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Effects of metocean conditions on selecting optimal location for wave energy production

George Lavidas, Eva Loukogeorgaki, Constantine Michalides, and Ioannis K. Chatjigeorgiou

Abstract—**Wave Energy Converters (WEC) have seen a wide variety of innovations capable to harness the vast untapped energy source of the seas. This wide range of WECs often has varied applicability and power production capabilities, making the selection of a device overwhelming. These uncertainties are increased when considering the interactions and suitability of the device with local metocean conditions, and the impacts to long-term reliable operation. The study focuses on the Mediterranean region and presents a comprehensive approach in selecting a WEC, using a novel Selection Index for Wave Energy Deployments (SIWED), which accounts for resource, extreme events, power production capabilities, reducing uncertainties and biases. As a case study our approach explores: (i) the viability of WECs at milder resource (ii) the use of SIWED to select the "optimal" location and (iii) an approach to optimise considering the multi-faceted resource impacts. The study provides a comprehensive assessment of the "hidden" benefits of wave energy in the Mediterranean and its methodology is universally replicable. Finally, a discussion and overview on the importance of this interdisciplinary method for WEC deployments is underlined.**

Index Terms—**Mediterranean Sea, Capacity factors, Optimal site selection, Wave energy**

I. Introduction

CLIMATE Change impacts are expected to have disastrous effects on human societies, with increased probabilities for extreme events, flooding, severe weather, and the socio-economic strata of human societies [1]. Amongst necessary steps to mitigate Climate Change, including the reduction of CO_2 emissions, several countries committed to ambitious targets at the Conference of Parties in 2015 [2]. European Union Member States have set ambitious targets for 2020 and 2030, with regards to greenhouse gas emissions and renewable energy [3]. Currently, National Energy and Climate Plans (NECPs) are under consultation, and it is clear that much has to be done in order to achieve the targets [4]. Common thread in all NECPs is the premise that all local renewable energy sources have to be used more. However, this premise encompasses several oversights and the need for innovative energies to be further incorporated.

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In most studies wind is expected to be a "base" load plant, with local resources availability differentiating the mixture. Some studies, included high fidelity assessment of multi generation [5], [6], showing that as the energy fraction increases, a system can attain "stability" with wave energy, stabilising variable wind and limited solar production. Such an example is the case of Denmark, where it was estimated that as wind increases PV and wave are needed, with wave obtaining a large significance due to its production profile [5]. The fact that wave energy is a complementary resource for wind, increases its value and potential for utilisation.

Wave energy presents a multi–layered challenge due to complexities in power production, and balances that must be achieved. Success in Wave energy converter (WEC) deployment is a combination of three main pillars: resource, extractable energy and economics (see Figure 1).

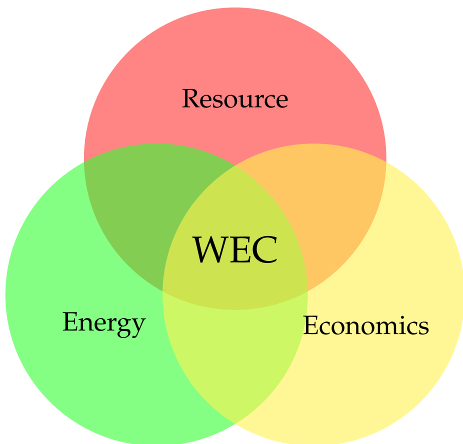

Fig. 1. Principles of balance for the development of any renewable energy technology.

The wave energy resource (P_{wave}) corresponds to the energy per unit of wave crest width, expressed in watts/meter (W/m). P_{wave} does not represent a value that is fully usable but only the resource potential, useful energy produced depends on WEC characteristics such as efficiency. Extracted energy is highly dependent on WEC geometry and hydrodynamic interactions with local metocean conditions [7], [8]. Energy refers to extracted energy (power produced) by a WEC, using a power matrix [9], based on the statistical properties from significant wave height (H_{m0}), wave

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direction (P_{kDir}), and wave period(s) (energy (T_{m10}), peak (T_{peak})).

Economics refers predominately to the capital require for the development of a WEC. Majority of expenditure in a WEC is the Capital Expenditure (CapEx) which is a "one-off" cost. There is a diverse selection of WECs that are applicable at different depths, and have distinct construction requirements. For example a coastal WEC will require more CapEx for structures, while for a floating WEC at deeper waters large portion of CapEx correspond to moorings.

In the present study, a novel formulation to account for all different aspects, by reducing uncertainties and biases in wave energy is used. The formulation is the Selection Index for Wave Energy Deployments (SIWED) and aims to account for the metocean and extreme conditions as they affect energy production. The index does not exclude expert judgement, but is rather an unbiased tool for the selection of an appropriate WEC.

II. Materials & Methods

The issue of selecting a WEC until now depend mostly on subjective expert judgement. Several authors have developed methodologies to select a WEC [10], [11] and/or the suitable region for deployment [12]–[18]. Such approaches focus only on specific resource or device characteristics. WEC production relies on resource availability, and it is often unique or within certain WEC(s) that share similar characteristics [19]. A high energy content does not indicate that it will be a appropriate location to install a WEC. Limitation of methodologies are that they either focus on resource, or only on energy production. They often do not investigate metocean trend interactions with energy production, wave stability, and omit to consider extreme events.

