [30]. On the contrary, they are called attenuators and terminators if they have a horizontal extension which is comparable with typical wavelength of the waves from which they are designed. Attenuators are aligned along the prevailing wave direction while terminators are positioned perpendicularly to the dominant direction of the incident waves. A more comprehensive classification system has been proposed by Hagerman [31] and further modified and updated by Brooke [32]. It classifies the wave energy conversion technologies on the basis of the energy extraction method (heave, surge, pitch, yaw or combined modes), the type of absorber (rigid, flexible or free surface), and the type of reaction point (inertial structure, sea–floor anchors or fixed structures) and the primary location of the device.

The first systems to be deployed (also named first generation devices) were mostly located on the shoreline or near-shore and were typically based on the method introduced by Masuda [33], named oscillating water column (OWC). They have the advantage of easier installation and maintenance but are exposed to a much less energetic wave climate. On the other hand the most recent wave energy technologies (third generation devices) are located offshore (>40 m depth) where high levels of energy are available but face problems due to mooring, access for maintenance and need of long underwater electrical cables. These systems are typically oscillating bodies, either floating or fully submerged, which provide a large power output either by a single device of large physical dimensions or by small modular devices deployed in arrays.

In this work a feasibility study of wave energy exploitation in Italian seas is carried out. The energy production of three of the most promising wave energy converters is estimated for two of the most energetic sites off the Italian West Mediterranean coast. The paper is organized as follows: in the first section we characterize the wave energy resource along the Italian coasts. In the second section we describe the wave energy converters considered for this analysis. Then we estimate the energy production of the hypothetical wave farms and we calculate the scale of the devices which would maximize their capacity factors at the study sites. Finally, in the last section some conclusions are drawn.

2. Wave energy resource

In order to study the feasibility of wave energy exploitation off the Italian coasts, the two most promising locations, where wave buoy records are available, were selected. According to the recent assessments of wave energy resource in Italian seas [14,28] the most energetic areas are located along the western coast of Sardinia and off the north-western and southern coasts of Sicily. The Italian Wave Energy Atlas, which is based on the wave measurements of the Italian Wave Network (www.telemisura.it) shows that the wave buoys locations with the highest wave energy potential are Alghero, on the western coast of Sardinia and Mazara del Vallo, on the Sicily Strait (Fig. 1). For these promising sites, where the hypothetical wave farms were assumed to be located, 21 years of wave measurements, covering the period from 1990 to 2011, were collected. Wave data consists of pairs of significant wave height (H_S) and peak period (T_p) measured every 3 h or every half-hour (depending on the value of wave height and on the year of measurement). To obtain more robust estimates of the average annual values, the measurement period of each station was restricted to the years with less than 5% of missing data. As a result, the wave records used for the Mazara buoy were limited to 15 years while the wave data at the Alghero location was reduced to 17 years. In this way the percentage of missing data over the whole series reduced to 0.7% for Alghero and to 0.5% for Mazara.

For each recorded sea state, the wave power per unit of wavefront length (kW/m) was estimated by the following equation:

$$P = \frac{1}{64\pi}\rho g^2 H_S^2 T_e \tag{1}$$

where ρ is the seawater density (1025 kg/m^3), g is gravity and T_e is the energy period, i.e. the ratio between the spectral moment of order -1 and of order 0. The energy period of a sea state is equivalent to the period of a single sinusoidal wave that would have the same energy as the sea state. The spectral moment m^{-1} was calculated assuming a JONSWAP spectrum [34] for the sea states and adopting the shape parameters provided by the atlas of Italian seas for the two locations [35].

Fig. 1. Location of wave buoys of the Italian wave network and case study locations.

The resulting average annual wave power is 10.3 kW/m at Alghero and 4.0 kW/m at Mazara del Vallo confirming results by Vicinanza et al. [36]. The available annual wave energy is 90 MWh/m at Alghero and 35 MWh/m at Mazara del Vallo. The monthly distribution of the wave power potential (Fig. 2) shows a strong seasonal variation of the resource. At both the study sites, the months from December to February account for about 40% of the annual wave energy while the events occurring from June to August provide only 10% of the annual output. The most energetic month is December with an average power of 18.9 kW/m at Alghero and 8.0 kW/m at Mazara del Vallo while the less energetic month is August with 3.5 kW/m and 1.0 kW/m, respectively. Mazara del Vallo is characterized by higher intrannual variability with a coefficient of variation of the monthly wave power equal to 58% versus 48% at Alghero.

