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Field based estimates of wave power at a nearshore Mediterranean locale for sustainable wave energy harnessing

Spyros Foteinis [a,*], Costas Emmanuel Synolakis [b,c]

[a] Research Centre for Carbon Solutions, School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK
[b] Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA 90089, USA
[c] Research Centre for Natural Disasters, Academy of Athens, 10680 Athens, Greece

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ABSTRACT

Measurements from two Nortek/AWAC acoustic Doppler current profilers deployed for over three years at three sites were used to estimate the nearshore wave energy resource of the Gulf of Chania, in the island of Crete, Greece. Similar to other Mediterranean nearshore locations, low maximum and mean wave power values were observed, i.e., 133 and 2.57 kW/m at ~20 m depth, respectively. Even though the study sites were in close proximity, considerable differences were observed, highlighting the nearshore effects of shoaling, refraction, and focusing on wave power estimates, and the need for long-term measurements. Short-duration storms (lasting a few days) with high wave power potentials were observed. During summer, the sea was much calmer. The nearshore wave power resource was found unsteady, with coefficients of variation well above 2, while the capacity factors of Pelamis and Oyster wave energy converters were 3.65% and 9.57%, respectively. As a result, existing technology is currently commercially unattractive for the Mediterranean nearshore. Marine renewable energy can play an important role in EU's Blue Growth strategy and assist in meeting the 2050 carbon neutrality target. For this reason, research should focus on downscaling and redesigning wave energy technology to enable sustainable deployment in the Mediterranean nearshore.

Introduction

Ocean wave energy is a renewable energy source with vast potential that remains largely unexploited [1]. The global wave energy resource can roughly meet the world's total electricity demand; Gunn and Stock-Williams (2012) estimated the global wave power resource at 2.11 ± 0.05 TW [2], while the International Energy Agency (IEA) has estimated the average global electricity demand at about 2.4 TW [3]. Wave energy arises from the mechanical oscillations of seawater in a frequency range between ~0.05 to 0.2 Hz [4] and is a "by-product" of wind energy [5], which, in turn, is driven by solar energy, and some considered it an indirect form of solar energy [6]. The possibility of exploiting wave energy has attracted scientific interest for quite some time [7], with the earliest registered patent for a wave energy converter (WEC), taken out in France in 1799 [6]. WEC technologies are believed capable of power generation for up to 90% of the time [8], and can have substantial extraction efficiency [5]. In a sense, the ocean is analogous to an exceedingly large windmill [9].

The main disadvantage of wave energy is its variability over multiple time-scales, ranging from individual wave periods to storm durations and seasons [6]. Uncertainty in quantifying the resource over such range of timescales has held back deployment of WEC technologies [10]. Based on reliable wave climate estimates, appropriate device selection, power take-off, and storage technology, wave energy can offer a relatively continuous and predictable power resource, advantageous for electrical grid operation [11]. Clearly, wave climate estimates are important, particularly in low energy seas where wave energy harnessing might not currently appear as economically viable [12].

The Mediterranean is a low energy sea with the annual mean wave power (P_{mean}; wave energy per unit of length) potential ranging 3 – 5 kW/m [13] and annual maximum wave power (P_{max}) of 15.1 kW/m in NW Mediterranean Sea [14]. The Mediterranean wave climate is comparable to those of other low energy seas, such as the Black Sea ($P_{mean} <$ 6 kW/m) [12,15], while relatively energetic areas are located in Greece [13]. Here, the Gulf of Chania, Crete, Greece, is examined, given its apparent potential due to the relative high fetches by Greek standards and proximity to ports and harbours (Fig. 1). Crete is not fully connected to the mainland's electricity grid and does not consistently handle surges in power demand [16]. Moreover, existing wave power estimates for the

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[*] Corresponding author.
E-mail address: S.Foteinis@hw.ac.uk (S. Foteinis).

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Nomenclature

List of abbreviations/acronyms

ADCP	Acoustic Doppler current profiler
AWAC	Acoustic wave and current
BOF	bottom oscillating flap
CF	Capacity factor
COV	Coefficient of variation
EU	European Union
F2HB	Floating two body heave converter
GMT	Generic Mapping Tools
IEA	International Energy Agency
LCOE	Levelised cost of electricity
N	North
NE	Northeast
NW	Northwest
SD	Standard deviation
SWAN	Simulating WAves Nearshore
WEC	Wave energy converter