A. Selection Index for Wave Energy Deployments (SIWED)

The Selection Index for Wave Energy Deployments (SIWED) (see Eq 1) [20], aims to reduce the uncertainties and bridge the power capabilities with resource dependence, providing an unbiased selection of WEC.

$$SIWED = \frac{e^{-CoV_{H_{m0}}} \cdot CF}{\frac{H_{EVA}}{H_{max}}} \tag{1}$$

In Eq. 1 $CoV_{H_{m0}}$ is the Coefficient of Variation, CF is the capacity factor, H_{EVA} the value of return waves based on extreme value analysis, and H_{max} is the maxima value of wave height from the dataset.

If a region has high variability is "penalised" by reducing expected power performance, since a higher volatility indicates a potential larger rate of change in metocean conditions. In the denumerator, the ratio of estimated extreme return wave value over the maximum significant wave height, assists in quantifying the extent of which return values deviate from recorded maxima. This affects WEC survivability, and if the ratio is too high it will probably require more CapEx to ensure long-term and safe operation. Theoretically, SIWED can obtain values close to unity, the exponential of $CoV_{H_{m0}}$ goes from 1 to zero, with a zero $CoV_{H_{m0}}$ i.e. no expected variation the term obtains a positive high value. In the event of a high $CoV_{H_{m0}}$, the exponential drops near 0. The CF of a device can also acquire values up to 1 (100%), although for renewable energies this is not realistic. Finally, if no variation exists then the expected return value will be close to the maximum H_{m0}, theoretically obtaining a value up to 1. Therefore, when SIWED obtains a higher value that indicate that the site and selected WEC have a better "match" and can deliver reliable power production.

Another important consideration when it comes to devices located in offshore sites, is their ability to survive extreme events. Estimation of wave return values are valuable for sizing of moorings, and strengthening work needed. Given the wide array of WECs that exist, return wave values can have a significant effect on CapEx.

The method for data preparation in this extreme value analysis is the Peak Over Threshold (POT), that can handle datasets of various temporal duration and lengths. Ensuring the recordings are not influenced by each other (identically independently distributed (i.i.d)) [21], [22], threshold was set with the 99.5^{th} percentile of H_{m0} with a 72 hours windows. This choice took into account the available data and record its effects of the final data length [23], [24].

$$z_p = u + \frac{\hat{\sigma}}{\xi}\left[(N \cdot \lambda_u)^{\xi} - 1\right] \tag{2}$$

$$\lambda_u = \frac{k}{n_{years}} \tag{3}$$

In the above equations, N (investigated) is the return value in years, λ_u is the rate of threshold, κ is the length of dataset by POT, n_{years} is the sample duration, while $\hat{\sigma}$ (scale) and ξ (shape) the Generalised Pareto Distribution (GPD) parameters. The return wave period is calculated by utilizing the fitted GPD parameters of each location and based on the reduced sample rate as estimated in Eqs 3 and 2 with the Maximum Likelihood. Most WECs have an expected lifetime of 20-25 years, so a return value of 30 year ($H_{EVA} = H_{30}$) is deemed appropriate. This allows not to over-estimate extreme events and therefore increase CapEx.

B. Area of Investigation and datasets

Metocean conditions for 35 years (1980-2014, end of 2014) are utilised to estimate all climate, power production and SIWED parameters. The datasets belong to a calibrated and validated two way nested system [25]–[27], based on the phased averaged Simulating WAves Nearshore (SWAN), that was adapted to the region. The locations (see Figure 2) used in this study are obtained by the second nested higher fidelity domains for Greece, Italy, Spain, France, Tunisia, Libya with a spatial resolution $\approx$ 2 Kilometres.

The locations used in this study, represent depths 50 $\leq$ d $\leq$ 150 meter (m), thus the wave energy converters considered are applicable at nearshore to deep waters. Table I displays the representative WECs [20].