The above presented statistics of monthly and annual wave power are mostly useful to identify the attractive locations for electricity generation. However, the design of wave energy converters as well as the selection of the WECs to be installed at a site requires the knowledge of the composition of the resource in terms of sea states. The wave energy converters have different efficiencies in the different ranges of wave height and periods and cease to operate in stormy seas. The optimum device at a given location should have the maximum efficiency for the prevalent moderate waves providing the bulk of energy. Extreme wave events even if more energetic occur very seldom and do not contribute very much to the annual energy. Moreover the exploitation of these sea states is usually not convenient because it requires over-dimensioned devices. Fig. 3 shows the contribution of the different sea states, characterized by H_S and T_p pairs, to the annual energy at the study sites.

At Alghero about 50% of the total annual wave energy is associated with wave heights between 2 and 4 m and more than 75% is provided by waves with height between 1 and 5 m. With regard to the wave periods, sea states with peak period between 8 and 10 s account for almost 50% of the total energy and about 70% of the resource is associated with swells with period between 8 and 12 s. The extreme wave events ($H_S > 7$ m) provide only 4% of the annual wave energy. In terms of sea states the main contribution to the annual energy, higher than 50%, is provided by waves with heights between 2 and 4 m and periods in the range 8–12 s.

At Mazara del Vallo the resource is more concentrated in terms of both wave period and wave height. Sea states with significant wave height between 1 and 3 m account for almost 70% of the annual energy and more than 80% of the available resource is provided by swells with periods between 6 and 10 s. As a result 60% of the annual wave energy is associated with sea states with significant height between 1 and 3 m and peak period between 6 and 10 s. As well as in Alghero, the stormy events contribute very little to the annual energy: only 1% of the annual energy is associated with events with $H_S > 5$ m.

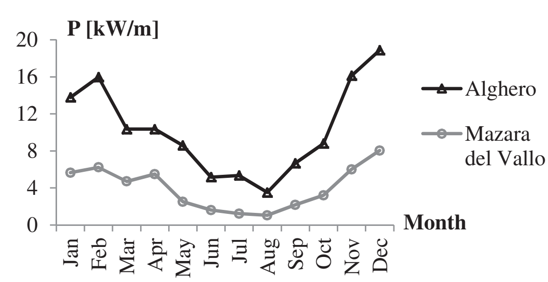

Fig. 2. Average monthly wave power at Alghero and Mazara del Vallo.

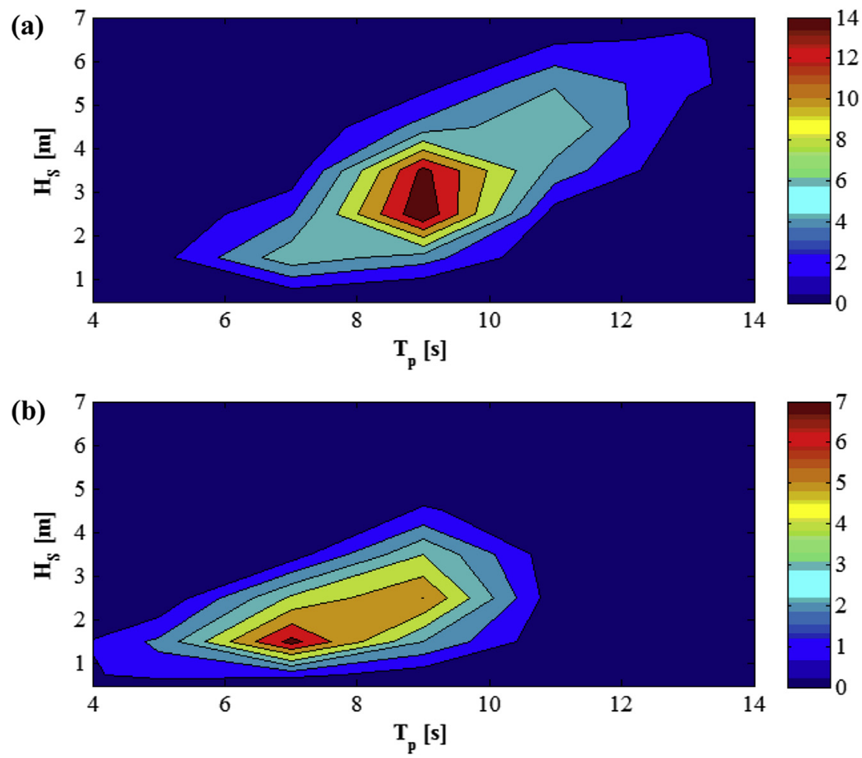

Fig. 3. Percentage of the annual energy corresponding to the different sea states, identified by H_S and T_p couples, at Alghero (a) and Mazara del Vallo (b).

3. Wave energy converters

Three wave energy converters were considered to estimate the energy production off Alghero and Mazara del Vallo. The choice was motivated by the following considerations: (1) the selected devices have reached an advanced development stage, (2) the performance data of the energy converters have been made publicly available, (3) the technologies belong to the third generation and (4) the devices are characterized by different working principles. The main features of the selected wave energy converters are summarized in Table 1.

