Wave power technologies for the Mediterranean offshore: Scaling and performance analysis

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The work investigates the potential of the Mediterranean offshore for wave electricity production, providing basin-scale results useful for future smaller-scale studies on specific areas of interest. At this purpose, the per-formance of a selection of offshore wave energy converters (WECs) is assessed all along the Mediterranean coastline (at 10 km resolution), on the basis of a 37-year hindcasted wave data and public WEC performance data. As the analyzed technologies were designed for more energetic wave climates, smaller devices have been considered, downscaled according to the Froude similarity criterion, in order to match Mediterranean wave conditions. At each location, the best device size is determined by simulating different scaled versions of the WECs and then selecting the scaling factor, which maximizes the mean annual capacity factor.

The results show that large part of the Mediterranean coastline can be successfully exploited by properly downscaled versions of the WECs. More specifically, six of the studied wave power technologies can reach a capacity factor higher than 0.2 along 40% of the coastline and three WECs (AquaBuOY, Pelamis and Wavebob) can operate with a capacity factor exceeding 0.3 at 8% of the studied locations. The coastal regions with the highest WEC performance are of the Gulf of Lion, the Sicily channel, the Alboran Sea, the Libyan coast, Crete and Cyprus. The optimal size of the WECs at these locations is between 1/4 and 1/3 of the full WEC size and the resulting rated powers are between 10 and 30 kW. Noteworthy, a quite low performance is found for the most energetic areas of the Mediterranean (for example in western Sardinia), because a large part of the available energy is provided by extreme and rare events, for which the WEC efficiency is very low.

Keywords:
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1. Introduction

In the last decades, growing energy demand, increasing evidence of climate change and supply security concerns have urged governments to foster the development of the renewable energy sector. In this context, electricity production from ocean waves has attracted increasingly interest, thanks to the huge wave energy potential at the global scale. Wave power technologies are not yet commercially viable since reliability and affordability of the devices are still unresolved issues. However, strong support policies have been implemented, especially in Europe, to foster the technology development, to reduce the associated risk for investors and to overcome environmental and administrative barriers (Magagna and Uihlein, 2015a).

The wave energy sector currently shows many competing technologies to harness energy from ocean waves. Indeed, the lack of consensus among the different technical solutions has been highlighted as one of the main barriers hampering sector's development (Magagna and Uihlein, 2015b). According to the classification of the European Marine Energy Center (EMEC), existing wave energy converters can be grouped into six categories, on the basis of their operating principle. However, four device classes account for more than 80% of research efforts: point absorbers, oscillating wave surge converters, oscillating water column (OWC) and attenuators (Magagna et al., 2016). Point absorbers are floating or submerged structures, which absorb energy from all directions through a small floater, much smaller than the typical wavelength of the incident waves. Oscillating wave surge converters consist of pitching flaps anchored to the sea bottom, oscillating about a hinge aligned orthogonally to wave direction. As the energy is harnessed only by the horizontal water motion, these devices are conceived for intermediate and shallow water depth. Oscillating water columns are partially sub-merged hollow structures (floating, bottom-standing or shore-mounted) with a chamber open to the sea, enclosing a column of water and a

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trapped air pocket above it. The wave induced oscillation of water inside the chamber pushes the air back and forth through a bidirectional turbine, which generates electricity. Attenuators are floating structures oriented along the wave direction, having a horizontal extension comparable to the wavelength. Oscillating water columns and point absorbers are considered to be the most advanced device classes, in terms of technology readiness level (Magagna et al., 2016).

Over the last years, the wave energy resource has been extensively characterized at many worldwide coastal areas. Wave resource assessments typically provide information on resource availability, average and extreme wave conditions, intra-annual variability and energy distribu-tion among sea states. These are essential information, but they need to be integrated with device characteristics to proper design wave energy projects. Looking only to wave climate data does not provide the full picture and may lead to erroneous or misleading results. For example, locations with high energy potential may be less productive than others with lower energy content, if the bulk of the energy is provided during sea states for which device efficiency is low (Veigas et al., 2014; Rusu, 2014). Each WEC has different efficiencies in the different ranges of wave height and periods and also different operational ranges. For this reason, in the last years feasibility studies have been conducted for various lo-cations worldwide, aimed at selecting the best device for a specific site or, conversely, to find the most appropriate location for a given WEC.

Recently, an increasing attention is being paid to wave energy conversion in sheltered waters and enclosed basins, such as the Baltic Sea, the Black Sea and the Mediterranean Sea. This is due to the fact that high-energy sea-environments are typically characterized by extreme events, which cannot be profitably harnessed and can compromise device survivability (Magagna and Uihlein, 2015b). Moreover, energetic wave climates imply higher costs of construction, installation, operation and maintenance, which could possibly not be balanced by the larger productivity of wave power plants (Arena et al., 2015). On the other hand, small-scale technologies, tailored for sheltered waters and moderate sea states, may offer a wide range of potentials benefits, such as increased survivability, reduced maintenance costs and lower financial risks (Magagna and Uihlein, 2015b). Moreover, it is currently believed that the development of small-scale WECs in sheltered seas could speed up the learning curve of the sector, thus reducing the risks in the demonstration phase of wave power technologies (Magagna and Uihlein, 2015b).

In this context, the feasibility of wave energy exploitation in the Mediterranean Sea has recently been explored in a number of studies. Rusu and Onea (2015) evaluated the performance of ten WECs at three possible deployment sites in the Mediterranean Sea and showed that the Pontoon Power Converter is the most promising solution with capacity factors between 6% and 15%. Lavidas and Venugopal (2017) compared the performance of six wave energy converters at different locations in the Greek Seas. They showed that the areas with the highest capacity factors are the southern Aegean Sea and the Crete Island and that the best device is the Wavestar, thanks to its ability to operate at nominal power for low wave heights and periods. A further study on Greek Seas has been carried out by O'Connor et al. (O'Connor et al., 2013), who estimated the energy output and economic performance of Pelamis and Wavestar, in a location off the Greek Ionian coast. In order to better match local wave conditions, the work considered three different ratings of the devices, obtained upscaling or downscaling the original power matrices, according to Froude similitude. The results indicated that the most suitable solution for the Greek site is a wave farm of small rated Pelamis units. Sierra et al. (2014) evaluated the performance of Pelamis, AquaBuOY and Wave Dragon at 12 points along the coast of Menorca, obtaining capacity factors around 10%, 9% and 11%, respectively. The same technologies were considered by Aoun et al. (2013) to explore the potential of wave electricity generation off the Lebanon coasts. For this coastal region, the study reported much lower values of capacity factor, equal to 4%, 5% and 5% for Wave Dragon, Aqua Buoy and Pelamis, respectively.

In the last years, a number of studies have investigated the feasibility of wave energy exploitation off the Italian coasts. Bozzi et al. (2014) evaluated the energy production and the performance characteristics of AquaBuOY, Pelamis and Wave Dragon at two of the most energetic Italian locations. The study showed that the WECs would have relatively low capacity factors (between 4% and 9%), but that a much better performance can be achieved if they are downscaled according to local wave climate conditions. A similar approach was followed by Iuppa et al. (2015) with regards to Sicily. The study indicated that resizing the existing technologies would lead to capacity factors higher than 30% at some sites along the western coast. More recently, Vannucchi and Cappietti (2016) demonstrated that the most suitable offshore devices, in terms of capacity factor, are Wave Dragon for Tuscany and Liguria coasts and Pelamis for Sardinia and Sicily. Finally, Zanuttigh et al. (2015, 2016) investigated the potential of multi-purpose offshore installations for combined wind-wave energy generation and aquaculture in two Italian sites located in the Northern Adriatic Sea and in the Sardinia Island.

Overall, the studies on the Mediterranean Sea are few, cover a small portion of the whole coastline and often consider a limited number of wave power technologies. A comprehensive overview of the potential of Mediterranean waters from the perspective of wave electricity production is still lacking. Given this background, this work investigates the potential for future wave energy exploitation in the Mediterranean Sea by evaluating the performance of a selection of offshore wave energy converters along the coastline, on the basis of a 37-year wave hindcast data (Mentaschi et al., 2013a, 2015). As the selected technologies have been designed for more energetic wave climates, the analysis considers smaller devices, downscaled to match local wave conditions, as in previous works on mild climates (e.g. (O'Connor et al., 2013; Fernández--Chozas et al., 2013; Sinden, 2005)). After optimizing device scale, the best deployment sites are identified for each technology and, conversely, the optimal devices for the most promising coastal areas are determined, allowing for a combined WEC-site selection at the scale of the whole Mediterranean. The final aim of the work is to provide advice for future wave energy projects in the Mediterranean Sea.

The paper is organized as follows: section 2 presents the materials and methods used in the work. Here, details on wave data and WEC characteristics are provided, together with a description of the methodology for device scaling and energy production estimation. The next section presents the results of the research. It is subdivided into a global scale subsection, presenting the results at the whole Mediterranean scale and a local scale subsection focusing on specific coastal regions, which emerged as promising sites for future WEC installations. Finally, in the last section some conclusions are drawn.

2. Materials and methods

The performance assessment of a wave energy converter at a particular coastal location is based on wave climate information and WEC performance data. These data are described in the following two subsections while details on the procedures for device scaling and energy production estimation are provided in subsections 2.3 and 2.4, respectively.

2.1. Wave data

Wave data employed in the present study belong to a 37 years (1979–2015) hindcast of the whole Mediterranean Sea implemented with a spatial resolution of 0.1° in both longitude and latitude and a sampling time step of 1 h for integrated quantities (significant wave height, peak period, energy period, mean direction, peak direction and first three spectral partitions). WRF-ARW v3.3.1 (Skamarock et al., 2008) and WaveWatchIII v3.14 (Tolman, 2009) have been employed to model atmospheric forcing and wave generation and propagation, respectively. The reader concerned with models' implementation, validation, reliability and performances can refer to (Bove et al., 2014; Cassola et al., 2015) for the atmospheric fields and to (Mentaschi et al., 2013a, 2015, 2013b) for the wave simulations. Hindcast data have been previously employed successfully for extreme and climatic analysis (Sartini et al., 2015a, 2015b, 2016; Besio et al., 2017) and for wave energy assessment in the Mediterranean Sea (Besio et al., 2006). For the present study we employed those hindcast point falling in a buffer area of 10 km width from the coastline in order to investigate areas that would be feasible for wave energy exploitation (mainly concerning the costs for the grid connection).