List of symbols/notations

$\boldsymbol{\theta}$	Direction of propagation of the spectral component $(^{o})$
$\boldsymbol{\mu}$	Mean (kW/m)
$\boldsymbol{\lambda}$	wavelength (m)
$\boldsymbol{\rho}$	Water density (kg/m^3)
$\boldsymbol{\sigma}$	Standard deviation (kW/m)
Cg	group velocity/celerity (m/s)
d	Water depth (m)
f	Frequency (Hz)
g	Acceleration of gravity (m/s^{-2})
$\mathbf{H_{m0}}$	Significant wave height (m)
$\mathbf{M_{dir}}$	Mean wave direction $(^{o})$
P	Wave power (kW)
$\mathbf{P_{max}}$	Maximum wave power (kW)
$\mathbf{P_{mean}}$	Mean wave power (kW)
S	Directional wave spectrum (m^2/Hz)
Te	Energy period (s),
Tp	Peak period (s)

Gulf of Chania, and for the Greek Seas in general, usually refer to offshore sites (deep water), and have been generated using hindcast (wind) data, which can be associated with large errors at nearshore locations [17].

Furthermore, support infrastructure has to be located nearby to limit cabling, transmission, and maintenance costs, implying that wave energy harnessing is likely to take place nearshore. Yet, only a small number of studies have focused on WEC performance at the Mediterranean nearshore. Specifically, Iuppa et al used SWAN (Simulating WAves Nearshore) wave model to estimate the nearshore wave energy potential of the coast of Sicily, Italy. Even though promising sites were identified, profitability was constrained because most WECs are designed for areas with high wave energy potentials [18]. Monteforte et al also used SWAN and identified nearshore wave energy hotspots in west Sicily, which were also beneficial for WEC emplacement due to: i) shorter lengths for underwater transmission cables, ii) possible co-location with other coastal structures such as breakwaters, and iii) possible co-benefits from increased coastal protection [19]. In this regard, Rusu et al also noted that if WECs were to be emplaced in the nearshore of Giglio Island, Italy these could also protect the local beach from incoming waves [20].

Lavidas and Venugopal studied the performance of three nearshore WECs (bottom oscillating flap (BOF), WaveStar, and a floating two body heave converter (F2HB)) in the Greek seas and, in general, low capacity factors (CFs) were identified for all devices, which negatively affected their economic viability [21]. Note that the CF is the ratio of the energy produced by the WEC over a given period to the energy it would have produced if it had operated at the rated capacity during this period [22].

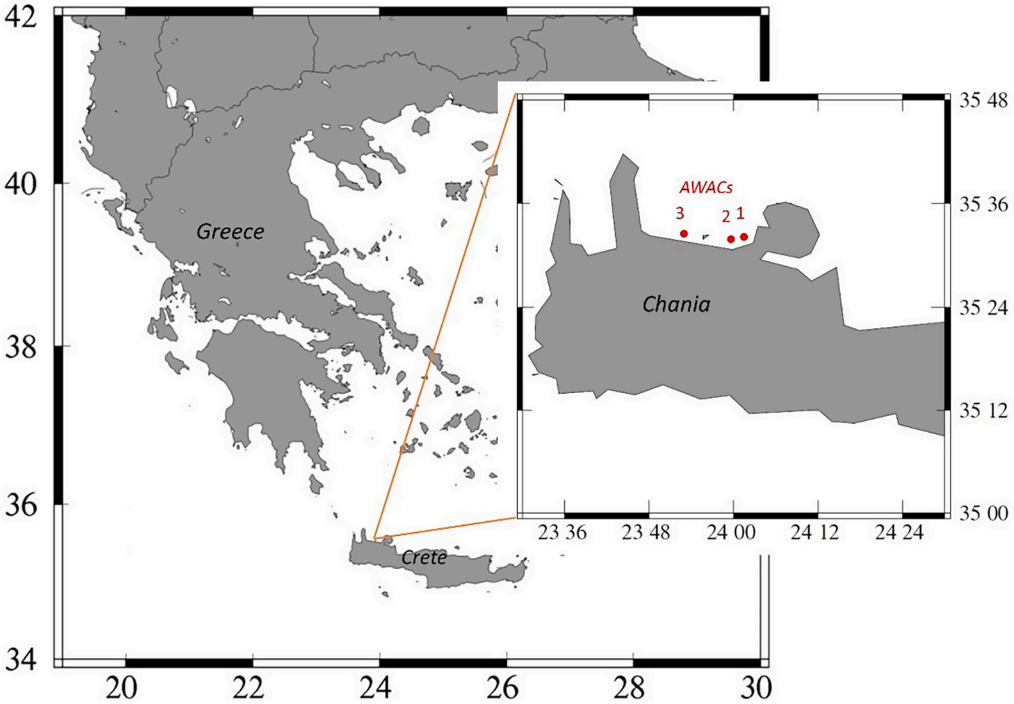

Fig. 1. The study area showing the three data record locations, i.e., (1) Agia Kyriaki; (2) Venetian Harbour; and (3) Gerani. Maps produced using Generic Mapping Tools (GMT) software [32].