The AquaBuOY is a point absorber device developed by Finavera Renewables Inc., formerly AquaEnergy Group Ltd. [37]. It is a floating buoy mounted above a piston contained inside a tube, opens on both ends, with a hose pump attached to each end. As the buoy oscillates, the hose pumps produce a flow of pressurized water that drives a Pelton turbine, connected to a generator. Each 40-ton AquaBuOY has a rated power of 250 kW. The device is modular and can be scaled from a small cluster to hundreds of buoys combined into arrays providing an annual energy production from a few hundred kilowatts to several hundred megawatts.

The Pelamis wave energy converter is developed by the Scottish Company Pelamis Wave Power Ltd., formerly known as Ocean Power Delivery Ltd. [38]. Linear absorber or attenuator, which works aligned with the dominant wave direction. The machine is a semi-submerged, articulated structure composed of four cylindrical sections linked by hinged joints. The wave-induced motion of the joints (either by heaving or swaying) is resisted by hydraulic rams, which pump high-pressure oil through hydraulic motors driving electrical generators. The machine is designed for offshore locations with water depths of 50–70 m and it is flexibly moored so as to swing head on to the incoming waves. Several devices can be connected together and linked to shore through a single seabed cable. The version used in this study is 150 m long and 3.5 m in diameter and has a power output of 750 kW. A full-scale prototype

Table 1
Main features of the wave conversion technologies considered in the study.

	AquaBuOY	Pelamis	Wave Dragon
Company	Finavera Renewables	Pelamis Wave Power Ltd.	Wave Dragon ApS
Country	Canada	UK	Denmark
Installation depth	Offshore (>50 m)	Offshore (>50 m)	Offshore (>25 m)
Classification	Point absorber	Attenuator	Terminator
Structure	2 body floating system	4 body (snake-like) floating system	Floating platform with an overtopping ramp, two wave reflectors and a reservoir
Size	Diameter 6 m Draught 30 m	Diameter 3.5 m Length 150 m	Width 300 m Length 170 m
Energy mode	Heaving	Heaving and swaying	Overtopping
Power take off	High-head hydraulic turbine (Pelton type)	High-pressure hydraulic motors and electrical generators	Low-head hydraulic turbines (Kaplan type) and electrical generators
Rated power	250 kW	750 kW	7000 kW