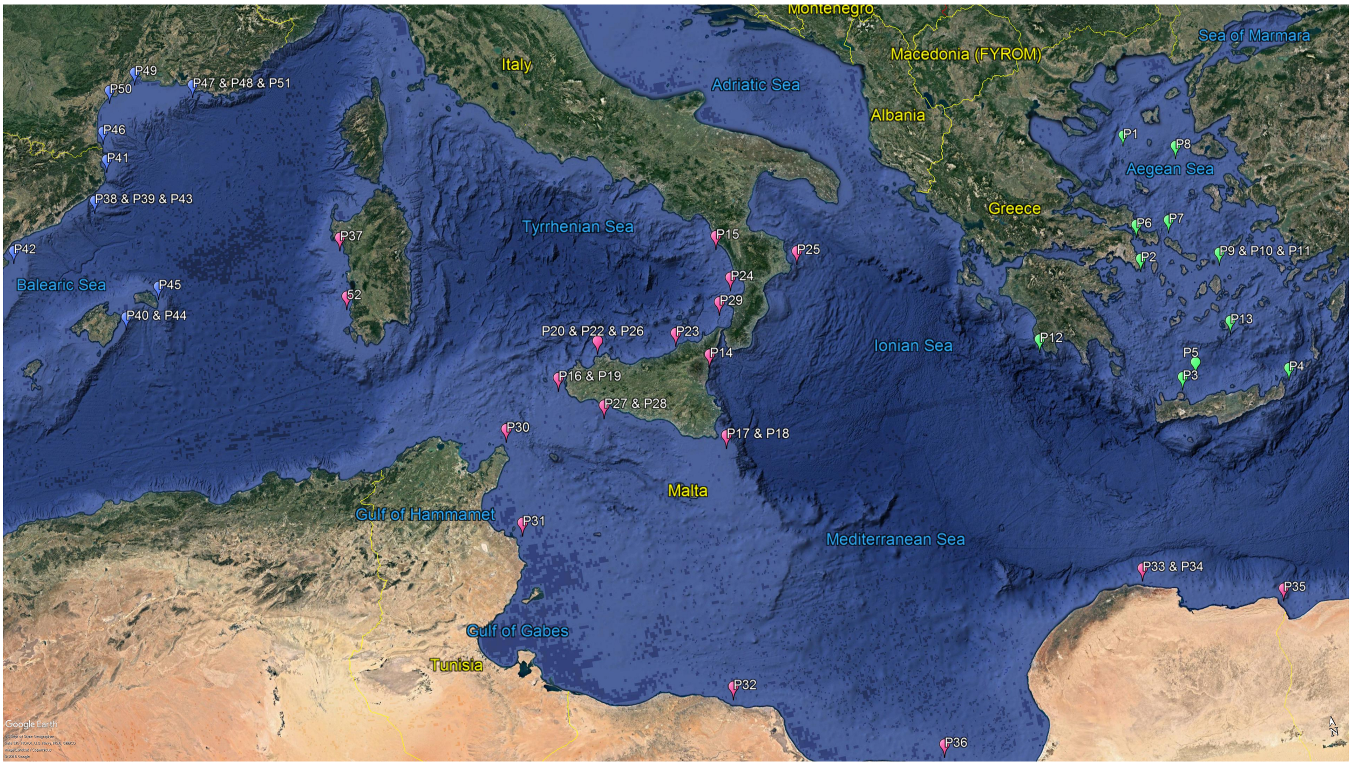

Fig. 2. Distribution of locations. (Google Earth, JS Dept of State Geographer, Data SIO, NOAA, US Navy, NGA, GEBCO, Image Landsat/ Copernicus, 2021 Google.)

TABLE I
WECs USED IN THIS STUDY

Name	Type
WaveStar (600 kW)	Point Absorber
F2HB (1000 kW)	Point Absorber
AquaBuoy (250 kW)	Point Absorber
AWS (2470 kW)	Point Absorber
BSHB (260 kW)	Point Absorber
FHBA (3619 kW)	Point Absorber
OceanTech (500 kW)	Attenuator
FOWC (2880 kW)	Oscillating Water Column
WaveDragon (7000 kW)	Overtopping

III. Results

The Mediterranean sea is home to several coastal nations, its general wave climate can be characterised as moderate to low, with sharp gradients of bathymetric changes. This suggests that the bathymetry around Mediterranean countries can be challenging, as changes can occur at close proximity to each other. Accessibility as a metric is defined as the percentage of time for which the conditions met at a location are equal or less than a specific threshold. This ensures that the deployment of vessels, crews, and offshore works is performed under safe conditions. In the Mediterranean, near the coastlines and below 150 m depth accessibility is $\geq$ 80%, see Figure 3. Deeper water locations $\geq$ 200 meter depth show reduced levels, however, currently WEC and other offshore renewables are not expected to be deployed at such conditions.

For all locations, key metocean conditions were firstly estimated (see Table II), locations P1-P10 belong to the Hellenic sea space. The region is at the North East part of the Mediterranean and can be divided into 4 regions, which is at the North Aegean (P1,P8,P6,P7), the Central Aegean (P2,P9-P11)), the South Aegean (P3,P4,P5,P12,P13) and the Ionian Sea. In terms of H_{m0} mean values for most locations are ≤ 1 meter, however, this does not mean that their conditions are always low. In fact, the standard deviation and coefficient of variation indicate that the wave conditions have large volatility. In terms of maxima, almost all locations have $H_{max} \geq 5.5$ meters, with Central Aegean locations reaching up to 7.79 meters. Throughout extracted locations mean P_{wave} is 3.51 kW/m, with maxima values $\geq$ 12 kW/m.

TABLE II
DESCRIPTIVE METOCEAN STATISTICS FOR LOCATIONS IN GREECE

Location	H_{m0}	H_{max}	H_{STD}	P_{wave}
		meters		kW/m
Athos (P1)	0.81	6.82	0.79	3.89
Attika (P2)	0.62	5.60	0.52	1.71
Crete1 (P3)	0.80	6.26	0.64	3.54
Crete2 (P4)	1.05	6.65	0.75	5.28
E1mea (P5)	0.72	6.20	0.61	2.87
Euboia (P6)	0.67	6.55	0.68	2.96
Kythnos (P7)	0.86	6.26	0.73	3.68
Lesvos (P8)	0.89	6.99	0.77	4.06
Mykonos (P9)	0.88	5.18	0.61	2.87
Naxos (P10)	0.79	4.21	0.60	2.44
Paros (P11)	0.86	4.50	0.63	2.89
Pylos (P12)	0.94	7.79	0.73	4.74
Santorini (P13)	1.01	5.84	0.71	4.64

Locations in the Italian Seas (P15-37, P52) (see Table III) have similar mean H_{m0} with South-West locations being have the highest. Variation and standard deviation of the conditions indicate changes annually, with highest waves (H_{max}) values $\approx$ 1 meter higher than Greece. The 99^{th} percentiles indicate that all location