Lo Re et al calculated the nearshore wave energy potential in Mazara del Vallo, Sicily to determine the best WEC technology for the local conditions. They found that Oyster 2 better dissipated wave energy while Wave Dragon had the highest efficiency [12]. Furthermore, Majidi Nezhad et al examined different nearshore WECs for installation in Favignana Island, Italy, using hindcast data, and Wave Dragon (500 kW) better fitted the local conditions [23]. Finally, Foteinis noted that nearshore WECs could become commercially attractive in the Mediterranean if properly downscaled [12], but there is a long way to go. To wit, there is only one device that has been deployed and tested in the Mediterranean nearshore [14].

Clearly, studies for the Mediterranean nearshore are required to highlight both: i) nearshore effects on wave energy harnessing, such as such as shoaling and focusing which can significantly alter the distribution of incident power and cannot be effectively captured by wave hindcast estimates from offshore, and ii) examine if existing wave energy technology can sustainably be deployed in mild wave climates in nearshore locales.

This study provides insight on both, since it uses nearshore wave surface field elevation measurements and wave directional spreading, rather than hindcast estimates, to assess the nearshore wave energy resource of a typical Mediterranean nearshore locale. Then, these comprehensive descriptions of the full set of local wave characteristics, which are required in WEC performance assessments [24], were employed to provide information on the performance of existing technology and its sustainability under the specific mild wave regime. For this reason, the CFs, and by extension the performances of two typical WEC technologies that were commercially available, i.e., Pelamis 750 kW and Oyster 315 kW, were estimated under the local wave regime.

Marine renewable energy has great potential to assist in decarbonisation, even in low energy seas [12]. Therefore, the new knowledge, as provided here, can shed light on WEC performance, guide sustainable scaling for the Mediterranean nearshore, be instrumental in promoting sustainable wave energy ventures, and underpin EU’s Blue Growth strategy and 2050 carbon neutrality target.

Study site

The Gulf of Chania is a 25 km-long embayment in NW Crete, Greece. The Gulf is bound from the east by Acrotiri and from the west by Rodopou peninsulas (Fig. 1). The Gulf faces relatively large fetch lengths, by Greek standards, i.e., >250 km to the north, and >300 km to the NE. Chania is the second largest city, after Heraklion, lying in its NE coast. The island of Crete is one of the largest and most visited Mediterranean islands but is unable to sustainably meet its power demand. Marine renewable energy could be an option and the Gulf of Chania is promising since electricity and support infrastructure are already in place and accessibility is high.

Here, the gross wave power potential of three nearshore locations, two at the eastern end (Agia Kyriaki and Venetian Harbour) and one approximately near the center (Gerani) of the Gulf of Chania (Fig. 1), were examined. These locations were chosen primarily for research purposes regarding the contribution of infragravity waves and resonance in the local harbour, known as the Venetian Harbour, during storm conditions [25,26], but also for helping site a future marina [27]. Specifically, in each of the three locations there is a local harbour nearby i.e., Agia Kyriaki deployment location is off the homonymous fishing harbour, Gerani is near Platanias Harbour, while the Venetian Harbour deployment is off the homonymous harbour (Fig. 1, inset). Even though, these deployment locations are nearby, anecdotal evidence from eyewitnesses suggested that during winter storms each harbour performs differently, implying that nearshore effects have a large impact on incoming waves.

The existence of the harbours themselves has also altered the local bathymetry, further affecting the characteristics of incoming waves, while an offshore breakwater installed three decades ago off the Venetian Harbour offers little protection [28]. Further, the sandy beach at the lee of the Gerani deployment location is also actively eroding [17]. Therefore, the existence of the harbours and the need for coastal protection provide additional cost-sharing opportunities for future wave energy harnessing through harbour integration and coastal protection [29].