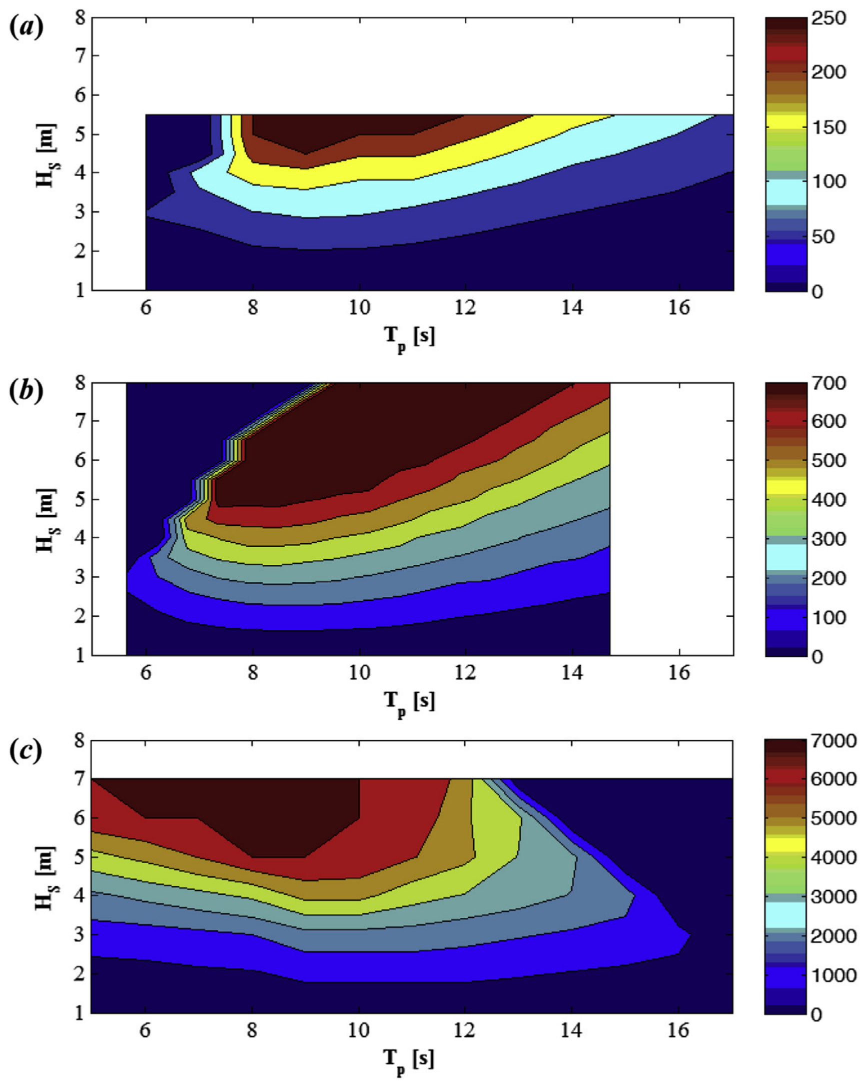

Fig. 4. Power matrices (kW) of (a) AquaBuOY, (b) Pelamis and (c) Wave Dragon devices (data from Dunnett and Wallace [41]). Blank areas stand for non-operating conditions.

was tested in Scotland in 2004 and then in 2008 a set of three devices was deployed off the northern coast of Portugal at a 50 m depth, making it the world's first commercial wave farm. Currently, a second generation Pelamis device (P2) has been developed and is been tested at the European Marine Energy Centre (EMEC). It consists of five sections with a total length of 180 m, 4 m in diameter and a rated power of 750 kW.

The Wave Dragon is a floating, slack-moored energy converter of the overtopping type invented by Erik Friis–Madsen and developed by Wave Dragon Ltd. with funding support from the European Union and different European countries [39]. It basically consists of two wave reflectors focussing the waves towards a ramp. Behind the ramp there is a large reservoir where the overtopping water is collected and temporarily stored. The water leaves the reservoir through a number of Kaplan turbines which convert the hydraulic head into electricity like in hydropower plants. The Wave Dragon is currently the largest device – by rated power and physical dimensions – under development. The first prototype connected to the power grid was deployed off the coast of Denmark at Nissum Bredning in 2003. A larger prototype is currently been developed

Table 2
Characteristics and performance of the full scale devices at Alghero and Mazara del Vallo.

	Alghero			Mazara		
	AquaBuOY	Pelamis	Wave Dragon	AquaBuOY	Pelamis	Wave Dragon
Rated power [kW]	250	750	7000	250	750	7000
Mean power output [kW]	22	71	616	9	32	270
Annual energy output [MWh]	192	619	5400	81	278	2362
Full load hours [h]	766	825	771	323	371	337
Capacity factor [%]	8.7	9.4	8.8	3.7	4.2	3.9
Coefficient of variation of monthly time series [%]	42	43	44	66	62	62
Correlation coefficient between energy input and output [–]	0.97	0.98	0.98	1.00	1.00	1.00

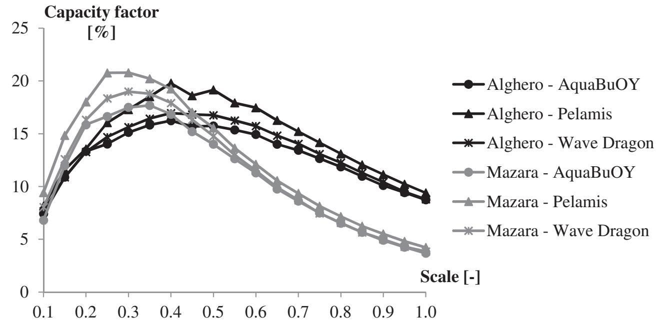

Fig. 5. Capacity factors at Alghero and Mazara del Vallo for different device dimensions.

and it is expected to be deployed offshore Hanstholm at the test center DanWEC, Denmark.

A well-established method to assess the performance of the wave energy converters is based on the so-called power matrices, which are published by the WEC manufacturers as a concise way to present the performance of their products in real sea states. The power matrices are bivariate matrices indicating the power output of a device (in kW) as a function of significant wave height and wave period. The latter can be either peak period — as for AquaBuOY and Wave Dragon — or energy period or power period, which is the period of a single sinusoidal wave with the same power as the sea. The Pelamis performance data, which is published in terms of power period, was converted to a function of peak period for the present analysis. The power matrices of the three devices considered in the study work are shown in Fig. 4.

It can be noticed that all the WECs have a power band at rated capacity for wave heights larger than 5 m and that they do not generate electricity for a number of sea states. AquaBuOY and Pelamis are unresponsive to large waves with short period while Wave Dragon energy production is very small or null in case of long waves. All the devices do not produce electricity for waves shorter than 1 m and cease to work in extreme wave events.