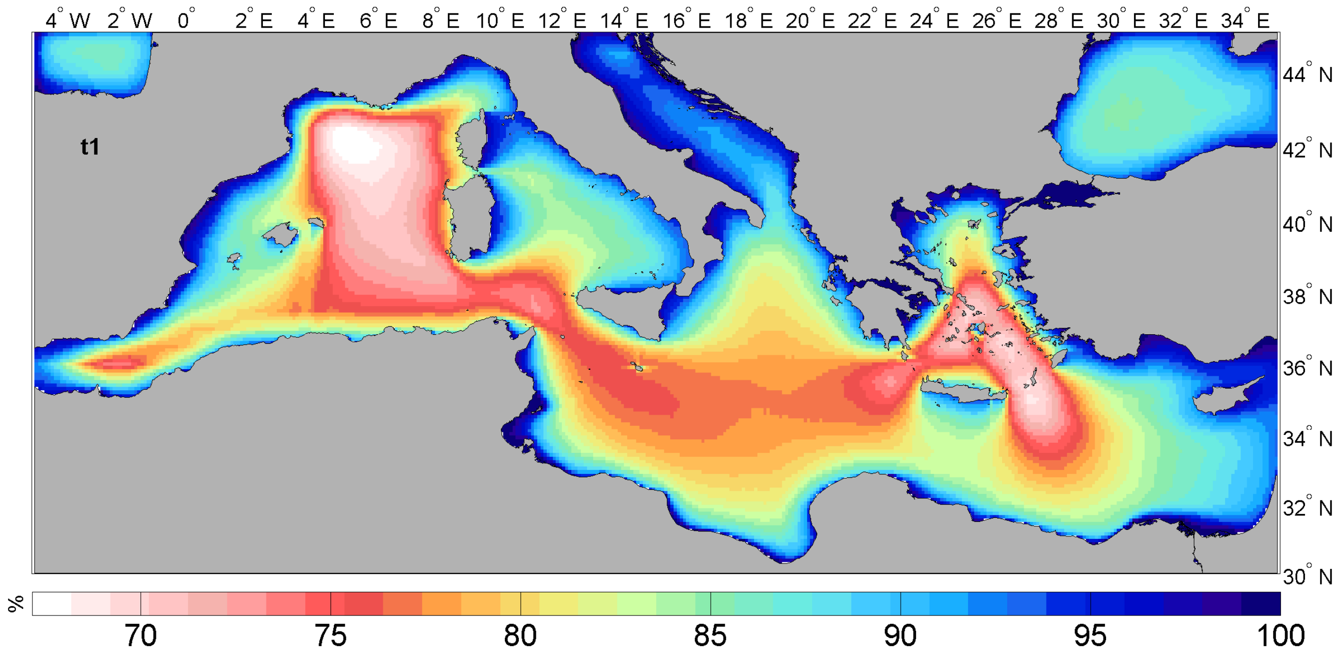

Fig. 3. Accessibility for $H_{m0} \leq 1.5$ meters (m).

are below 4.13 meters. However, their most maxima are $\geq$ 6 meter with the highest value being at 8.15 meters (P24). That location has a big disparity between mean and max value, reaffirming the volatility of the resource. Wave energy content is in most cases slightly $\geq$ 4 kW/m.

TABLE III
DESCRIPTIVE METOCEAN STATISTICS FOR LOCATIONS IN ITALY

Location	H_{m0}	H_{max}	H_{STD}	P_{wave}
		meters		*kW/m*
Catania (P14)	0.37	4.66	0.39	1.02
Cetraro (P15)	0.60	7.49	0.56	2.50
Desil (P16)	1.08	7.65	0.86	6.86
GasilA (P17)	0.95	6.20	0.71	4.95
GasilB (P18)	1.05	6.86	0.78	6.06
Italy1 (P19)	0.84	6.22	0.67	4.10
Italy2 (P20)	0.80	6.54	0.72	4.13
Italy3 (P21)	0.68	4.97	0.51	2.50
Italy4 (P22)	0.81	5.62	0.58	3.26
Italy5 (P23)	0.50	6.51	0.50	1.78
Italy6 (P24)	0.59	8.15	0.57	2.55
Italy7 (P25)	0.62	6.83	0.56	2.24
Mazzaro (P26)	0.93	6.74	0.75	5.12
Palermo (P27)	0.93	6.74	0.75	5.12
Ronmaz (P28)	0.93	6.74	0.75	5.12
Tauro (P29)	0.51	7.74	0.53	1.97
ItalyAl (P52)	0.91	7.19	0.87	6.56

Seldom explored locations in Tunisia and Libya are also examined (see Table IV). H_{max}, especially near the Straits of Messina are above 7 meters, with most locations in Libya showing similar levels of maxima. Mean conditions follow the patterns in Greece and Italy. However, due to positioning, especially for Libya, most swells are dissipated and dispersed with 99^{th} percentiles below 2.7 meters. Wave power is only highest at the Northern Tunisian location (P30) with a mean value of 6.16 kW/m, while at the remainder locations in the regions is $\approx$ 3.35 kW/m.