Finally, the locations were also convenient for the deployment and recovery of the two sea-floor mounted, acoustic Doppler current profilers (ADCPs), made by Nortek As and referred to as AWACs. They recorded the water particle velocities, surface elevations, directions, and spectra. These field measurements were then used to estimate the nearshore wave power potential of the Gulf of Chania. Specifically, the AWACs were variously deployed in these three locations for over three years, i.e., end of 2010 to beginning 2014, and captured the local wave characteristics for this reference period. These measurements also reflect the current situation and provide a snapshot of the wave power potential for the Gulf of Chania. Even though global warming has already affected the global wave power resource, in the Mediterranean Sea the effect appears to be more subtle compared to the oceans [30], with existing projections suggesting that by the end of the century the mean annual wave energy flux in most of the Mediterranean Sea, including our case study, could even decrease between 10 and 20% [31].

Materials and methods

Wave measurements and AWAC deployment locations

Two bottom-mounted upward-facing 600 kHz Nortek AWAC sensors were deployed in the Gulf of Chania for over a three-year period taking bursts of 1024 samples at 1 Hz. The AWAC combines a directional wave gauge with ADCP and encompasses a vertically-oriented transducer which echo-ranges the water surface. Directional wave measurements were obtained by logging time series of pressure, near-surface velocity components, and free surface elevation [33].

The AWACs were rotated among the three sites (Fig. 1). One AWAC was deployed about 1 km offshore of Agia Kyriaki harbour at ∼20 m mean depth, from 15 December 2010 to 10 March 2012. This same AWAC was then deployed offshore of Gerani at ∼20 m mean depth, from 26 October 2012 to 3 April 2014. The second AWAC was deployed around 500 m N off the Venetian Harbour at ∼24.5 m mean depth from 6 October 2011 to 22 January 2013.

Nearshore wave power potential estimation

The wave energy resource in the Gulf of Chania was evaluated in terms of the available wave power, i.e., energy flux per unit of wave crest length (P, in kW/m), and it can be obtained from the spectral output of the wave propagation model [34] through:

$$P = \rho g \int_0^{2\pi} \int_0^{\infty} S(f,\theta) C_g(f,d) df d\theta \tag{1}$$

where ρ is the water density, g is the acceleration of gravity, $S(f,\theta)$ is the directional wave spectrum, f is the frequency, θ is the direction of propagation of the spectral component, C_g is the group velocity or celerity and d is the water depth. Equation (1) can be approximated [34,35] by:

$$P \approx \frac{1}{16} \rho g C_g H_{m0}^2 \tag{2}$$

where H_{m0} is the significant wave height determined from measurements, and Cg is calculated from:

$$C_g = \left[1 + \frac{4\pi d}{\lambda \sinh\left(\frac{4\pi d}{\lambda}\right)}\right] \frac{gT_e}{4\pi} \tanh\left[\frac{2\pi d}{\lambda}\right] \tag{3}$$

where T_e *is* the energy period, and λ is the wavelength:

$$\lambda = \frac{gT_e^2}{2\pi} \tanh \frac{2\pi d}{\lambda} \tag{4}$$

Nortek's *Storm* software was used to process AWAC's wave measurements and determine the H_{m0} and the peak period (T_p) (Fig. 2). Then, T_e was estimated by assuming that $T_e = 0.9T_p$ [35–38], corresponding to a standard JONSWAP spectrum with a peak enhancement factor $\gamma = 3.3$ [39]. For a Pierson-Moskowitz spectrum a lower coefficient (0.86 instead of 0.9 [40]) is used. However, the short fetch lengths in the Mediterranean basin do not allow for the fully developed sea states considered in the Pierson-Moskowitz spectrum. Therefore, the 0.9 coefficient better fits the limited fetch lengths in the Mediterranean Sea [41].

Then, the monthly, seasonal, and annual P_{mean} and P_{max} of each location were estimated. Finally, the coefficient of variation (COV) was also used to estimate the variability of wave energy in the Gulf of Chania. COV is a common index for assessing temporal variability and for the case of wave power the temporal variability of the series *P(t)* can estimated by taking the ratio of the standard deviation (SD) to the mean (μ) [36]:

$$COV = \frac{SD(P(t))}{\mu(P(t))} \tag{5}$$

Results and discussion

Nearshore wave power estimates for the Gulf of Chania

Wave power potential at Agia Kyriaki

Available data for Agia Kyriaki span from 15 December 2010 to 10 March 2012. About 0.22% of data is missing, corresponding to when the AWAC battery was occasionally replaced. During autumn (September to November) 2011, the maximum wave power (P_{max}) was 65.75 kW/m and P_{mean} 3.26 kW/m. The mean wave direction (M_{dir}) was NNW-N, with ~40 % of wave power concentrated within the 335° – 345° sector (where $P_{mean} = 4.7$ kW/m), and ~35% concentrated within the 345° – 355° sector (where $P_{mean} = 2.6$ kW/m).