4. Energy production

Electricity production of a wave energy converter is usually calculated by multiplying the expected power output of the sea state bins of the power matrix by their occurrence. The procedure is approximate since it associates the same power output to all sea

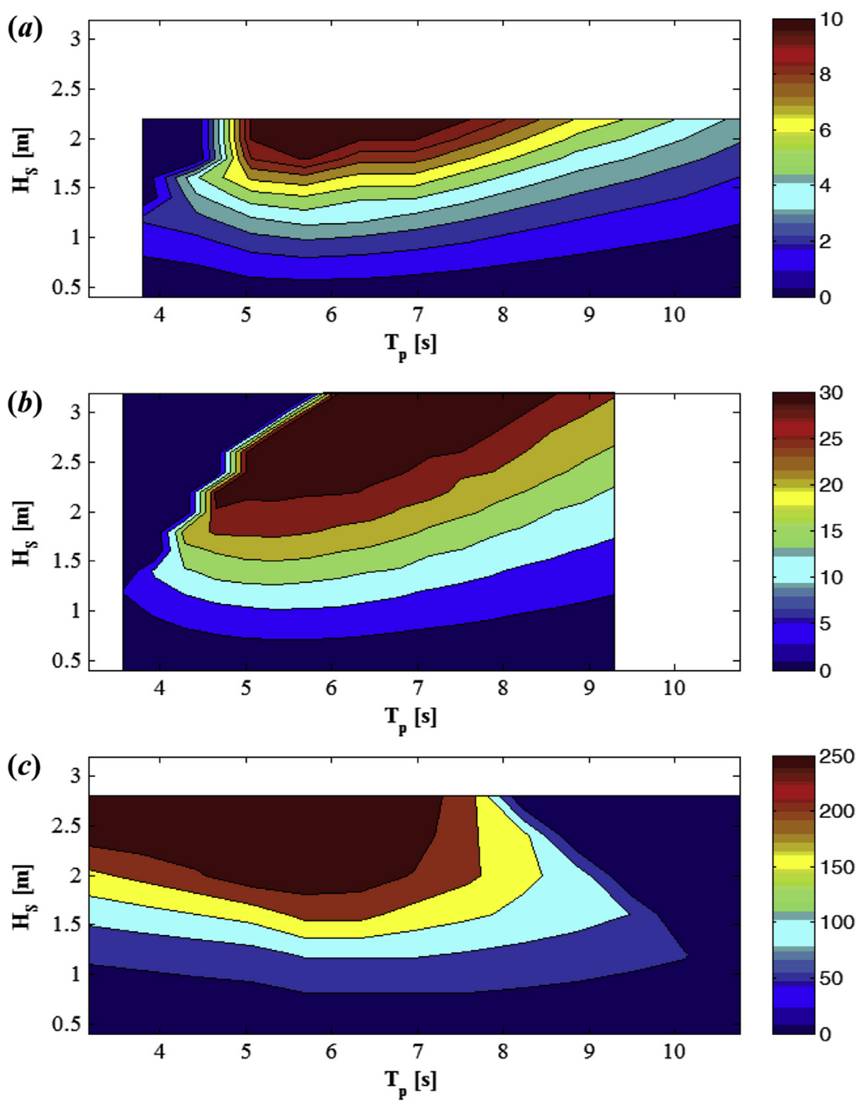

Fig. 6. Power matrices (kW) of the downscaled devices for the Alghero site: (a) AquaBuOY, (b) Pelamis and (c) Wave Dragon.

states of a given bin. To get more accurate estimates of energy production our procedure was not based on wave activity data, but on the original records of the Italian Wave Network, that give the significant wave height and peak period at consecutive time intervals. We calculated the device power output corresponding to each data record interpolating the power matrix in both H_S and T_p with a bilinear interpolation scheme. Then, the energy production of each sea state was estimated by multiplying the power output by the time of occurrence (equal to 3 h or half-hour). Finally, we summarized the energy production of each year and we took the annual average over the whole time series record length. For the calculation, we assumed that the devices have zero power output outside the upper and lower boundaries of the power matrices and that they work without downtimes.

The annual energy output (AEO), i.e. the mean annual energy production, of the AquaBuOY, Pelamis, and Wave Dragon devices at Alghero are respectively equal to 192 MWh, 619 MWh and 5400 MWh while at Mazara del Vallo are somewhat less than one half (Table 2). The energy production of all the hypothetical wave farms shows a strong seasonal variation: the winter months account for about 40% of the annual output while in summer the electricity production represents around one-tenth of the annual energy. The coefficients of variation of the time series of monthly outputs are around 40% for the wave farms at Alghero and around 60% for the devices deployed at Mazara del Vallo. The monthly distributions closely match the ones of the wave energy resource: the correlation coefficient between the time series is about 0.98 at Alghero and almost one at Mazara. This means that the energy output variability is mainly due to the resource availability and not to device performance characteristics.