Spain and France have a diverse resource, in terms of mean H_{m0} across all examined locations the lowest

TABLE IV
DESCRIPTIVE METOCEAN STATISTICS FOR LOCATIONS IN TUNISIA & LIBYA

Location	H_{m0}	H_{max}	H_{STD}	P_{wave}
		meters		*kW/m*
Tunisia1 (P30)	1.04	7.25	0.81	6.16
Tunisia2 (P31)	0.63	4.14	0.42	1.69
Libya1 (P32)	0.87	6.95	0.58	3.94
Libya2 (P33)	0.89	7.34	0.65	4.58
Libya3 (P34)	0.86	5.53	0.49	3.24
Libya4 (P35)	0.86	5.53	0.49	3.24
Libya5 (P36)	0.84	5.32	0.49	3.38

conditions are found in P38-P39 (see Table V). French Mediterranean locations also have lower means well below 0.8 meter. However, variations in the conditions are higher than expected, P45 experiences one of the highest H_{max} of 8.05 meters with a mean of only 1.01 meters, with 99^{th} percentile being at 4.49 meters. Spanish locations have the lowest standard deviation amongst the examined locations; however, the coefficient of variation is similar to Greece and Italy.

Power production has been estimated for every year and for each location, considering the bivariate distributions. All WECs are tested at all locations; however, consistently the following four converters are most preferred: Wavestar, F2HB, Aquabuoy and OceanTech. In Figure 5 the results for both capacity factor and SIWED are displayed for all marine locations in Greece. In terms of CF, Wavestar is the best WEC for all locations, except locations P9-P11 (Table II) in Central Aegean and P13 (Santorini in South Aegean), where OceanTech is better. However, if all the metocean interactions, variability and extremes are considered long term then WaveStar out performs even at location where power performance favours OceanTech, see Figure 5.

Locations at Italy, Tunisia, Libya, Spain and France show similar behaviour in terms of favourable WECs, see Figures 6-9. In Italy (Figure 6) expected power pro-

TABLE V
DESCRIPTIVE METOCEAN STATISTICS FOR LOCATIONS IN SPAIN & FRANCE

Location	H_{m0}	H_{max}	H_{STD}	P_{wave}
		$meters$		kW/m
Alghero (P37)	1.02	7.83	0.97	8.03
Barca1 (P38)	0.50	3.85	0.38	1.27
Barca2 (P39)	0.50	3.77	0.37	1.24
Capder (P40)	0.81	6.16	0.62	3.76
Palamos (P41)	0.63	5.16	0.48	2.09
Spain1 (P42)	0.46	3.60	0.31	0.93
Spain2 (P43)	0.48	5.10	0.39	1.28
Spain3 (P44)	0.86	7.21	0.71	4.50
Spain4 (P45)	1.01	8.05	0.91	7.13
Fr61191 (P46)	0.49	6.08	0.43	1.21
Fr61284 (P47)	0.65	5.50	0.49	1.81
Fr61289 (P48)	0.74	5.25	0.56	2.43
Fr6190 (P49)	0.47	5.57	0.43	1.16
France1 (P520)	0.47	5.63	0.42	1.17
France2 (P51)	0.67	5.77	0.51	1.95

duction is less than Greece with higher mean CF at P18 equal to 16.5%. For most locations WaveStar is more suitable followed by OceanTech, both 6% $\geq$ 16.5%. Lowest CF ($\leq$ 2%) is obtained by a large overtopping device. For Tunisia and Libya (Figure 7) similar CF performance with no deviations in SIWED. Spanish locations have an expected power performance below 20%, while for most locations Wavestar is still the preferred option. In Alghero AWS is the next most suitable WEC; however, if the variation and extremes ratios are factored in then OceanTech becomes again the second most suitable alternative. A similar mismatch is observed at P48 (Figure 9)) where the OceanTech outperforms all devices. Nevertheless, in terms of overall suitability the optimal selection is Wavestar.

IV. DISCUSSION

With wave energy still being an un-tapped resource, it is important to examine critically the potential for power generation to each area separately. High energy conditions at the Atlantic coastlines carry the largest energy potential, this does not, however, preclude the utilisation of wave energy for moderate resources. On the contrary, this should be accompanied by a selection process that will deliver fitted solutions to a different statistical metocean environment.

The coastlines around most of the Mediterranean countries indicate a high degree ($\geq$ 90%) of accessibility, that can be highly beneficial for deployment, maintenance and operation activities. The higher accessibility indicates that in the Basin, most conditions are less than 4 meters, which in turn suggests that the probability of joint distributions will be different than the Atlantic. Therefore, WECs that are developed for highly energetic environments are not suitable.

In Greece Wavestar is most suitable for nearly half of the examined locations, with the other half indicating OceanTech. Using SIWED allows us to assess the long-term expected behaviour of the device, and how it will perform matching resource variability and its relationship to extremes. This in fact changes the distribution and indicates that the resource variability over the long term is more suited for operating the Wavestar device. Figure 4 shows the spatial distribution of CF over the Greek territorial water, for Wavestar, the device that was deemed most relevant through the use of SIWED (see Figure **??**).