2.2. Wave energy converters

Eight wave energy technologies were considered in this work: AquaBuOY, AWS, Langlee, OE buoy, Pelamis, Pontoon, SeaPower and Wavebob. Device selection was based on the following criteria: (1) the WEC are designed to operate in deep waters, (2) the technologies have reached an advanced, even if not commercial, development stage with testing in real sea conditions, (3) the performance data have been made publicly available and (4) the devices are characterized by different working principles. Even if some of the WECs are no more under development, they have anyway been considered in the analysis. The reasons are twofold. On one hand a study limited to the existing technologies would have reduced too much the number WECs and hence the extent of the work (unfortunately, no power performance data are available for recently developed technologies). On the other hand, the most critical issues for the dismissed technologies were WEC survivability (e.g. AquaBuOY, Pelamis) and financial difficulties (e.g. Wavebob), all but their performance. As a consequence, it is worthwhile to investigate if downscaled versions of these devices perform efficiently in mild wave climates, where smaller wave loads and lower deployment costs reduce the risks of both mechanical and financial failure.

According to the EMEC classification, the WECs considered in the analysis comprise three point absorbers, one multiple point absorber, two attenuators, one oscillating water column and one oscillating wave surge converter. The rated power (i.e. the peak power output) ranges between 250 kW and 3.6 MW and the power take off systems (PTOs) include linear generators, hydraulic motors and turbines. More details on the wave energy converters are provided in Table 1. The appendix reports WEC performance data (retrieved from the reference sources indicated in Table 1) in terms of the so-called power matrix, which is a bivariate matrix providing the device power output as a function of significant wave height and wave period. WEC performance characteristics are compared in Fig. 1, which reports for each device the percentage of power bins having normalized power output (with respect to peak power) higher than different thresholds.

The AquaBuOY is a point absorber consisting in a floating buoy mounted above a piston contained inside a tube, opened 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. Its rated power is 250 kW and the power matrix has a wide power band at rated capacity and about 15% of the opera-tional range shows a power production higher than 0.8 of the maximum power (Fig. 1).

The Archimedes Wave Swing (AWS) is a heaving point absorber. It consists of a fully submerged air filled chamber, with a lid, which can move vertically with respect to a basement, fixed to the sea bed. As a wave passes over the device, the changes in water pressure induce the movement of the lid, which is linked to a linear generator that converts the motion into electrical energy. The maximum power is 2470 kW. However, unlike the other devices, this WEC has no effective rated power level, but the power output continues to rise along with both wave height and period.

The Langlee is an oscillating wave surge converter, which consists of four hinged flaps connected to a common frame. Excited by waves, flaps move back and forth and their motion, relative to the supporting structure, is converted into electricity by a hydraulic PTO system. The rated power is about 1660 kW. The performance of the device is strongly dependent on wave period with a well-pronounced peak in power output for $T_P = 7$ s and rapidly decreasing performance for longer waves. As a result, for most of the sea states the performance is very low: about 80% of the operational range has a normalized power output lower than 0.2 (Fig. 1).

The OE Buoy is a floating oscillating water column device. It has a semi-submerged chamber open below the sea surface, keeping a trapped air pocket above a water column. The column is forced to oscillate by the incident waves forcing the air through a bidirectional turbine converts the airflow into electricity. The rated power is 2880 kW. The power output steadily increases with wave height with a maximum at $H_S = 7$ m. With respect to wave period, the power production peaks at $T_P = 11$ s and decreases away from the peak, more steeply for lower than for higher wave periods. Only 3% of the operational range shows a power production higher than 0.8 of the maximum power.

The Pelamis is an attenuator device which consists of a series of semi-submerged 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 motors driving electrical generators. The Pelamis has a rated power of 750 kW. Compared to the other devices, it has the highest power band at rated capacity (16%) and about 30% of the operational range at normalized power higher than 0.8 (Fig. 1).

The Pontoon Power Converter is a multiple point absorber WEC, which is composed of many heaving buoys connected to a common submerged structure via a hydraulic PTO system. The power matrix used in this analysis (Babarit et al., 2012), consider 10 heaving buoys yielding a maximum power output of about 3600 kW. The device is quite unresponsive to both short and long waves so that the power matrix has only 12% of the bins with normalized power output higher than 0.4.

The SeaPower is a wave attenuator composed of two large concrete pontoons oscillating about a hinge. Depending on the PTO system, the relative motion of the pontoons can be converted into electricity or used to pump pressurized seawater to shore by a subsea pipeline. The maximum power output is about 3600 kW. The power performance shows a strong dependence on wave height and a normalized power output below 0.4 for many sea states (about 80% of the operational range).

The Wavebob is an axisymmetric self-reacting point absorber consisting of a torus sliding along a vertical float linked to a submerged tank, which acts as a high-inertia body. The power is generated by the relative motions between the two bodies by a hydraulic PTO system and the rated value is 1000 kW. Power production depends on both wave period and height but is not monotonic with respect to period. The power output peaks at intermediate values of the period and declines at lower and higher values. The power matrix has a wide power band at rated capacity with about 13% of the operational range producing more than 80% of the rated power.

2.3. Device scaling

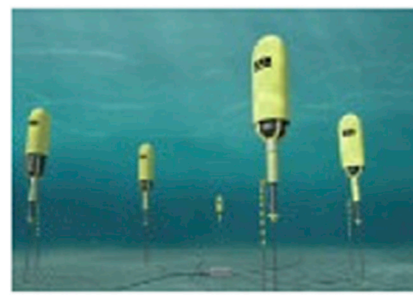
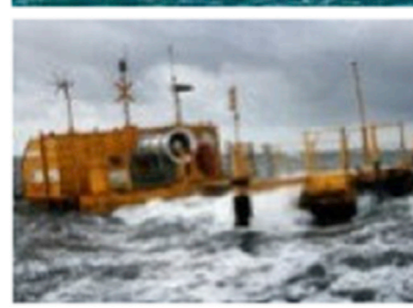
The WEC considered in this study have all been designed and optimized for moderate to high energy sea states. They are oversized with respect to milder wave climates (as that one of the Mediterranean Sea), where they cannot perform satisfactorily and cannot be economically viable. To work in less energetic climates, the WECs should be scaled down to match local wave conditions. A proper size reduction allows capturing the energy of the small waves, which typically prevails in mild environments. This allows to maximize the power production of the devices by matching the most frequent sea states with the power bins at rated capacity.

In this work, different WEC scales were considered, from 0.1 to full scale with steps of 0.05, in order to capture the optimal scale for each studied location of the Mediterranean basin. To estimate the electrical output of the devices after size reduction, Froude similitude was used, as currently done in physical modelling of WECs and in similar previous works (e.g. (O'Connor et al., 2013; Bozzi et al., 2014; Zanuttigh et al., 2016; Fernández-Chozas et al., 2013)). According to Froude scaling law, wave heights scale linearly with the geometric scale λ, wave periods with the square root of λ and power scales as $\lambda^{3.5}$.

2.4. *Energy production*

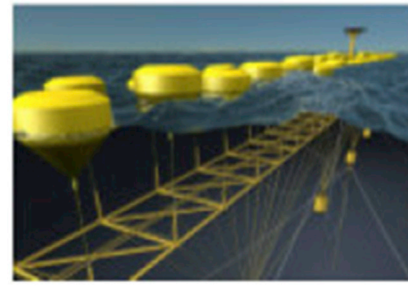
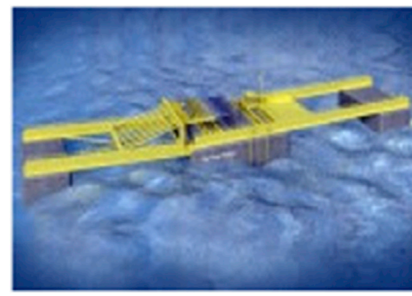
The energy production of a wave energy converter at a site is the result of the combination of the power matrix of the device with the wave climate data of the location. It is typically estimated by multiplying the

Table 1
Main features of the studied wave energy converters.

Name	Structure	Classification	Energy mode	PTO	Rated power [kW]	Ref.	Picture
AquaBuOY	Two-body floating system	Point absorber	Heave	High-head water turbine	250	Dunnett and Wallace, 2009	
AWS	Two-body submerged system	Point absorber	Heave	Linear generator	2470	Sinden, 2005	
Langlee	Semi-submerged three-body structure	Oscillating wave surge converter	Surge	Hydraulic motor	1665	Babarit et al., 2012	
OEbuoy	Single-body floating system	Oscillating water column	Surge	Bidirectional air turbine	2880	Babarit et al., 2012	
Pelamis	Four-body floating system	Attenuator	Heave and sway	Hydraulic motor	750	Dunnett and Wallace, 2009	

(*continued on next page*)

Table 1 (*continued*)

Name	Structure	Classification	Energy mode	PTO	Rated power [kW]	Ref.	Picture
Pontoon	Multibody floating structure	Multiple point absorber	Heave	High-head water turbine	3619	Babarit et al., 2012	
SeaPower	Two-body platform	Attenuator	Pitch	Pump or hydraulic motor	3587	Sea Power Ltd, 2017	
Wavebob	Two-body floating system	Point absorber	Heave	Hydraulic motor	1000	Babarit et al., 2012	

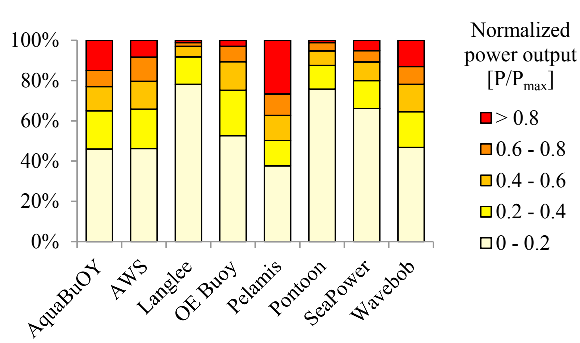


Fig. 1. Percentage of power bins having normalized power output higher than different thresholds (normalized with respect to rated power).

expected power output of each bin of the power matrix by the expected number of hours/year of occurrence of that bin. At this aim, the wave climate data has to be represented by a resource characterization matrix having the same resolution (i.e. bin size) of the WEC power matrix and indicating the occurrence of the different sea states. This procedure associates the same power output to all the sea states falling into each bin, so it can introduce large errors when bin resolution is too low. Previous works (Dunnett and Wallace, 2009; Reikard, 2013) showed that the typical size of the energy bins of the power matrices is insufficient for an accurate estimate of annual electricity production and that linear interpolation should be used to increase power matrix's resolution. In this work, the availability of hourly series of wave height and period, instead of aggregated information, as the location characterization matrix, allowed to use a more accurate method. At each location, the device power output corresponding to each record was estimated interpolating the power matrix in both H_S and T_P with a bilinear interpolation scheme. Then, the annual energy production was calculated by summing the records of each year and, finally, the annual average output (AEO) was estimated by taking the mean over the 37 years of the dataset. For the calculation, it was assumed that the devices have zero power output outside the upper and lower boundaries of the power matrices. This is a conservative assumption, since downscaled devices are expected to have higher survivability limits due to the use of the same structural materials (Chakrabarti, 2005).