The performance of the hypothetical wave farms can be evaluated in terms of full load hours or capacity factor. The full load hours are defined as the mean annual production divided by the rated power of the wave energy converter. The capacity factor (or load factor) is the ratio of the average annual power and the rated power, or equivalently the annual energy output divided by the energy production that would be obtained if the device was running at its nominal power during all of the hours of the year. The capacity factors of the three WECs are approximately equal to 9% at Alghero and to 4% at Mazara del Vallo (Table 2). At both locations the Pelamis wave energy converter has the highest capacity factor, about 10% higher than the other devices.

The estimated capacity factors are low compared to the ones obtained for the same wave energy converters in other offshore

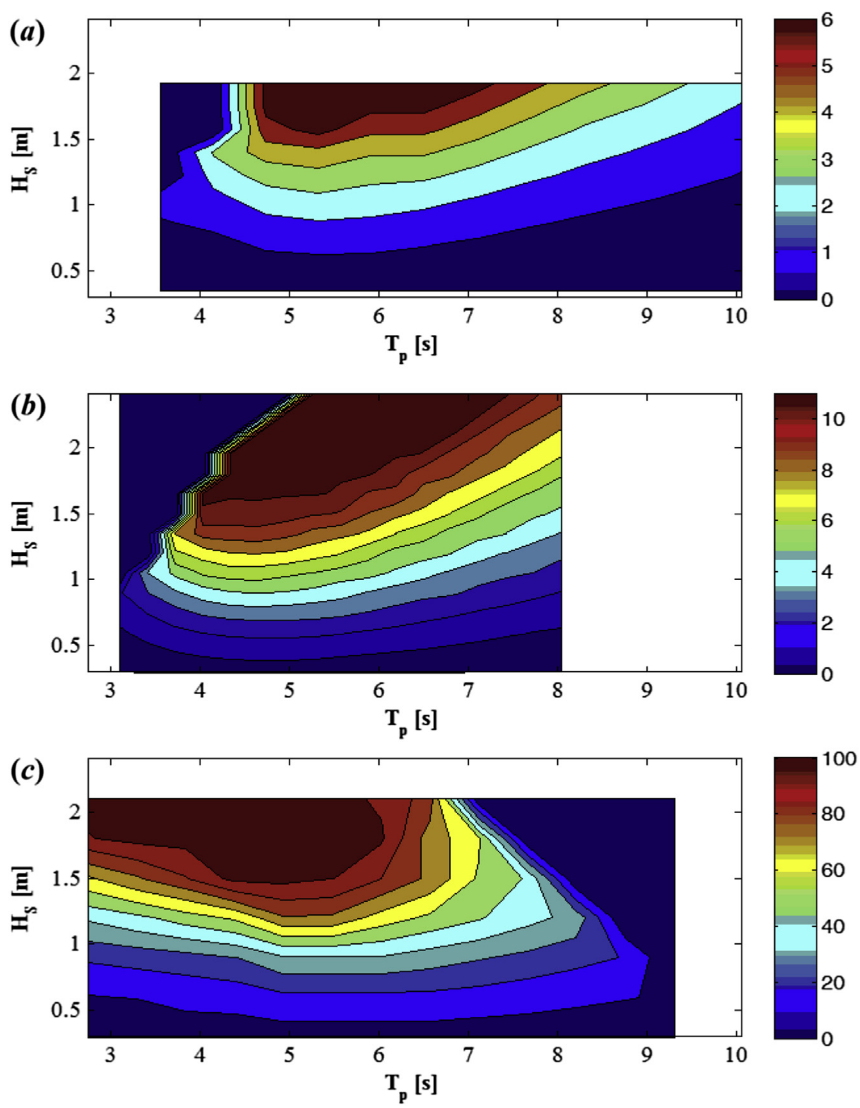

Fig. 7. Power matrices (kW) of the downscaled devices for the Mazara site: (a) AquaBuOY, (b) Pelamis and (c) Wave Dragon. Blank areas stand for non-operating conditions.

locations in Europe and Canada [16,40,41]. The main reason is that the AquaBuOY, Pelamis and Wave Dragon devices are designed for more energetic wave climates than the Italian offshore. They reach the maximum power output for wave conditions typical of oceanic coastlines and randomly found in Italian seas and they work very far to their optimal rating for most of the sea states of the studied locations. As an example, the same devices would have capacity factors between 10% and 15% if they were installed in the Portuguese continental nearshore, where the average annual wave power ranges between 18 kW/m and 27 kW/m [40]. An even better performance would be achieved by deploying the three WECs in the Madeira Archipelago, which is characterized by a substantial wave energy resource, above 50 kW/m [16]. In the most promising site of the Madeira Islands the capacity factors would be equal to 20%, 18% and 23% for the hypothetical wave farms of AquaBuOY, Pelamis and Wave Dragon, respectively.