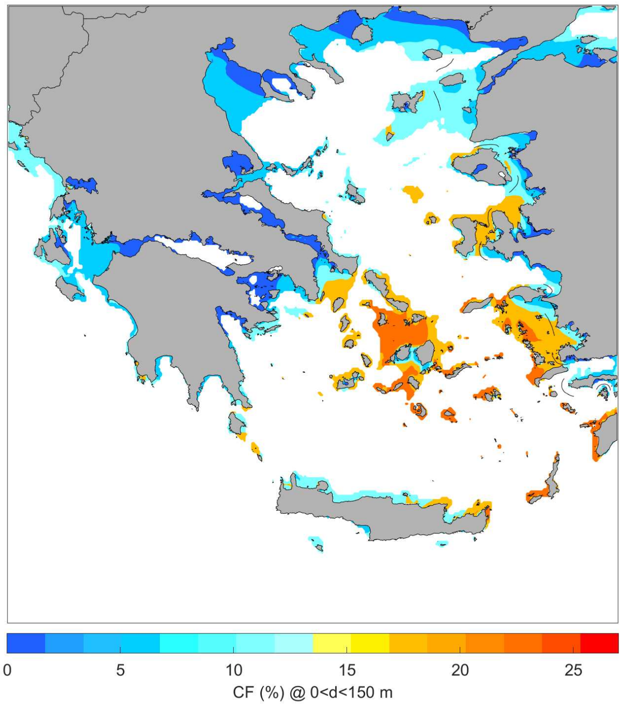

Fig. 4. Spatial CF distribution of most suitable WEC for Greece, considering SIWED selection.

The use of SIWED also showed that a high CF does not mean a good location match. An example of this is the power performance in Alghero (see Figure 8) where the second best WEC is the AWS followed by Aquabuoy. However, when the metocean conditions are taken into account the OceanTech performs better with less variability in expected power production. The importance of FR61284 (see Figure 9), and ItalyAl (see Figure 8) is that the variability expected reduce the effectiveness of most wave energy converters, indicating that alternatives differ per locations.

V. CONCLUSIONS

This study aimed to analyse the suitability of several WECs under different locations in the Mediterranean Sea, with the introduction of a novel index. The Mediterranean Basin is often overlooked when it comes to wave energy, however, the high levels of accessibility beneficial for offshore developments. The overall resource potential is from 3.8-6 kW/m at locations of water depth $\leq$ 150 meters. Wave conditions are described by mean H_{m0} values of less than 1 meter, with dataset H_{max} at 8.15 meters and mean H_{max} of 6.12 meters. Highest waves are encountered at the Balearics and Sardinia, while at Greece the South West and central Aegean region encounter highest waves with values of H_{max} equal to 7.5-7.8 meters. This large variation in wave conditions is also responsible for large variations in deeper locations at the Mediterranean.

The conditions found across all locations favour small scale WECs, often in terms of capacity factors

≥ 12-15% up to 30%. Common characteristics of these WECs are their small rated capacity, and subsequently range of operations. From the comparison, it is evident that the principle of operation should not be the main criterion for selection. In this study three different WECs based on different principles can be considered viable. Findings seem to be in agreement with the suggestion by Falnes that "small is beautiful" [28]. Most favourable devices are ≤ 700 kW and in comparison with larger capacity WEC are described by smaller dimensions. Among the WECs considered in the present investigation a point absorber was the most suitable across most locations, followed by a attenuator. Both of the suggested solutions have a common characteristic; namely they can both be considered as low resource devices. In both cases the maxima nameplate capacity of 600 kW (Wavestar) and 500 kW (OceanTech) are obtained for H_{m0} equal to 3 and 2.5 meters, respectively.

When metocan variations and extremes conditions are factored in even a high CF device is not the optimal. With long-term climate variations considered WaveStar becomes the preferred device, due to its operational matrix more adaptive to the Mediterranean wave climate. Fine balances between resource, WEC and extremes should also be part as main selection criteria, as they affect energy production and costs.

With the suggested approach all potential WEC technologies can be assessed by also taking into account the metocean condition variability, and extreme events, resulting to a more custom "resource-to-production" approach. The interactions between metocean conditions and potential power performance, are the vital components for selecting suitable region. The index can provide a robust approach to determine the optimal WEC for a location/region/area. SIWED provides an "optimal" selection, by considering long-term metocean variations that have negative effects on annual power production, and CapEx.

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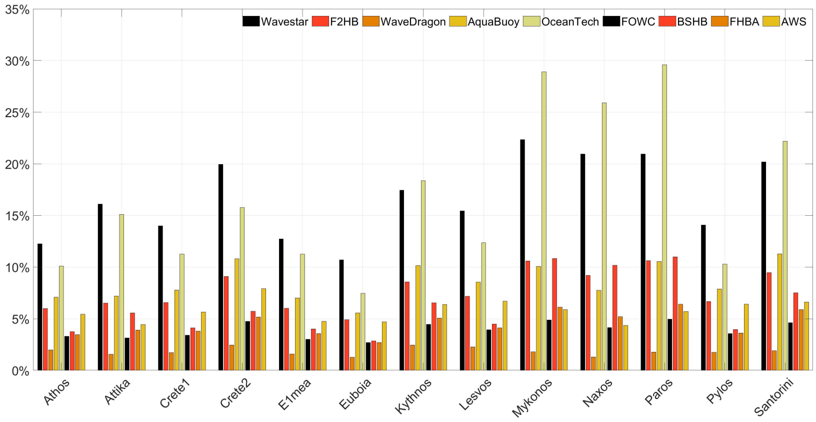
APPENDIX