The analysis was performed for 1647 points, discretizing the Mediterranean coastline and at each point the power production was estimated for all the different versions of scaled devices, for a total of 152 computations at each location (i.e. 8 technologies and 19 scales per technology). All the estimates of mean annual power production were normalized with respect to rated power in order to get the mean annual capacity factor (CF), which represents one of the most important performance indices for renewable energy technologies. It indicates the annual energy delivered by the device compared to the maximum possible if it had been working at the rated power for the whole year or, equivalently, the percentage of the time in a year during which the device is running at its maximum power. Then, for each location it was determined the best scaling factor of each technology, i.e. the size reduction which would allow for the maximum capacity factor. Finally, as Mediterranean wave climate shows high seasonal variations, the coefficient of variation of monthly power production (CV) was computed in order to assess intra-annual variability of electricity generation. This parameter represents the ratio of the standard deviation of monthly power production to the monthly mean.

3. Results and discussion

The results, in terms of different performance parameters, are presented in the following two subsections. The first one extends over the whole Mediterranean coastline while the second one focuses on the most promising locations and WEC-site combinations.

3.1. Mediterranean scale

Fig. 2 shows the scaling factors which maximize the capacity factors at each location along the Mediterranean coastline. As expected, for all the devices the optimal scale shows a large spatial variability, being a function of local wave climate. More specifically, the best WEC size depends on the available wave energy resource, being higher at more energetic sites and lower in calmer regions. This is because the maximum capacity factor is achieved where the prevalent sea states coincide to those with the highest WEC performance. Hence, the lower the wave energy potential at a location, the higher the scale reduction required to

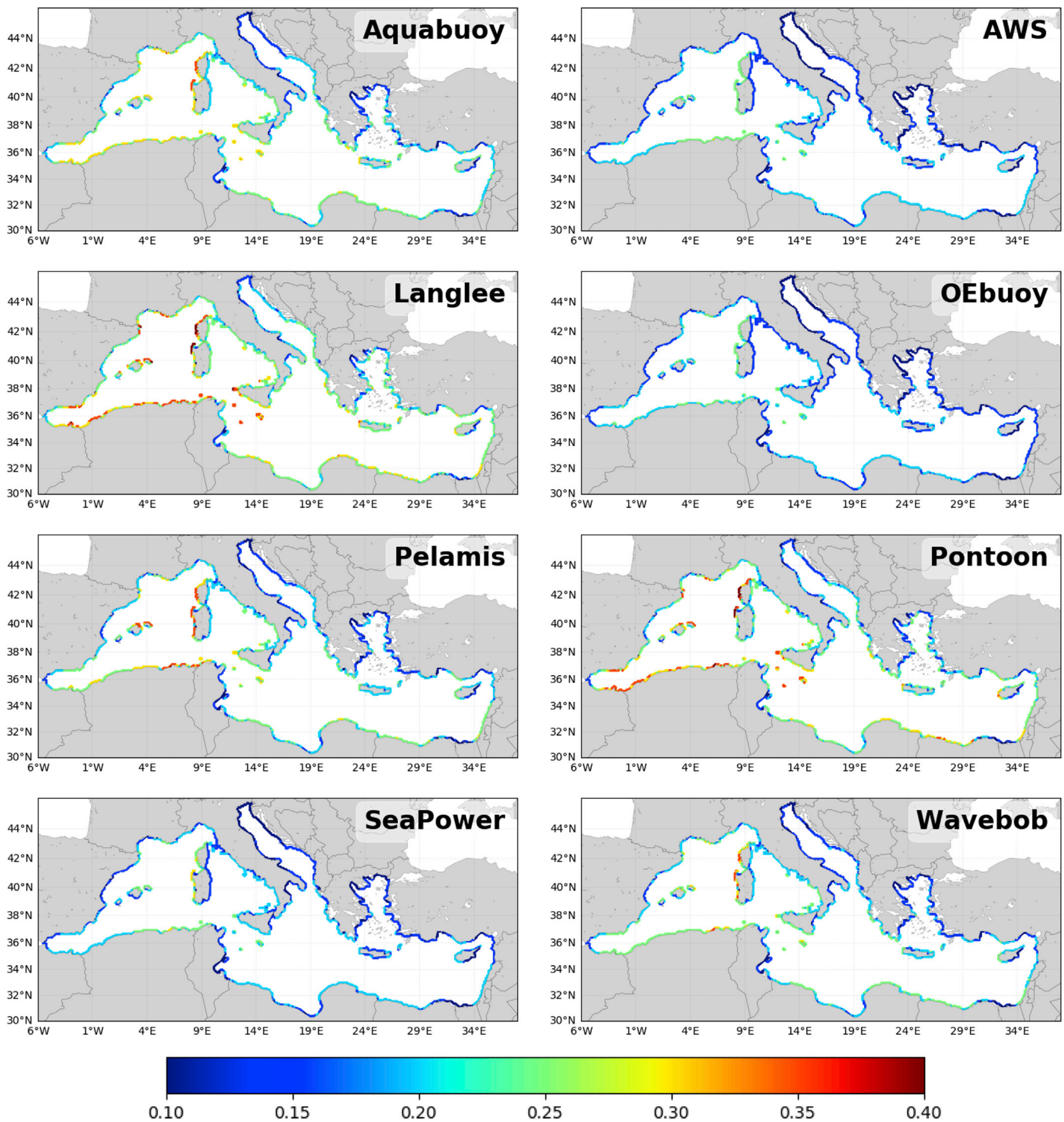


Fig. 2. Optimal scale of the devices.

shift the peak of the power output to the peak of the occurrences distribution. As a result the same spatial pattern is observed for all the WECs, even if the optimal scale at each location varies depending on the technology considered. The highest values of the optimal WEC scaling are located in the most productive area of the entire Mediterranean – average wave energy potential between 9 and 12 kW/m – between the Balearic Islands, the western coast of Sardinia and Corsica and northern coast of Algeria. Slightly lower values are found in the Strait of Sicily, which is characterized by an average wave energy flux per unit crest between 6 and 9 kW/m. Intermediate values are found in areas with moderate wave energy potential, around 5–7 kW/m, such as the Alboran Sea, the Tyrrhenian Sea, the western part of the Levantine basin and the southern Ionian Sea (Besio et al., 2006). Finally, the least energetic areas of the Mediterranean Sea, i.e. the Adriatic and Aegean Sea, with annual wave potential about 3 kW/m, are associated to the lowest values of the optimal device size.

On the other hand, it is evident that the scale required to maximize the capacity factor at a given location depends on the technology. At the most energetic sites, the optimal size of Langlee, Pelamis and Pontoon should be between 0.4 and 0.45 of the original size, AquaBuOY, AWS,