A better insight on the device performances can be achieved by looking at the capacity factor distributions which show the percentage of time in a year each WEC operates at the different capacity factors (Fig. 8). It stands out that more than 75% of the year the devices operate at a rating that is about one order of magnitude of their optimal rating. In fact, they spend idle the main part of the year (around 60% at Alghero and 70% at Mazara del Vallo)

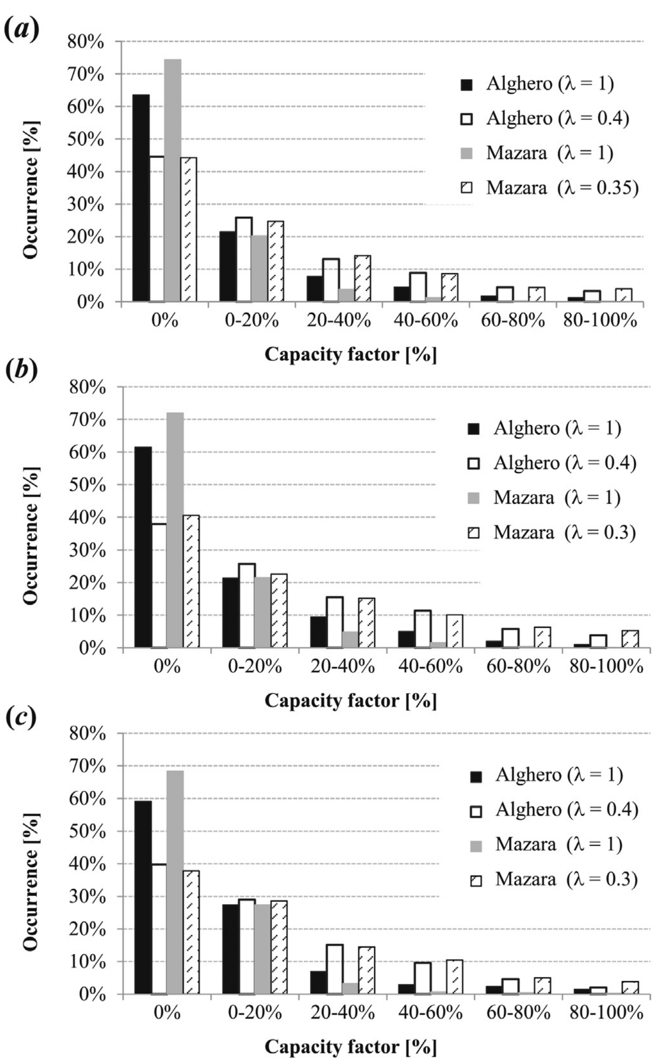

Fig. 8. Capacity factor distributions at Alghero and Mazara del Vallo for (a) AquaBuOY, (b) Pelamis and (c) Wave Dragon devices.

and they work at about 20% of their nominal power for another 20% of the year. This poor performance can be easily explained by comparing the wave climate data of the studied locations with the device power matrices (Fig. 4). All the devices have zero power output for sea states with significant wave heights below 1 m which have a probability of occurrence of 60% at Alghero and 70% at Mazara del Vallo. Moreover, the three studied WECs have an average power output below 10% of the nominal power for wave events with $H_S < 2$ m which have a very high probability of occurrence at the study sites (82% at Alghero and 93% at Mazara del Vallo).

These results indicate that, as expected, the WECs considered in the analysis are oversized with respect to local wave climate and that a more efficient energy conversion could be possibly obtained by downscaling the devices. As suggested by Dalton et al. [42] for the Canada West Coast and the USA East Coast smaller, also in the Italian seas wave energy converters with lower nominal power (corresponding to the typical wave height and period of the location) would be more suitable and promising.

To explore the performance of smaller rated devices at Alghero and Mazara del Vallo, we calculated the AEO and the corresponding capacity factor of AquaBuOY, Pelamis and Wave Dragon of different dimensions. For each downscaled device we estimated the associated power matrix according to Froude similarity as typically done in physical modelling of the WECs [see e.g. Ref. [43]]. Froude scaling law implies that given the geometric scale λ, the time scale is $\lambda^{0.5}$ and the power scale is $\lambda^{3.5}$. Fig. 5 shows the capacity factors as a function of scale for the hypothetical wave farms of AquaBuOY, Pelamis and Wave Dragon at Alghero and Mazara del Vallo.