In winter 2010–2011 (December to February) $P_{max} = 50.72$ kW/m, $P_{mean} = 2.89$ kW/m, with the predominant direction NNW-N and ~30 % of wave power in the 335° – 345° sector ($P_{mean} = 4.8$ kW/m) and ~20% in the 345° – 355° sector ($P_{mean} = 3.8$ kW/m). Winter 2011–2012 was significantly more energetic, with P_{max} and P_{mean} estimated at 132.69 kW/m and 4.15 kW/m, respectively. Again, the main wave direction was NNW-N, with ~31 % of wave power in the 335° – 345° sector ($P_{mean} = 9.4$ kW/m) and ~20% in the 345° – 355° sector ($P_{mean} = 5.9$ kW/m). In spring 2011 (March to May), the power estimates were again high, with $P_{max} = 106.30$ kW/m and $P_{mean} = 3.22$ kW/m; wave power was concentrated within the 335° – 345° (~30 %) and 345° – 355° (~26 %) sectors, having P_{mean} values of 6.3 kW/m and 3.5 kW/m, respectively. For summer 2011, $P_{max} = 8.65$ kW/m and $P_{mean} = 0.90$ kW/m, with ~31% of wave power located in the 345° – 355° sector (1.62 kW/m). The remaining power estimates were low (<1 kW/m) and in the NNW direction.

Fig. 3a shows the annual wave power rose diagram for 2011 at Agia Kyriaki, divided into 36 sections. The area of each petal is proportional to the percentage of wave power of the corresponding directional sector. Wave power intensity is indicated by colour, blue represents calm conditions and azure represents storm waves. $P_{max} = 106.30$ kW/m and $P_{mean} = 2.57$ kW/m. M_{dir} predominates in the NNW sector, with ~29 %

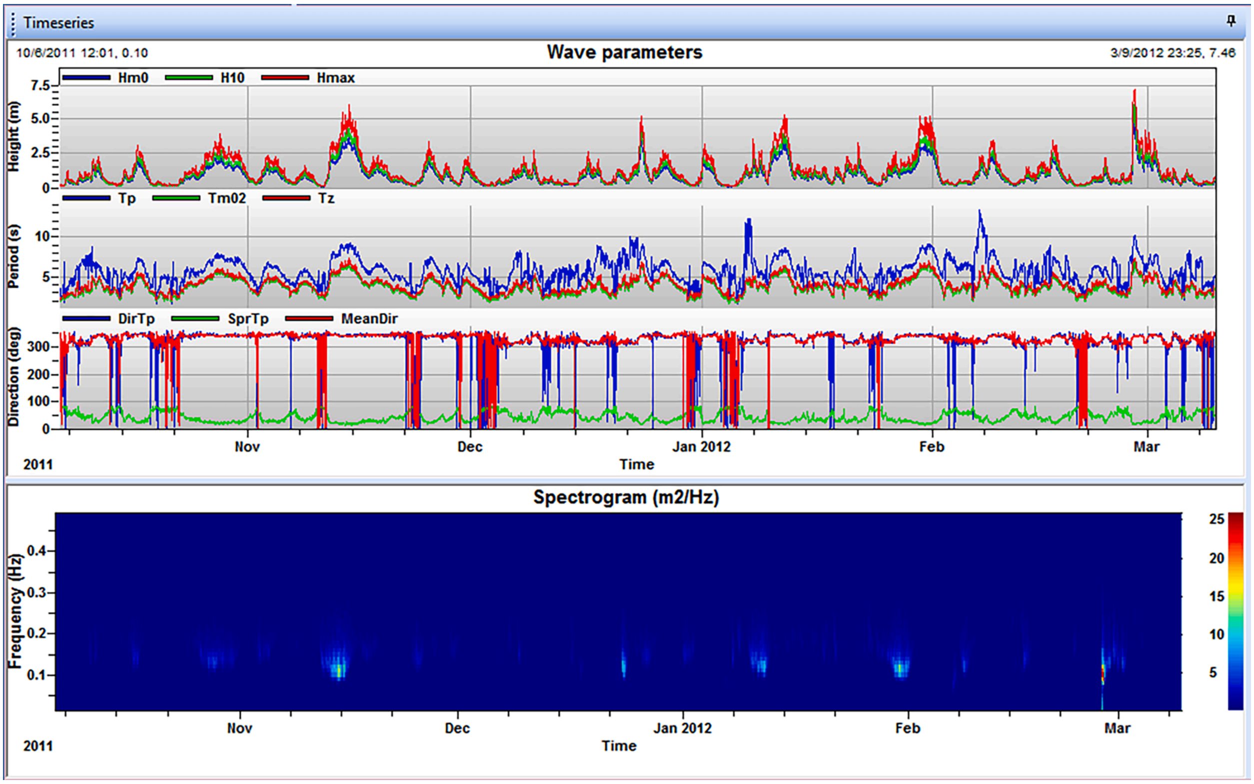

Fig. 2. Processed AWAC measurements using Nortek *Storm* software for Agia Kyriaki from 6 October 2011 to 10 March 2012.