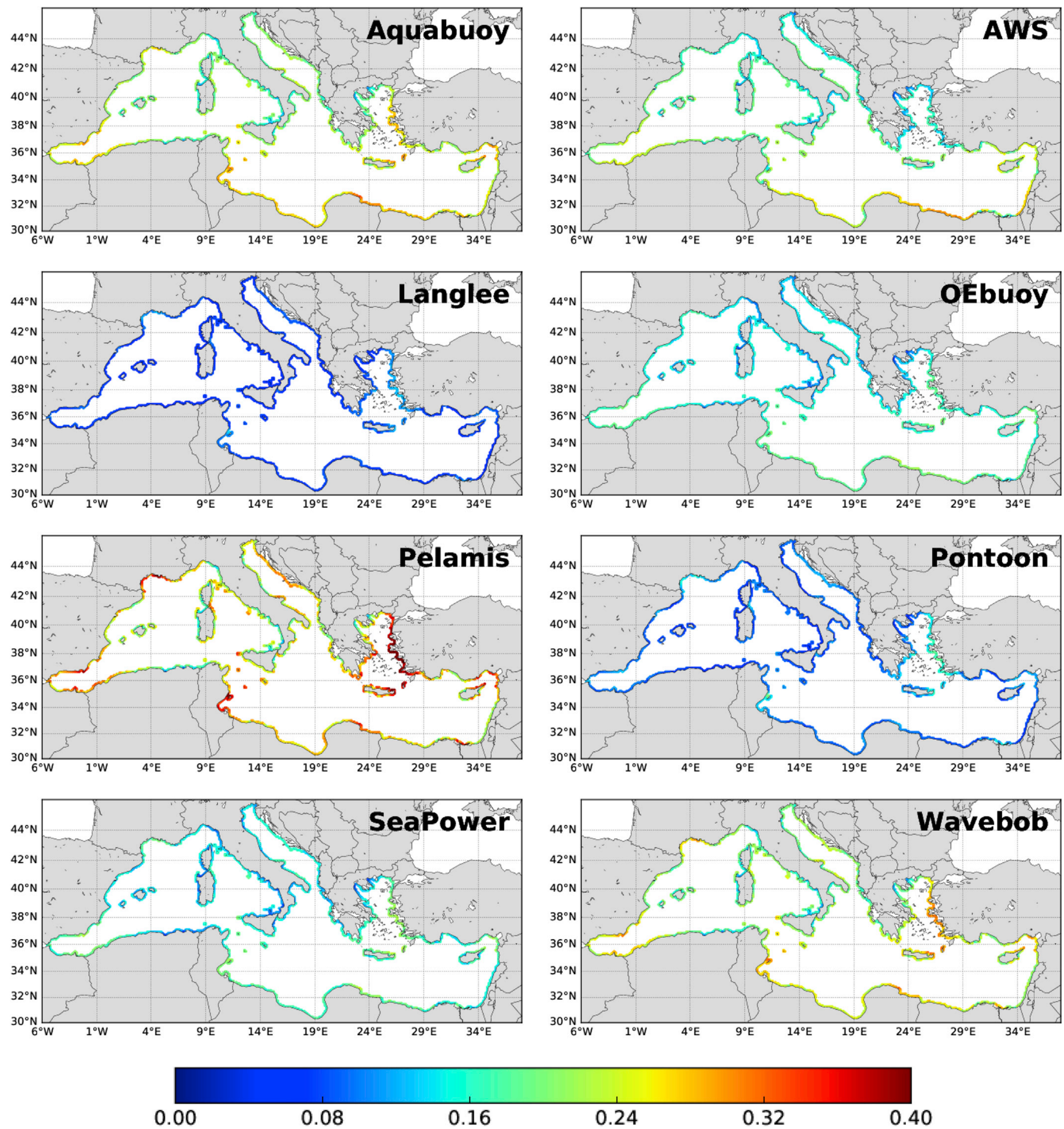


Fig. 3. Capacity factor of the downscaled devices.

SeaPower and Wavebob should be scaled down to about one third of the original dimensions and the OE buoy should be resized with a scaling factor of 0.25. The same relative differences can be found in the other locations: Pontoon and Langlee are always the WECs requiring the smallest scale reduction followed by Pelamis, AquaBuOY, Wavebob, SeaPower, AWS and OE buoy.

It is interesting to notice that the optimal WEC scale does not depend on the rated power of the original WEC design. This means that at a given location there is no optimal installed capacity, but rather it depends on the technology under consideration. At the sites with the highest energy levels, for example, the best rated power of the devices resulted to be equal to 6 kW for AquaBuOY, about 24 kW for Wavebob and OE buoy, about 33 kW for AWS and Pelamis and equal to 53, 102 and 221 kW for SeaPower, Langlee and Pontoon, respectively. This is due to the different performance characteristics of the WECs: some technologies have a large power band at rated capacity while others achieve their maximum power output only for a specific combination of wave height and period. In the latter case, the peak power output can be misleading because it is not representative of the actual WEC behavior in energetic sea states.

The capacity factors resulting from the optimal site-specific downscaling are shown in Fig. 3. Relevant differences can be observed between the technologies, in terms both of values and spatial distribution. The Langlee shows the lowest capacity factors and a quite constant performance along the Mediterranean coastline, with values in the narrow range 0.03–0.14. The capacity factors of Pontoon, OE buoy and SeaPower are also characterized by a limited spatial variability with values between 0.03 and 0.24 and maxima located in the Aegean Sea along the Turkey coast, in the Gulf of Lion and in proximity of the Gulf of Gabes (southern coast of Tunisia, from Sfax to Djerba). AWS, AquaBuOY and Wavebob show a large variation of power performance across the different regions of the Mediterranean basin with maximum CFs of 0.31, 0.33 and 0.34, respectively. These maxima are achieved in different areas depending on the technology: AWS shows the highest CFs in the Levantine sea, along the northern coast of Egypt; AquaBuOY performs best along the eastern coast of Crete and Cyprus and in the Libyan Sea; Wavebob has the highest performance in a wider range of environments such as the Aegean coast of Turkey, off the islands of Crete and Rhodes, in the Libyan Sea, close to the Gulf of Gabes and along the Spanish coast of the Alboran Sea. Finally, the Pelamis WEC shows the largest regional variability with capacity factors exceeding 0.4 at different locations in the Aegean Sea, along the southern coast of Tunisia and in the Gulf of Lion.

Noteworthy, the highest capacity factors are not achieved at the most energetic locations of the Mediterranean Sea, which are located between the Balearic Islands and the western coast of Sardinia (Besio et al., 2006). These areas are instead characterized by quite low values of WEC performance. For example, at Alghero, on the western coast of Sardinia, the capacity factors of the downscaled WECs range between 0.06 and 0.25, depending on the technology. Similar results were found by Bozzi et al. (2013, 2017), who showed that a point absorber device deployed at Alghero and Mazara del Vallo – in the Sicily strait – would have the same energy production, despite the first site has twice as much wave power potential. The wave energy distribution of the locations can explain this unexpected result. At the sites off the Sardinia coast almost half of the available resource is due to sea states with extremely low probability of occurrence (about few percent). These events can only marginally contribute to WEC power production, because wave energy converters are not designed to exploit them, but rather to survive them and to perform at best for the moderate sea states with largest probability of occurrence. In other words, when the bulk of occurrences and the bulk of energy does not match, the capacity factors are low because a large part of the available energy is exploited with low efficiency.

Overall, it is worth noticing that the performance is higher for the devices having a larger power band equal or close to rated capacity, i.e. AquaBuOY, AWS, Pelamis and Wavebob. This can be clearly observed in Fig. 1: the relative frequency of power bins with normalized power output higher than 0.6 is about 0.35 for Pelamis, around 0.2 for AquaBuOY, AWS and Wavebob and considerably lower for the other devices. For SeaPower and OE buoy it is around 0.1 and for Langlee and Pontoon is even lower, equal to 0.03 and 0.05, respectively. However, it should be noticed that there is no single device performing better than the others along the whole Mediterranean coastline. More generally, it can be stated that the performance ranking of the technologies varies depending on the location, as already observed in previous studies (e.g. (Dunnett and Wallace, 2009; Rusu and Soares, 2012; Carballo et al., 2014)).

An additional parameter which deserves special attention is the temporal variability of wave electricity production. Particularly in the Mediterranean basin, which is characterized by large seasonal fluctuations of wave resource (Besio et al., 2006), the average capacity factor does not provide the full picture of WEC performance. To provide an insight into intra-annual variability, Fig. 4 shows the coefficient of variations of the monthly power production along the Mediterranean coastline. Low values of CV indicate that the devices have a more constant energy production throughout the year and work closer to their nominal power even in the less energetic summer months. Conversely, high values of CV mean that the WEC operates far from nominal conditions for a large part of the year. All the studied technologies have a coefficient of variation of the monthly power output exceeding 0.2 along almost all the Mediterranean coastline. On the other hand the CV is above 0.4 only at few locations, less than 4% of the whole coastline. These sites with high power fluctuations at the monthly scale are generally located in different areas, depending on the technology. However, regions where almost all the devices show a strong temporal variability of the energy output can be observed, namely the northeastern coast of the Levantine Sea, the gulf of Sirte, the southern Tyrrhenian coast of Italy, the west coast of Sardinia and Corsica and the Balearic Sea. Considering the whole Mediterranean coastline, the devices with the most unsteady power output resulted to be the Pelamis, Pontoon and SeaPower and the ones with the lowest monthly fluctuations the AquaBuOY and Langlee.

3.2. *Local scale*

This section provides a closer look to the results, giving more detailed information on the performance of the studied WECs, which may be of practical use in the design of wave energy projects in the Mediterranean Sea. Firstly we identify the coastal regions where the scaled versions of the devices can achieve the highest performance and secondly we char-acterize them with respect to wave climate and WEC performance. The aim of this analysis is to show the optimum sites for each technology regardless of the value of performance attained therein. Finally, we determine the WECs which perform best in the Mediterranean Sea and we show a number of WEC-site combinations with promising power performance, worthwhile to be considered in future economic feasibility studies.

In order to provide information of more practical use, the local analysis presented herein is limited to the sites where the optimal WEC scale is higher than 0.2, because it is considered that smaller devices are not technically feasible. Among these locations, the ones with the highest WEC performance were identified. Fig. 5 shows the ten locations with the highest capacity factors, for each technology. It illustrates two key features of wave power technologies: first, that each WEC has a different optimum location, as already outlined in the previous section; second, that each technology is characterized by a different range of adaptability. The latter can be inferred from the spatial distribution of the locations with the highest CFs, which can be either clustered in a single region or in a couple of areas only, or widely distributed across the Mediterranean basin. In the first case, the device has a smaller range of adaptability because it performs well only in few specific wave climates, while in the second one the technology is more flexible with respect to local wave conditions because it can achieve a good performance in several coastal environments. The results show that the technology with the largest range of adaptability is the AWS, followed by Pelamis, Wavebob,