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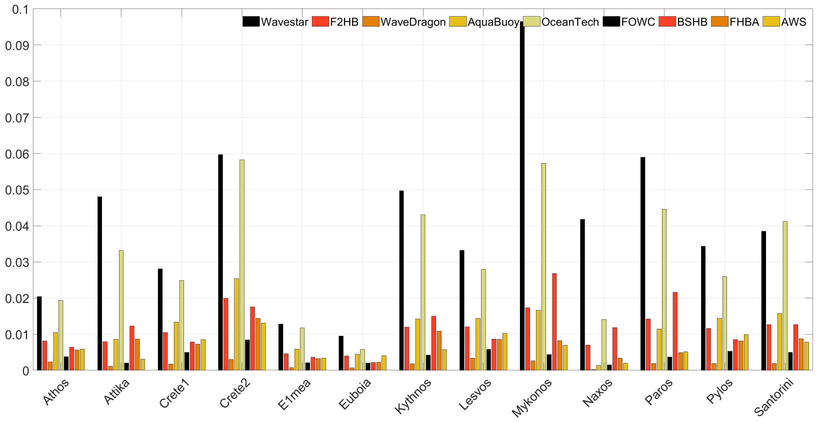
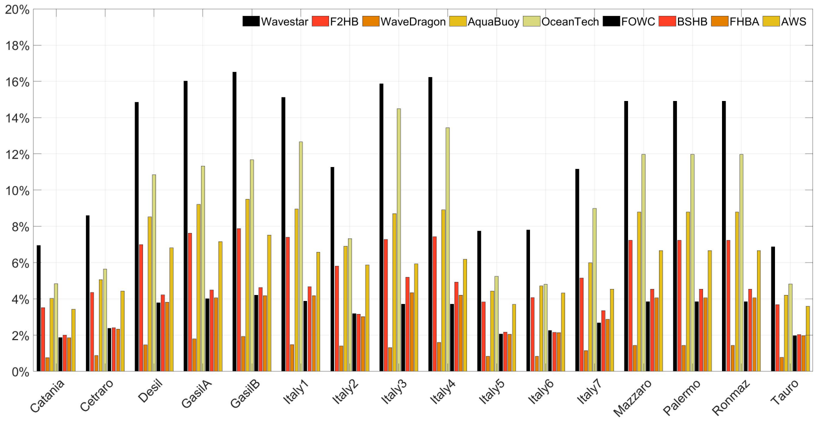


(b) SIWED

Fig. 5. Greece points estimation of for all WECs.



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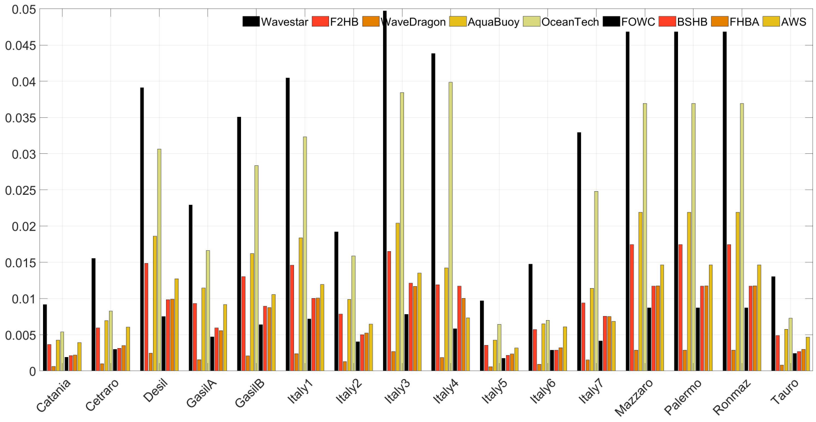

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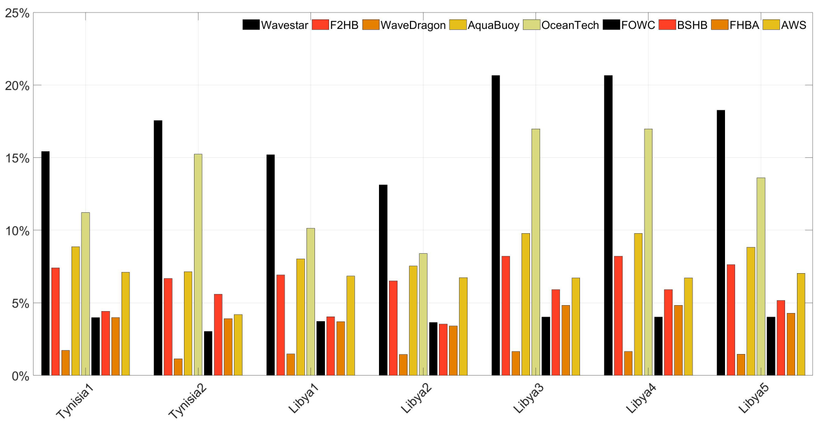
Fig. 6. Italy points estimation of for all WECs.