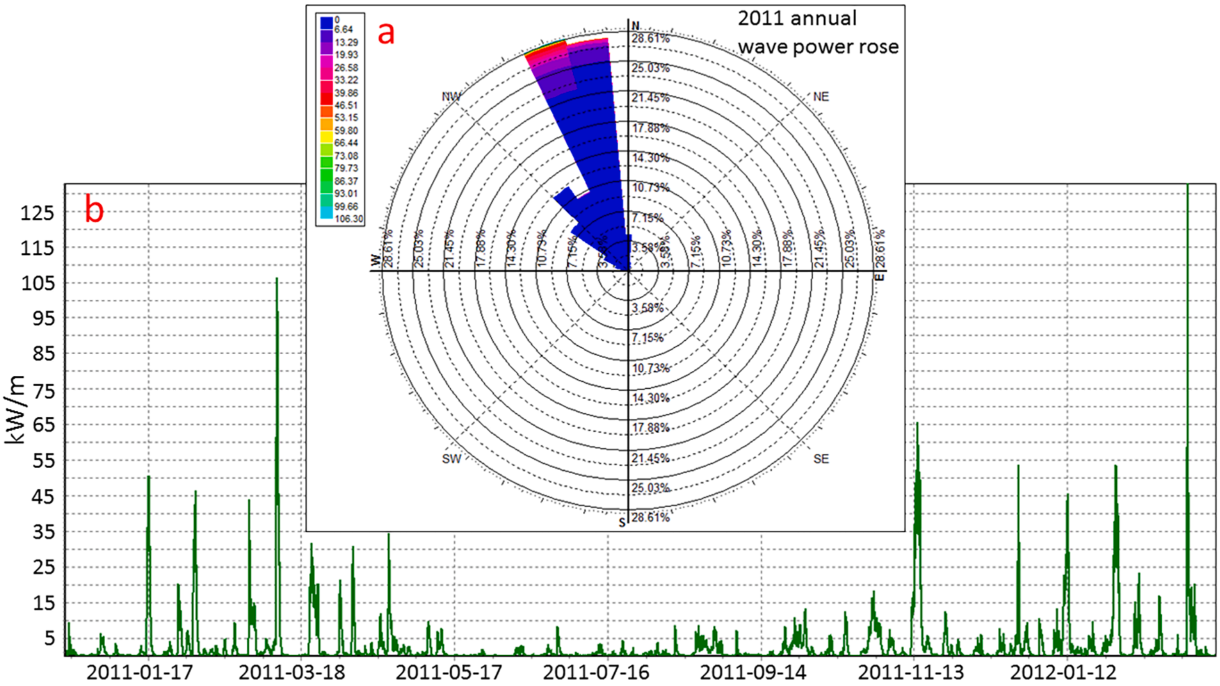

Fig. 3. Wave power estimates at Agia Kyriaki, Gulf of Chania, Crete (mean water depth ~20 m): a) annual wave power (kW/m) rose obtained for 2011, missing data ~0.27%; b) gross wave power potential (kW/m) time history from 15 December 2010 to 10 March 2012 (missing data ~0.22%).

of energy in the 335° − 345° sector ($P_{mean} = 5.5$ kW/m) and ~28% in the 345° − 355° sector ($P_{\text{mean}} = 2.7$ kW/m). The remaining wave power estimates are predominantly in the NW direction but are low (<1 kW/m).

Fig. 3b shows the gross wave power potential at Agia Kyriaki over the entire reference period. The estimated $P_{\max}$ was ~133 kW/m and occurred during a storm on 28 February 2012. It should be noted that during severe storms, when wave breaking result to many bubbles in water thus impeding acoustic signal, the AWAC pressure sensor provides parallel, albeit less accurate, wave measurements [42]. The second highest wave power value was ~106 kW/m and was obtained on 8 March 2011. Seven more storms with $P_{\max} > 40$ kW/m were recorded