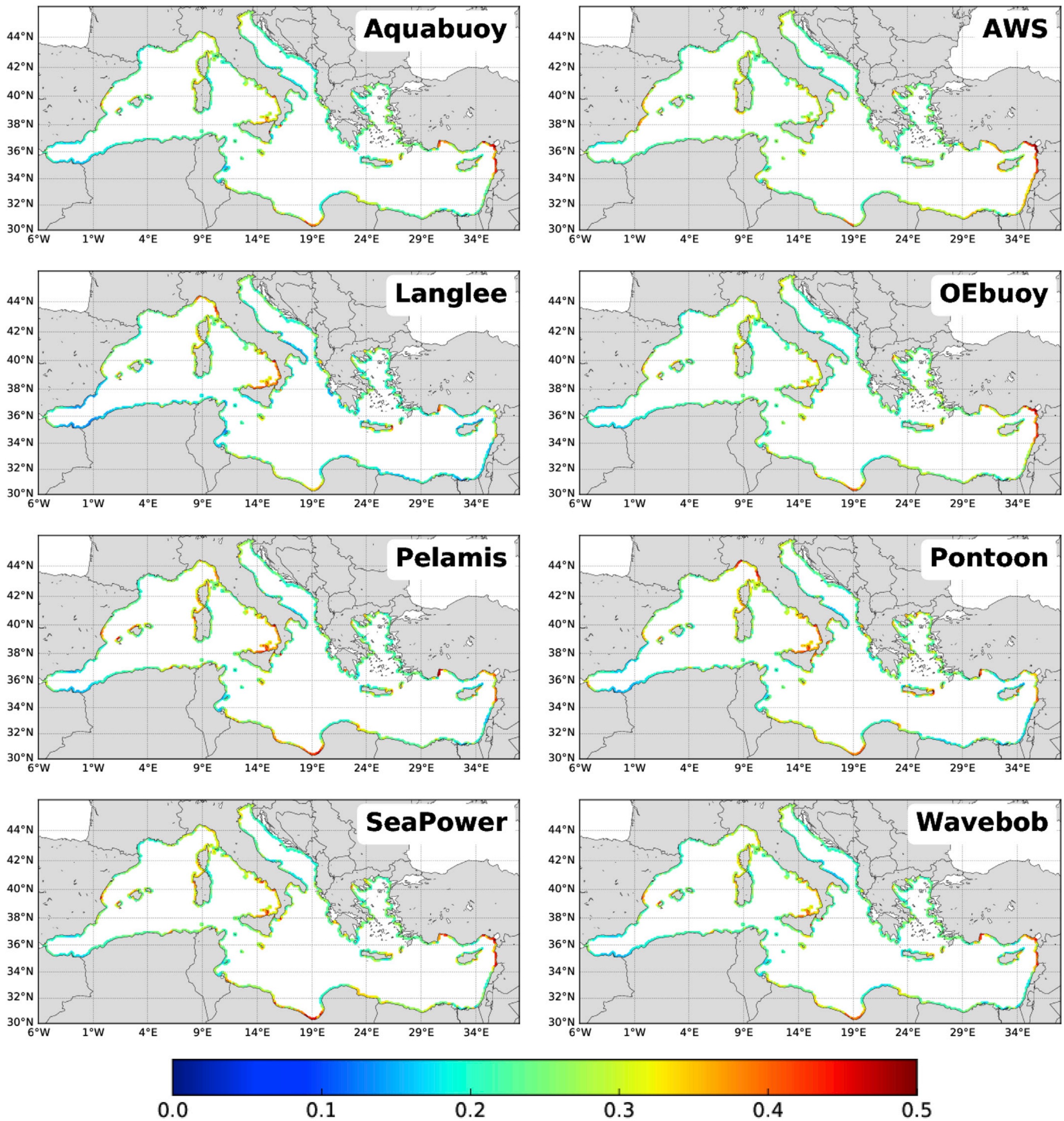


Fig. 4. Coefficient of variation of monthly energy production of the downscaled devices.

AquaBuOY and SeaPower, while OE buoy, Langlee and Pontoon are the WECs with the lowest adaptability.

Fig. 5 also shows that the Mediterranean locations with the highest performance do not distribute evenly across the Mediterranean basin but rather gather into clusters, corresponding to some specific coastal regions pertaining to different sub-basins characterized by different wave climates. More specifically, the locations with the highest capacity factors can be grouped into the 15 geographic areas (Fig. 6). In this figure, each region of interest is marked with a label reporting the first initial of country name and it is associated to the values of the capacity factors of the WECs, which perform best in one or more locations within the area. The areas of highest performance of the studied WECs resulted to be the following: Cyprus (C1), the Greek islands of Rhodes and Crete (G1 and G2, respectively); the Turkish coast near Bodrum (T1); the Libyan coast in the vicinity of Misurata (L1) and close to the Egyptian border (L2); the Aegadian islands off the northwest coast of Sicily (I1) and the Italian islands of Pantelleria and Lampedusa (L2 and L3, respectively); the French coast along the gulf of Lion (F1 and F2); Minorca Island (S1) and

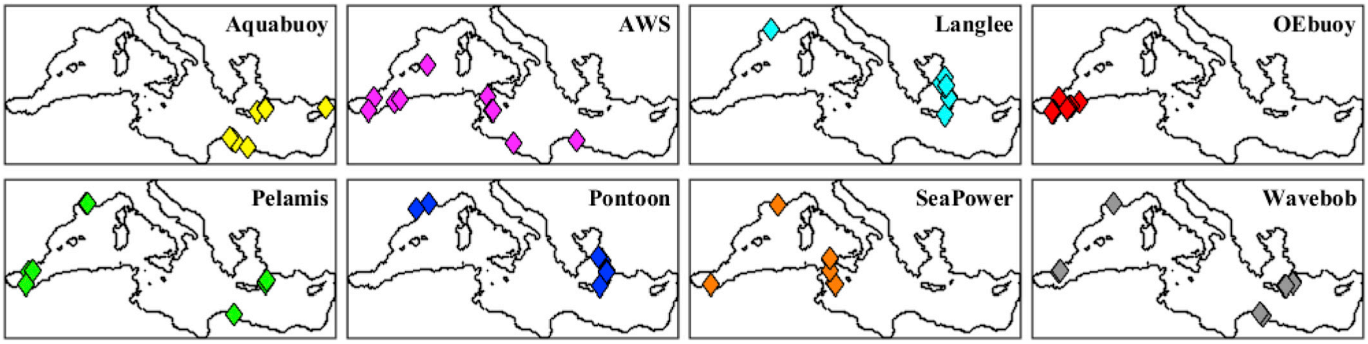


Fig. 5. Top 10 locations, in terms of capacity factor, for the deployment of the downscaled devices.

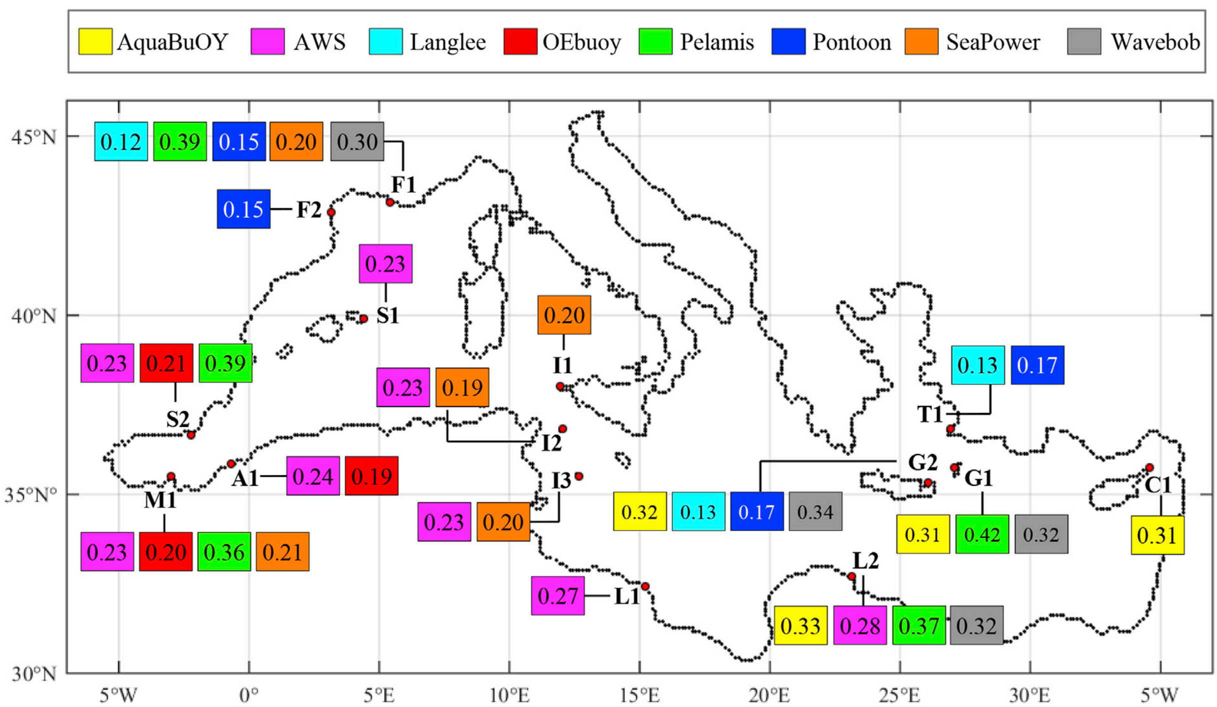


Fig. 6. Locations with the highest performance of the downscaled devices and associated values of capacity factors.

the southwestern coast of Spain, close to Almería (S2); the north-west coastline of Algeria, near Oran (A1) and the Moroccan coast close to the Algerian border (M1).

Regarding the values of the capacity factors associated to the ten sites with the highest performance, they fall into the following ranges: 0.31–0.33 (AquaBuOY), 0.23–0.28 (AWS), 0.12–0.13 (Langlee), 0.19–0.21 (OE buoy), 0.36–0.42 (Pelamis), 0.15–0.17 (Pontoon), 0.19–0.21 (SeaPower) and 0.30–0.34 (Wavebob). These CFs are achieved by rescaling device dimensions by a factor of 0.25–0.3 for AquaBuOY, Pelamis and Langlee and 0.25 for the other technologies. The resulting downscaled versions of the WECs have the following rated powers: 4–6 kW (AquaBuOY), 19 kW (AWS), 13–25 kW (Langlee), 23 kW (OE buoy), 6–11 kW (Pelamis), 28 kW (Pontoon), 28 kW (SeaPower) and 8 kW (Wavebob).

Additional details on WEC performance are reported in Table 2, for the three sites with the highest performance of each technology. The data show that the annual energy output of the most promising WEC-site combinations are approximately the following: 9 MWh (AquaBuOY), 44 MWh (AWS), 18 MWh (Langlee), 39 MWh (OE buoy), 21 MWh (Pelamis), 40 MWh (Pontoon), 50 MWh (SeaPower) and 22 MWh (Wavebob). Regarding power output variability at the monthly scale, the OE buoy has the most steady power production, followed by Pelamis, AWS and SeaPower. Much higher variability should be expected for AquaBuOY, Langlee, Pontoon and Wavebob.