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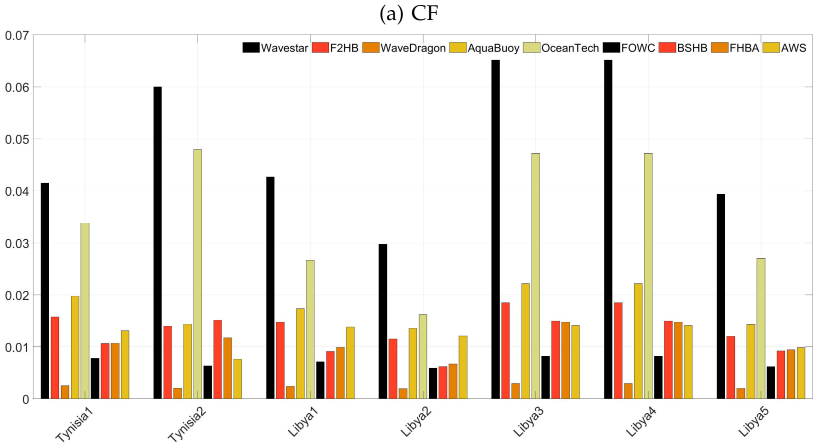
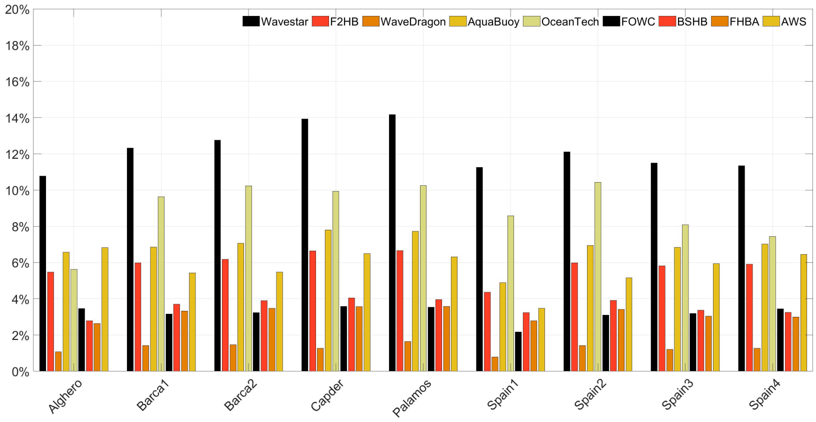


(b) SIWED

Fig. 7. Tunisia and Libya points estimation of for all WECs.



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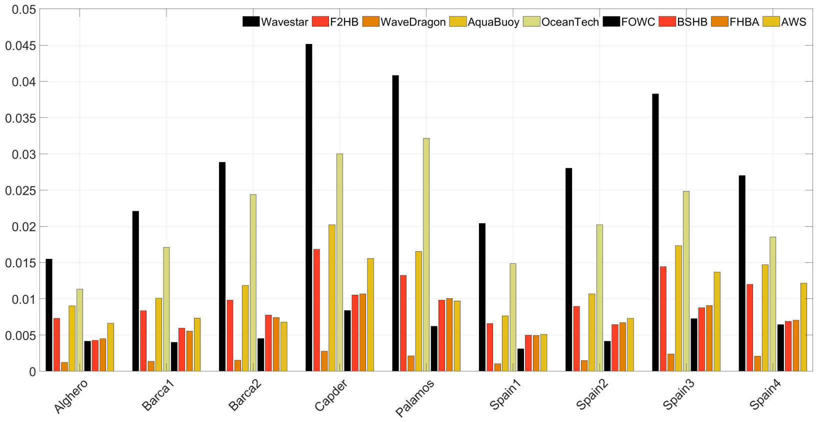
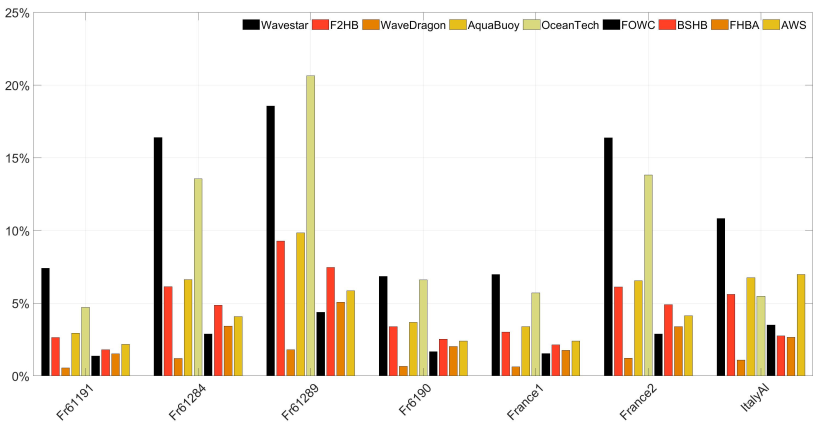


(b) SIWED

Fig. 8. Spain points estimation of for all WECs.



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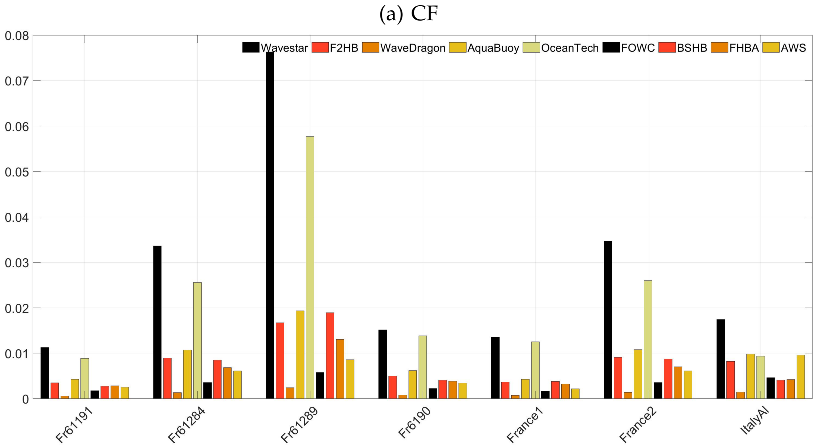

(b) SIWED

Fig. 9. France points estimation of for all WECs.