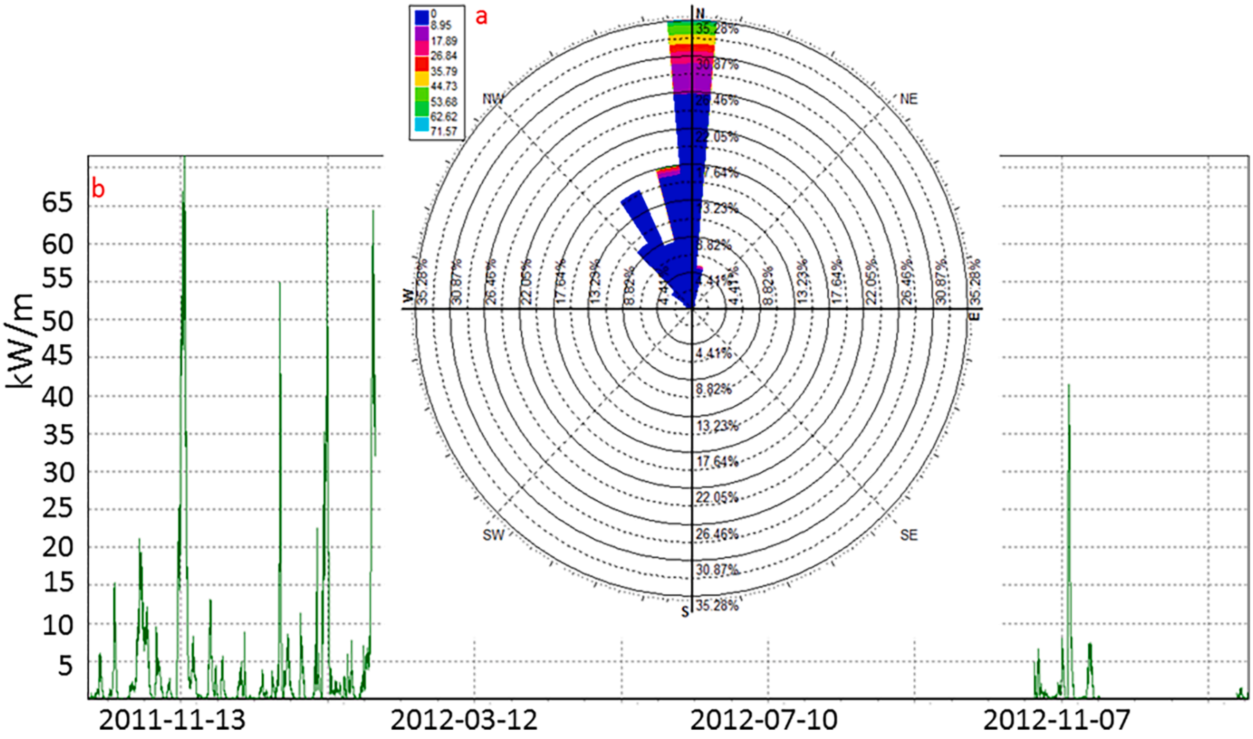

Fig. 4. Wave power estimates at Venetian Harbour, Gulf of Chania, Crete, from 6 October 2011 to 31 January 2012 and from 26 October 2012 to 22 January 2013 (mean water depth ~24.5 m): a) annual wave power (kW/m) rose; and b) gross wave power potential (kW/m) time history.

(Fig. 3b). The overall pattern is one of short-duration storms (lasting no more than a few days) with high wave power potentials, followed by low energy seas in the intervening periods between storm events. During the summer, the sea is much calmer ($P_{mean} = 0.90$ kW/m and $P_{max} = 8.65$ kW/m) (Fig. 3).

Wave power potential off the Venetian Harbour

Off the Venetian Harbour the AWAC was deployed from 6 October 2011 to 22 January 2013, in ~24.5 m depth. Due to a failure of the underwater battery canister, the AWAC did not record any data between 31 January 2012 and 26 October 2012. Hence, no seasonal or annual analyses were possible.

Fig. 4a shows Venetian Harbour's wave power rose, with $P_{max} =$ 71.57 kW/m and $P_{mean} = 4.22$ kW/m. The prevailing M_{dir} is N, with ~35 % of wave power within the 355° – 5° sector ($P_{mean} = 8.98$ kW/m) and ~18% in the 345° – 355° sector ($P_{mean} = 3.25$ kW/m). Moreover, ~5% of wave power was in the 5° – 15° sector ($P_{mean} = 2.87$ kW/m) and ~10 % in the 315° – 325° sector ($P_{mean} = 1.16$ kW/m). For waves predominantly from the NW, P_{mean} is lower than 1 kW/m.