An additional aspect to consider is the probability of occurrence of sea states, which deviate from intended operating conditions, leading to unplanned downtimes and/or survivability issues. This is measured by two statistics reported in Table 3: the probability of events outside the upper (EoUB) and lower (EoLB) boundary of the WEC power matrix. The first statistic indicates the fraction of the time in a year the WEC is placed in non-operating survival mode, while the second one measures the amount of time spent idle, because of too low wave energy levels.

Table 2
Performance of the WECs at the three locations with the highest capacity factors. CV indicates the coefficient of variation of monthly power output, MaxP stands for rated power, EoUB and EoLB indicate, respectively, the probability of events outside the upper and lower boundary of the power matrices.

	Location	CF [−]	Scale [−]	AEO [MWh]	CV [−]	MaxP [kW]	EoUR [−]	EoLR [−]
AquaBuOY	L2 (Tobruk)	0.33	0.30	10.8	0.28	6.3	0.14	0.09
	G2 (Crete)	0.32	0.30	10.2	0.36	6.3	0.13	0.08
	C1 (Cyprus)	0.31	0.25	5.3	0.19	3.7	0.19	0.04
AWS	L2 (Tobruk)	0.28	0.25	46.9	0.22	36.5	0.18	0.02
	L1 (Misurata)	0.27	0.25	44.9	0.25	36.5	0.17	0.03
	A1 (Oran)	0.24	0.25	41.0	0.21	36.5	0.19	0.05
Langlee	G2 (Crete)	0.13	0.25	14.5	0.39	24.6	0.08	0.10
	T1 (Bodrum)	0.13	0.25	14.5	0.21	24.6	0.05	0.17
	F1 (Marseille)	0.12	0.30	24.8	0.23	42.2	0.07	0.04
OE Buoy	S2 (Almería)	0.21	0.25	40.8	0.19	42.6	0.18	0.04
	M1 (Nador)	0.20	0.25	38.6	0.18	42.6	0.19	0.05
	A1 (Oran)	0.19	0.25	37.6	0.18	42.6	0.17	0.05
Pelamis	G1 (Rhodes)	0.42	0.25	21.7	0.26	11.1	0.12	0.10
	F1 (Marseille)	0.39	0.25	20.1	0.22	11.1	0.11	0.12
	S2 (Almería)	0.39	0.25	19.9	0.18	11.1	0.18	0.04
Pontoon	G2 (Crete)	0.17	0.25	41.7	0.34	53.5	0.11	0.10
	T1 (Bodrum)	0.17	0.25	41.2	0.24	53.5	0.07	0.17
	F2 (Perpignan)	0.15	0.25	37.3	0.25	53.5	0.11	0.12
SeaPower	M1 (Nador)	0.21	0.25	51.2	0.17	53.1	0.17	0.02
	I1 (Aegadian Islands)	0.20	0.25	50.0	0.24	53.1	0.19	0.03
	I3 (Lampedusa)	0.20	0.25	49.4	0.27	53.1	0.15	0.03
Wavebob	G2 (Crete)	0.34	0.25	23.1	0.34	14.8	0.11	0.10
	G1 (Rhodes)	0.32	0.25	22.2	0.28	14.8	0.15	0.08
	L2 (Tobruk)	0.32	0.25	22.1	0.30	14.8	0.17	0.02

Table 3
Wave climate statistics of the locations with the highest performance of the downscaled devices.

Location	Lon.	Lat.	P [kW/m]	Significant wave height				Mean wave period			
				Mode [m]	Mean [m]	q_{95} [m]	CV [−]	Mode [s]	Mean [s]	q_{95} [s]	CV [−]
A1 (Oran)	0.7 W	35.9 N	5.02	0.57	1.05	2.41	0.67	4.70	5.03	7.20	0.24
C1 (Cyprus)	34.6 E	35.8 N	3.26	0.71	0.94	2.03	0.58	4.50	4.54	6.30	0.22
F1 (Marseille)	5.4 E	43.1 N	4.48	0.44	1.02	2.46	0.72	4.10	4.50	6.40	0.25
F2 (Perpignan)	3.1 E	42.9 N	3.24	0.45	0.87	2.07	0.75	3.70	4.05	6.50	0.31
G1 (Rhodes)	27.1 E	35.8 N	3.95	0.69	1.00	2.28	0.67	4.10	4.32	6.10	0.24
G2 (Crete)	26.1 E	35.3 N	3.54	0.54	0.96	2.09	0.67	4.00	4.11	5.90	0.25
I1 (Aegadian Islands)	11.9 E	38.0 N	7.82	0.79	1.23	3.01	0.73	4.50	4.99	7.40	0.26
I2 (Pantelleria)	12.0 E	36.8 N	6.19	0.65	1.12	2.68	0.71	4.50	5.02	7.40	0.25
I3 (Lampedusa)	12.7 E	35.5 N	5.06	0.75	1.07	2.45	0.66	4.30	4.95	7.00	0.23
L1 (Misurata)	15.2 E	32.4 N	4.61	0.65	1.02	2.19	0.61	4.70	5.18	7.50	0.24
L2 (Tobruk)	23.1 E	32.7 N	4.57	0.86	1.07	2.14	0.54	4.50	5.00	7.30	0.24
M1 (Nador)	3.0 W	35.5 N	5.50	0.59	1.11	2.58	0.68	4.80	4.97	6.90	0.23
S1 (Minorca)	4.4 E	39.9 N	9.12	0.70	1.24	3.19	0.77	4.50	5.39	8.20	0.28
S2 (Almería)	2.2 W	36.7 N	5.24	0.64	1.12	2.52	0.64	4.50	4.83	6.80	0.23
T1 (Bodrum)	27.0 E	36.8 N	2.10	0.25	0.76	1.82	0.73	3.60	3.72	5.20	0.24

Depending on the planned grid connection and on the final use of electricity, it may be important to reduce the probability of all the events outside WEC operational ranges, i.e. EoUB plus EoLB, or to minimize only threats to device survivability, i.e. EoUB. The downscaled versions of the WECs at the three most promising deployment sites spend idle between 2 and 17% of the year and are placed in non-operating survival mode during 5–17% of the time. On average, AWS, SeaPower and OE buoy are the technologies with the lowest EoLB while Pontoon and Langlee are the ones with the lowest EoUB. Considering the whole amount of time with null power production, i.e. EoUB plus EoLB, the lowest values are found for Langlee, SeaPower and Wavebob.

Details on the wave climate conditions of the locations with the best WEC performance are provided in Table 3, which summarizes wave climate statistics and in Fig. 7, which shows the average annual sea state occurrences. It can be noticed that the locations with the highest CFs are quite different with respect to the wave energy level. The mean annual wave power potential ranges between 2.1 kW/m along the Turkish coast and 9.1 kW/m off the island of Minorca. This confirms the importance to consider the technology of transformation in wave energy resource assessments and suggests that feasibility studies should not be limited to the most energetic sites. Fig. 8 shows that the wave climates are characterized by relatively small waves: H_S is below 1 *m* during at least 50%of the year and for more than 60% at the less energetic locations (G1, F2 and T1). The most frequent sea states have significant wave height in the range 0.3–0.9 *m* and mean periods in the short range between 4 and 5 *s*. Matching this information with power matrix data explains why the WECs need to be considerably scaled down to maximize the capacity factors. The power matrices (see Appendix) indicate that the largest power production (higher than 80% of the nominal power) is achieved for waves higher than 4.5 *m* (AquaBuOY and Pelamis), 5 *m* (Wavebob),

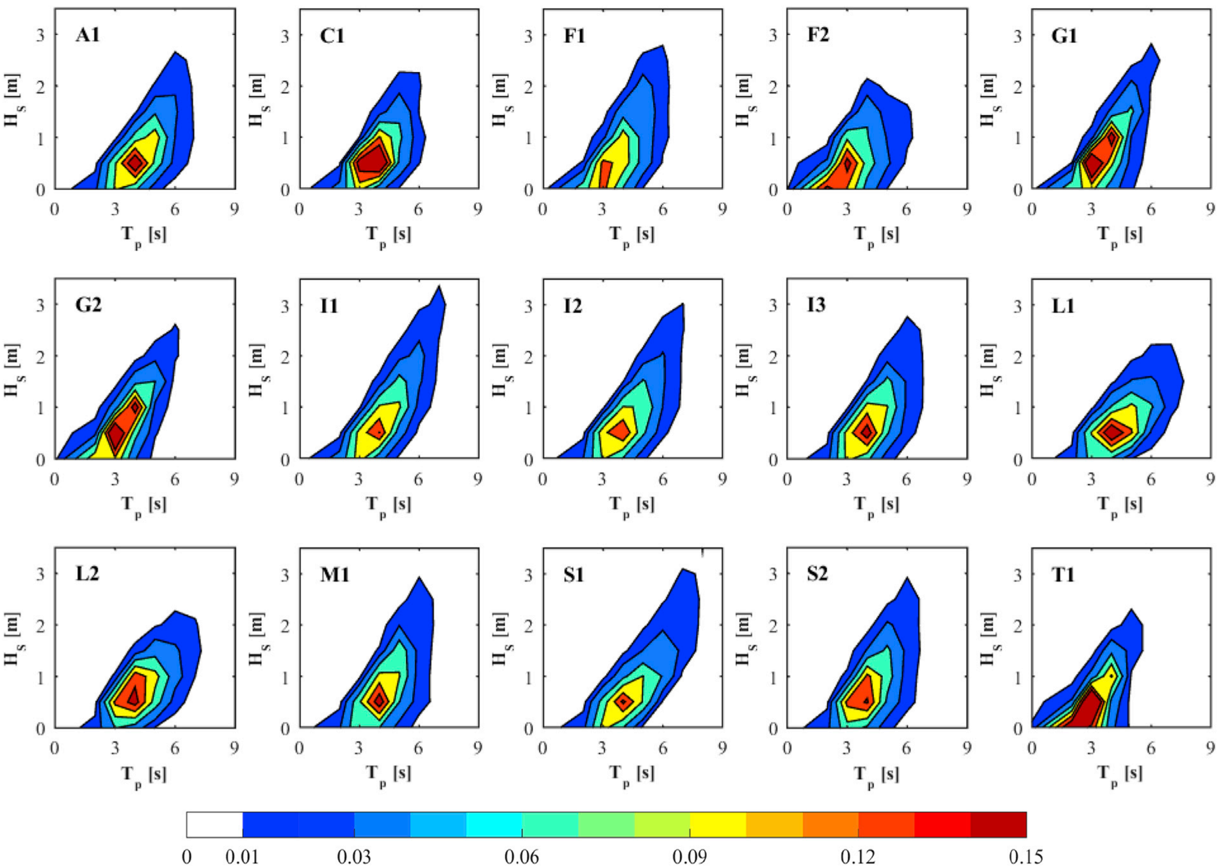


Fig. 7. Average annual sea state occurrences at the locations with the highest performance of the downscaled devices.