It is evident that by reducing the WEC size the capacity factor can substantially increase reaching the double or quadruple of that one of the corresponding full scale WEC, depending on the study site. It can also be noticed that for a given scale the highest capacity factor is always provided by the Pelamis device and the lowest by the AquaBuOY device, as already observed for the full scale WECs. The geometric scales of the devices maximizing the capacity factors at the study sites range between 0.3 and 0.4 and the corresponding capacity factors range between 16% and 21%. In particular, at Alghero the optimal device scale is equal to 0.4 for all the considered WECs while at Mazara del Vallo the best scale is 0.35 for AquaBuOY and 0.3 for Pelamis and Wave Dragon. The main characteristics and performance indices of these smaller rated devices are summarized in Table 3 while their power matrices are reported in Figs. 6 and 7, for Alghero and Mazara del Vallo respectively.

Table 3 shows that the smaller WECs would have a rated power which is one or two orders of magnitude lower than the one of the corresponding full scale device. For example the rated power of AquaBuOY would be 10 kW at Alghero and 6 kW at Mazara del Vallo instead of 250 kW and the nominal power of Pelamis would drop from 750 kW to 30 kW and to 20 kW, at Alghero and Mazara del Vallo respectively. Coherently, the reduced AquaBuOY, Pelamis, and Wave Dragon devices would have an annual energy production of 14 MWh, 53 MWh and 421 MWh at Alghero and equal to 10 MWh, 20 MWh and 175 MWh at Mazara del Vallo. On the other hand, by a site-specific downscaling of the devices their capacity factors become of the same order of magnitude of those calculated for hypothetical wave farms in Europe and Canada [16,40,41], showing that the most energetic Italian locations can be exploited for wave energy production, as well.

Moreover, it is important to notice that after the downscaling the coefficients of variation of the monthly time series decrease to about 20%, i.e. approximately half than in the original WECs. This means that the smaller rated devices have a more constant energy production throughout the year and work closer to their nominal power even in the less energetic summer months.

Table 3
Characteristics and performance of the downscaled devices at Alghero and Mazara del Vallo.

	Alghero			Mazara		
	AquaBuOY	Pelamis	Wave Dragon	AquaBuOY	Pelamis	Wave Dragon
Scale	0.4	0.4	0.4	0.35	0.3	0.3
Rated power [kW]	10	30	283	6	11	104
Mean power output [kW]	1.6	6.0	48.1	1.1	2.3	19.9
Annual energy output [MWh]	14	53	421	10	20	175
Full load hours [h]	1423	1735	1486	1551	1837	1686
Capacity factor [%]	16	20	17	18	21	19
Coefficient of variation of monthly time series [%]	21	2	22	28	25	23
Correlation coefficient between energy input and output [−]	0.81	0.87	0.86	0.87	0.86	0.80

The capacity factor distributions (Fig. 8) show that the percentage of time that the smaller rated devices stand idle is significantly lower than in the full scale WECs, about 40% in both the study sites. The devices can now capture the energy of the small waves ($H_S < 2$ m) which would otherwise be lost with the original WECs. This is the result of the scaling of the power matrices which shifts the power band at rated capacity from wave heights above 4 m to wave heights above 1.5 or 2 m depending on the wave farm.

5. Discussion and conclusions

Wave energy exploitation has significantly advanced in Europe over the last two decades and a number of wave energy converters are now at the end of their development stage while others are currently being deployed in real sea conditions. The wave energy potential along the Italian coasts is lower than in the Atlantic locations, but some sites in the Tyrrhenian Sea show an interesting energy potential: a number of offshore islands and specific locations around Sicily and Sardinia have an average annual wave power of the order of 10 kW/m. Moreover, the mild and steady wave climate of the Mediterranean could allow a significant reduction of the installation and operational costs of the wave energy converters.

However, the lower wave energy off the Italian coasts implies that deploying WECs designed for more energetic wave climates would not be cost effective. In this work we show that wave farms of AquaBuOY, Pelamis or Wave Dragon devices located at two of the most promising Italian sites (Alghero and Mazara del Vallo) would have relative low capacity factors. However, the same WECs would have a much better performance if they could be downscaled according to the wave climate conditions of the study sites. For example, at Alghero the deployment of 1:2.5 AquaBuOY, Pelamis or Wave Dragon devices would result in capacity factors around 20% and in a quite constant energy production throughout the year. Our results indicate that deploying classic wave energy converters in the Italian sea sites would not be cost effective but that if the devices could accommodate a proper downscaling, their performance in energy conversion could become attractive also for Italian seas.

Finally, the results of the present work suggest that an even better performance in wave energy conversion could be possibly attained if site-specific WECs could be designed for the Italian seas. In particular, it seems particularly attractive the installation of arrays of point absorbers specifically designed for small sea states, as recently shown by Bozzi et al. [44].

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