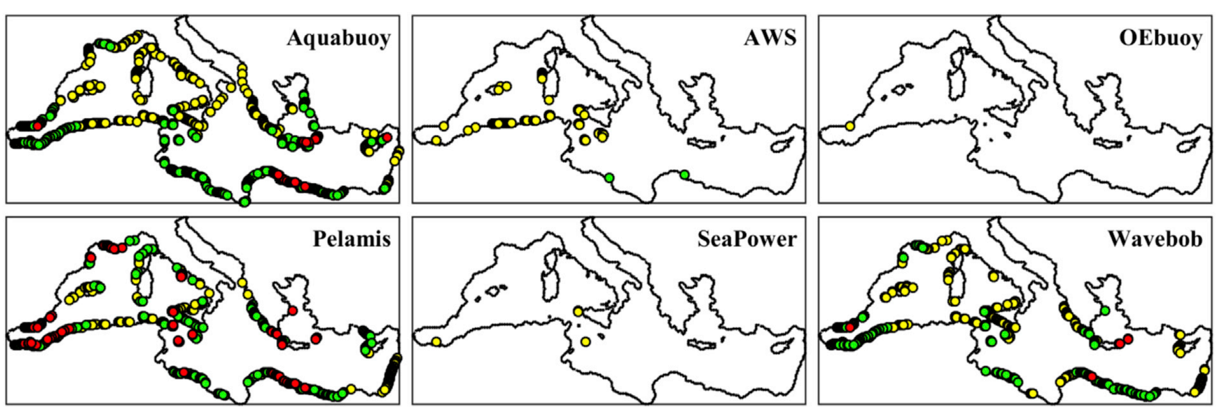


Fig. 8. Locations with capacity factors in the range 0.2–0.25 (yellow dots), 0.25–0.3 (green dots) and above 0.3 (red dots). Langlee and Pontoon data are not shown because have CF < 0.2. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5.5 *m* (AWS), 6.5 *m* (Langlee, OE buoy and Pontoon) and 7.25 *m* (SeaPower). At the same time, wave periods needs to be at least higher than 6.5 *s* (and up to 10.5 *s*) to exhibits such power performance. In order to match these values with the values of H_S and T_m providing the bulk of occurrence is therefore required a large scale reduction of the devices, about 0.25–0.3 of the original WEC size.

The second goal of the local scale analysis was to determine the WEC-site combinations with promising values of power performance. At this aim, the locations with capacity factors in the range 0.2–0.25, 0.25–0.3 and above 0.3 were identified for each technology (Fig. 8). Pontoon and Langlee resulted to have CFs lower than 0.2, so they were not taken into account. It can be noticed that large part of the Mediterranean coastline can be exploited with relatively high values of capacity factor: more than 40% with CF higher than 0.2 and about 8% with CF higher than 0.3. With regards to the devices, six WECs can reach CF > 0.2 at one or more site along the coasts, four allow achieving CF > 0.25 and three can exceed 0.3. More specifically, OE buoy and SeaPower have the lowest performance, with capacity factors above 0.2 at only one and four sites, respectively. AWS can reach values of CF between 0.2 and 0.25 at 60 locations in the western Mediterranean Sea and between 0.25 and 0.3 at two sites, along the Libyan coast. AquaBuOY and Wavebob can achieve capacity factors higher than 0.3 at 26 and 9 sites, respectively, located along the coast of Cyprus and Crete, in the Libyan Sea and along the Spanish coast of the Alboran Sea. Pelamis resulted to be the technology with the highest performance having CF > 0.3 at about 100 locations and CF > 0.35 at 15 sites. The best deployment sites for Pelamis are the same as for AquaBuOY and Wavebob, with the addition of the Sicily Channel, the Gulf of Lion, the southern Alboran Sea and some sites along the Greek coastline.

4. Discussion and conclusions

The present study gives a general picture of the Mediterranean potential for wave electricity production, thus helping future smaller-scale studies on specific areas of interest. The main outcomes of the work can be summarized as follows:

- Most of the studied wave power technologies can have a good performance in the Mediterranean, if properly downscaled to match local wave climate conditions. More specifically, about 40% of the coastline could be exploited with a capacity factor (CF) higher than 0.2 and about 8% would provide a CF higher than 0.3.
- The locations with the highest performance do not distribute evenly across the Mediterranean basin but rather gather into clusters, corresponding to some specific coastal regions (i.e. different wave climates). Capacity factors higher than 0.3 can be reached in the Gulf of Lion, in the Sicily channel, in the Alboran Sea, along the Libyan coast, at Crete and Cyprus.
- Noteworthy, the highest capacity factors are not achieved at the most energetic locations of the Mediterranean Sea, such as west coast of Sardinia and Corsica and the Balearic Sea, where instead quite low values of WEC performance result. This is due to the fact that at these sites large part of the available resource is provided by extreme and rare events for which WEC efficiency is very low. As a result, locations with high power potential but with a mismatch between the sea states providing the bulk of occurrences and the bulk of energy are not attractive for wave energy projects.
- The technologies allowing to reach capacity factors higher than 0.2 are six: AquaBuOY, AWS, Pelamis, OE buoy, SeaPower and Wavebob. Three of them (AquaBuOY, Pelamis and Wavebob) can work with a CF exceeding 0.3 at many locations along the coasts, thanks to their larger power band equal or close to rated capacity. Pelamis is the device with the highest performance with a CF higher than 0.35 at more than 10 sites.
- There is no single device performing better than the others at all the studied sites but rather the performance ranking of the technologies varies depending on location. However, at a given site the best performing WEC result to be always AquaBuOY, AWS, Pelamis or Wavebob.
- There is no best location for wave energy exploitation but rather the locations with the highest capacity factors depend on the specific technology. Moreover, the best deployment locations are characterized by quite different values of mean annual wave power potential, suggesting that energy distribution among sea states can be more relevant than mean energy level.
- The optimal locations – in terms of capacity factors - are the following. AquaBuOY, Pelamis and Wavebob achieve the highest capacity factors along the coast of Cyprus and Crete, in the Libyan Sea and along the Spanish coast of the Alboran Sea. Pelamis works well also in the Sicily Channel, in the Gulf of Lion, along the southern coast of the Alboran Sea and at some sites along the Greek coastline. AWS performs better in the western Mediterranean Sea and at few sites along the Libyan coast. SeaPower achieve the highest capacity factors in the Sicily channel, close to the gulf of Lion and along the Moroccan coast. Pontoon and Langlee perform better in the proximity of the Gulf of Lion and at different sites in the Aegean Sea. Finally, the OE buoy shows the highest performance at a number of sites off the northern and southern coast of the Alboran Sea.
- The optimal size of the WECs at the most promising coastal locations is between one 1/4 and 1/3 of the full WEC size. This scale reduction is required to capture the energy of the moderate sea states – prevailing in the Mediterranean wave climate – which otherwise would be lost by the original devices. The scale reduction is to shift the power bins at rated capacity to lower values of wave height and period, allowing the devices to reach the highest performance for the most frequent sea states. In fact, the maximum capacity factors are achieved when the WEC have the largest power production for the sea states providing the bulk of occurrences.
- The optimally downscaled versions of the WECs at the most promising sites have a nominal capacity about one or two orders of magnitude lower than the corresponding full scale devices. More specifically, the resulting rated powers are about 10 kW for AquaBuOY, Pelamis and Wavebob, around 20 kW for AWS, Langlee and OE buoy and almost 30 kW for Pontoon and SeaPower. It would have been expected that for a given site the installed capacity did not depend on the specific technology, being related only to the available wave energy resource. This behavior is due to the different performance characteristics of the WECs, namely to the different power output distribution with respect to sea states. Some technologies operate at the rated power only for few sea states, while others have a large power and at rated capacity. In the first case, the peak power does not well represent the maximum WEC performance and lower values should be probably adopted as nominal capacity.
- Intra-annual variability of power production depends both on the technology and the deployment location. At the optimal deployment sites of each technology the coefficients of variation of the monthly power production series range between 0.17 and 0.39. The technologies with the lowest power fluctuations are OE buoy, Pelamis, AWS and SeaPower, while much higher variability is observed for AquaBuOY, Langlee, Pontoon and Wavebob. The coastal regions with the strongest intra-annual variability are the northeastern coast of the Levantine Sea, the gulf of Sirte, the southern Tyrrhenian coast of Italy, the west coast of Sardinia and Corsica and the Balearic Sea.

In this work, no control strategies were considered. However, damping control methods strongly affect the hydrodynamic behavior and, ultimately, the power production of a WEC. Particularly, control strategies can enhance the efficiency of the WECs with a narrow power band, allowing them to work efficiently across a broader range of sea states. This aspect should be taken into consideration in future smaller-scale studies.

The work has focused on the performance of the wave energy converters because this is a key parameter in any feasibility study. However, it must be taken into account that power performance does not necessarily imply economic performance and that the capacity factor is just one of the several criteria, which should be taken into account in the decision-making process (Abaei et al., 2017). Other aspects deserving attention relates with device survivability, installation and maintenance costs, grid connection points, potential environmental conflicts, permitting requirements, shipping traffic and other uses of the sea area. For these reasons, the study has not shown the best technology for each site, but it has presented a number of WEC-site combinations with promising power performance, which are worth considering in future feasibility studies.

This study has been based on a long term wave data series with high temporal and spatial resolution. However, the performance assessment has also relied on power matrix data, which are known to be affected by a relevant degree of uncertainty (between 10 and 40% according to (Babarit et al., 2012)). As a result, this uncertainty source must be taken into account when looking at the results of the present analysis.

Appendix

Table A1
Power matrix of the AquaBuOY wave energy converter (kW).

Hs (m) \ Tp (s)	6	7	8	9	10	11	12	13	14	17
1	0	8	11	12	11	10	8	7	0	0
1.5	13	17	25	27	26	23	19	15	12	7
2	24	30	44	49	47	41	34	28	23	12
2.5	37	47	69	77	73	64	54	43	36	19
3	54	68	99	111	106	92	77	63	51	27
3.5	0	93	135	152	144	126	105	86	70	38
4	0	122	176	198	188	164	137	112	91	49
4.5	0	0	223	250	239	208	173	142	115	62
5	0	0	250	250	250	250	214	175	142	77
5.5	0	0	250	250	250	250	250	211	172	92

Table A2
Power matrix of the AWS wave energy converter (kW).

Hs (m) \ Te (s)	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13	13.5	14	14.5
1	2	7	13	19	26	34	41	48	58	68	81	93	105	118	131	144	153	163	183	203
1.5	4	15	28	41	56	72	85	99	121	143	173	203	226	248	266	285	309	334	357	380
2	8	26	49	73	100	127	150	172	210	247	292	337	366	395	418	442	482	523	543	563
2.5	15	43	78	113	159	205	234	263	320	376	438	499	531	563	603	643	675	708	741	774
3	25	61	111	161	227	293	339	386	453	521	600	680	722	765	827	888	897	906	945	984
3.5	35	92	155	218	305	391	454	517	605	694	772	851	913	975	1036	1096	1119	1141	1163	1185
4	35	114	194	273	380	486	572	659	776	894	961	1027	1103	1179	1227	1275	1316	1357	1365	1374
4.5	0	0	235	332	479	626	722	819	957	1096	1168	1240	1320	1401	1449	1497	1547	1598	1590	1583
5	0	0	280	400	592	784	899	1014	1144	1274	1380	1487	1569	1651	1691	1731	1785	1838	1807	1777
5.5	0	0	320	432	641	849	1033	1216	1331	1446	1568	1690	1778	1867	1919	1970	1977	1984	1994	2005
6	0	0	0	0	680	944	1155	1367	1495	1623	1759	1895	1936	2072	2137	2202	2205	2207	2226	2246
6.5	0	0	0	0	720	1123	1335	1547	1678	1809	1936	2116	2200	2284	2332	2380	2425	2470	2452	2434

Table A3
Power matrix of the Langlee wave energy converter (kW).

Hs (m) \ Tp (s)	4	5	6	7	8	9	10	11	12	13	14	15	16
1	19	29	47	57	52	37	29	20	17	13	9	7	7
1.5	42	63	92	111	109	65	56	38	29	22	19	13	11
2	66	99	151	201	165	105	85	59	52	41	29	24	19
2.5	0	160	242	262	226	166	118	83	70	57	39	29	26
3	0	213	319	372	327	211	152	116	94	75	66	45	42
3.5	0	0	436	503	408	293	203	148	115	93	75	58	44
4	0	0	554	540	521	355	261	192	144	123	84	81	56
4.5	0	0	645	746	587	379	302	236	190	154	106	90	74
5	0	0	796	926	695	486	341	287	211	168	136	111	94
5.5	0	0	0	955	808	603	430	343	231	201	150	120	97
6	0	0	0	1161	957	642	481	329	289	212	172	146	111
6.5	0	0	0	1476	1039	702	488	397	312	237	204	153	120
7	0	0	0	1665	1197	821	612	466	385	252	223	181	146

Table A4
Power matrix of the OE buoy wave energy converter (kW).

		Tp (s)												
		6	7	8	9	10	11	12	13	14	15	16	17	18
Hs (m)	1	8	17	27	42	56	59	52	44	40	38	40	38	30
	1.5	17	39	61	96	126	132	117	99	89	87	89	85	66
	2	30	69	108	170	224	235	208	177	159	154	159	151	118
	2.5	47	108	169	266	350	368	324	276	249	241	248	236	185
	3	68	155	244	383	504	530	467	398	358	347	357	340	266
	3.5	93	212	332	521	686	721	636	542	487	472	486	463	362
	4	121	276	433	680	896	942	831	708	636	616	634	605	473
	4.5	154	350	548	861	1130	1190	1050	896	805	780	803	765	599
	5	190	432	677	1060	1400	1470	1300	1110	994	963	991	945	739
	5.5	0	523	819	1290	1690	1780	1570	1340	1200	1170	1200	1140	894
	6	0	622	975	1530	2020	2120	1870	1590	1430	1390	1430	1360	1060
	6.5	0	730	1140	1800	2370	2490	2190	1870	1680	1630	1670	1600	1250
	7	0	847	1330	2080	2750	2880	2540	2170	1950	1890	1940	1850	1450

Table A5
Power matrix of the Pelamis wave energy converter (kW).

		Te (s)																
		5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13
Hs (m)	1	0	22	29	34	37	38	38	37	35	32	29	26	23	21	0	0	0
	1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
	2	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
	2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
	3	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
	3.5	0	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
	4	0	0	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
	4.5	0	0	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
	5	0	0	0	739	726	731	707	687	670	607	557	521	472	417	369	348	328
	5.5	0	0	0	750	750	750	750	750	737	667	658	586	530	496	446	395	355
	6	0	0	0	0	750	750	750	750	750	750	711	633	619	558	512	470	415
	6.5	0	0	0	0	750	750	750	750	750	750	750	743	658	621	579	512	481
	7	0	0	0	0	0	750	750	750	750	750	750	750	750	676	613	584	525
	7.5	0	0	0	0	0	0	750	750	750	750	750	750	750	750	686	622	593
	8	0	0	0	0	0	0	0	750	750	750	750	750	750	750	750	690	625

Table A6
Power matrix of the Pontoon wave energy converter (kW).

		Tp (s)												
		4	5	6	7	8	9	10	11	12	13	14	15	16
Hs (m)	1	180	166	153	171	125	87	72	65	85	85	37	29	16
	1.5	223	195	157	148	261	192	223	139	155	155	74	67	46
	2	0	0	214	227	396	335	237	235	172	138	115	104	70
	2.5	0	0	0	440	598	514	379	342	204	169	142	128	95
	3	0	0	0	681	801	735	594	486	199	174	151	134	121
	3.5	0	0	0	904	1035	949	788	617	239	209	183	164	146
	4	0	0	0	1131	1269	1163	982	743	285	248	216	195	175
	4.5	0	0	0	1358	1488	1374	1187	869	330	287	250	225	201
	5	0	0	0	1585	1712	1585	1392	988	380	334	285	263	226
	5.5	0	0	0	1812	1937	1798	2138	1107	429	381	323	301	261
	6	0	0	0	2040	2162	2010	2884	1234	439	416	361	336	295
	6.5	0	0	0	2267	2386	2221	3143	1360	449	450	406	372	329
	7	0	0	0	2494	2611	2433	3619	1483	506	464	451	408	363

Table A7
Power matrix of the SeaPower wave energy converter (kW).

Hs (m) \ Tp (s)	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5
0.75	4	13	24	31	35	35	34	31	30	31	32	29	16
1.25	0	37	66	87	98	99	93	87	84	86	88	81	45
1.75	0	73	129	171	192	193	183	171	165	168	172	158	88
2.25	0	120	214	283	317	319	302	283	273	278	285	261	146
2.75	0	0	546	423	474	477	452	422	408	415	426	391	218
3.25	0	0	0	591	662	666	631	590	570	580	595	545	305
3.75	0	0	0	787	881	887	840	785	759	772	792	726	406
4.25	0	0	0	1011	1132	1139	1079	1008	974	991	1017	933	0
4.75	0	0	0	0	1414	1423	1348	1259	1217	1238	1270	1165	0
5.25	0	0	0	0	1992	1739	1646	1538	1487	1512	1551	1423	0
5.75	0	0	0	0	0	2085	1975	1845	1784	1814	1861	1707	0
6.25	0	0	0	0	0	2085	2333	2180	2107	2143	2199	2017	0
6.75	0	0	0	0	0	0	2721	2543	2458	2500	2565	2353	0
7.25	0	0	0	0	0	0	3139	2934	2835	2884	2959	2714	0
7.75	0	0	0	0	0	0	3587	3353	3240	3295	3381	3102	0

Table A8
Power matrix of the Wavebob wave energy converter (kW).

Hs (m) \ Tp (s)	4	5	6	7	8	9	10	11	12	13	14	15	16
1	6	11	19	25	30	44	50	53	44	34	22	20	17
1.5	13	25	43	55	68	90	102	92	91	66	65	45	37
2	24	45	65	100	121	153	175	151	122	126	87	61	58
2.5	0	65	104	141	191	179	243	255	190	181	135	99	83
3	0	96	137	205	244	357	293	353	260	248	184	137	120
3.5	0	0	192	254	291	431	385	424	314	285	239	222	172
4	0	0	256	366	403	551	536	531	473	420	289	268	179
4.5	0	0	327	418	574	678	708	665	509	415	386	244	249
5	0	0	358	514	658	824	828	618	638	512	452	384	333
5.5	0	0	0	610	774	880	936	905	805	603	456	397	311
6	0	0	0	711	952	974	1000	838	886	648	501	503	396
6.5	0	0	0	788	1000	1000	1000	979	1000	727	577	435	424
7	0	0	0	781	1000	1000	1000	1000	1000	959	748	574	472

Table A9
Colour Legend.

P_{max}	Dark red
$0.8*P_{max} - P_{max}$	Red
$0.6*P_{max} - 0.8*P_{max}$	Dark orange
$0.4*P_{max} - 0.6*P_{max}$	Orange
$0.2*P_{max} - 0.4*P_{max}$	Yellow
$0 - 0.2*P_{max}$	Light yellow
0	White

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