Fig. 4b shows the time history of gross wave power potential at the Venetian Harbour. From October to January 2011 five storms were recorded with P_{max}>50 kW/m, with the peak value at 71.57 kW/m. Although data are rather limited for 2012, a storm with $P_{max} > 35$ kW/m was recorded (Fig. 4b). The existing data from 2011 and 2012, i.e., 1,234 hourly measurements in total, yield $P_{mean} = 5.07$ kW/m. For December and January, 744 and 851 hourly measurements were available, yielding P_{mean} values of 2.04 kW/m and 6.04 kW/m, respectively.

As in Agia Kyriaki, December is the least energetic winter month. Due to their proximity, both sites exhibit similar wave power potentials. Off the Venetian Harbour, M_{dir} was N, while in Agia Kyriaki M_{dir} predominates in the NNW sector. It is likely that the more energetic waves may have shoaled and refracted to the NW at Agia Kyriaki.

Wave power potential at Gerani

Measurements for Gerani exist for the period 26 October 2012 to 3 April 2014, hence the annual wave power potential can be approximated for 2013. In autumn 2012, $P_{max} = 61.87$ kW/m, $P_{mean} = 2.54$ kW/m, while M_{dir} had a north orientation, with 26% of wave power in the 355° – 5° ($P_{mean} = 4.95$ kW/m) and 34% in the 5° – 15° ($P_{mean} = 4.05$ kW/m) sector. In autumn 2013, $P_{max} = 23.58$ kW/m and $P_{mean} = 1.23$ kW/m; the main wave direction was NNE, with 26% of power between 15° – 25° ($P_{mean} = 2.19$ kW/m) and 22 % between 25° – 35° ($P_{mean} =$ 1.39 kW/m) sector. In autumn 2014, $P_{max} = 30.22$ kW/m, $P_{mean} = 1.91$ kW/m, and M_{dir} had a N direction, with 30% being in the 355° – 5° ($P_{mean} = 4.16$ kW/m) and 14% in the 345° – 355° ($P_{mean} = 2.36$ kW/m) sector. In winter 2013, P_{max} and P_{mean} were estimated at 63.78 kW/m and 2.21 kW/m respectively, with the main direction being N (25 % in the 355° – 5° sector, with $P_{mean} = 3.94$ kW/m; and 22 % in the $5^{o} - 15°$ sector with $P_{mean} = 2.95$ kW/m). In spring 2013, P_{max} and P_{mean} were 35.82 kW/m and 1.49 kW/m respectively, M_{dir} was primarily at NNE (26 % in the 5° – 15° sector with $P_{mean} = 3.57$ kW/m and 20% in the 15° – 25° sector with $P_{mean} = 0.47$ kW/m). Finally, in summer 2013, $P_{max} =$ 18.08 kW/m, $P_{mean} = 1.10$ kW/m, and M_{dir} had a NNE direction, with 38 % of wave power in the 15° – 25° ($P_{mean} = 1.67$ kW/m) and 30% in the 25° – 35° ($P_{mean} = 1.41$ kW/m) sector.

Fig. 5a shows the annual (2013) wave power rose for Gerani, with $P_{max} = 63.02$ kW/m and $P_{mean} = 1.50$ kW/m. The wave power was concentrated at N-NNE, with about 14% in the 355° – 5° sector ($P_{mean} = 2.20$ kW/m) and about 24% in the 5° – 15° sector ($P_{mean} = 2.27$ kW/m). Moreover, about 24% of wave power was associated with the 15° – 25° sector, having $P_{mean} = 1.38$ kW/m.

Fig. 5b shows the time series of gross wave power potential at Gerani. Three storms had $P_{max} > 60$ kW/m, two more $P_{max} > 30$ kW/m, and the remaining ones had P_{max} between 10 and 30 kW/m. As in Agia Kyriaki, high wave power storms were observed during autumn, winter, and (a few) in spring, each lasting no more than a several days; the remaining data indicate low wave power potentials. Compared to Agia Kyriaki, the storms in Gerani had significantly lower values of P_{max}, leading to a lower annual P_{mean}, i.e., 1.50 kW/m for 2013 in Agia Kyriaki compared to 2.57 kW/m for 2011 in Agia Kyriaki. This likely suggests high wave power inter-annual variability Moreover, M_{dir} at Gerani was N-NNE, whereas that at Agia Kyriaki was NNW.

Table 1 summarises the estimates of wave power at Agia Kyriaki and Gerani, expressed as hourly mean values. For Agia Kyriaki (15 December 2010 to 10 March 2012) more data (higher data count) were obtained during winter and spring months. SD is quite large for most of the year,

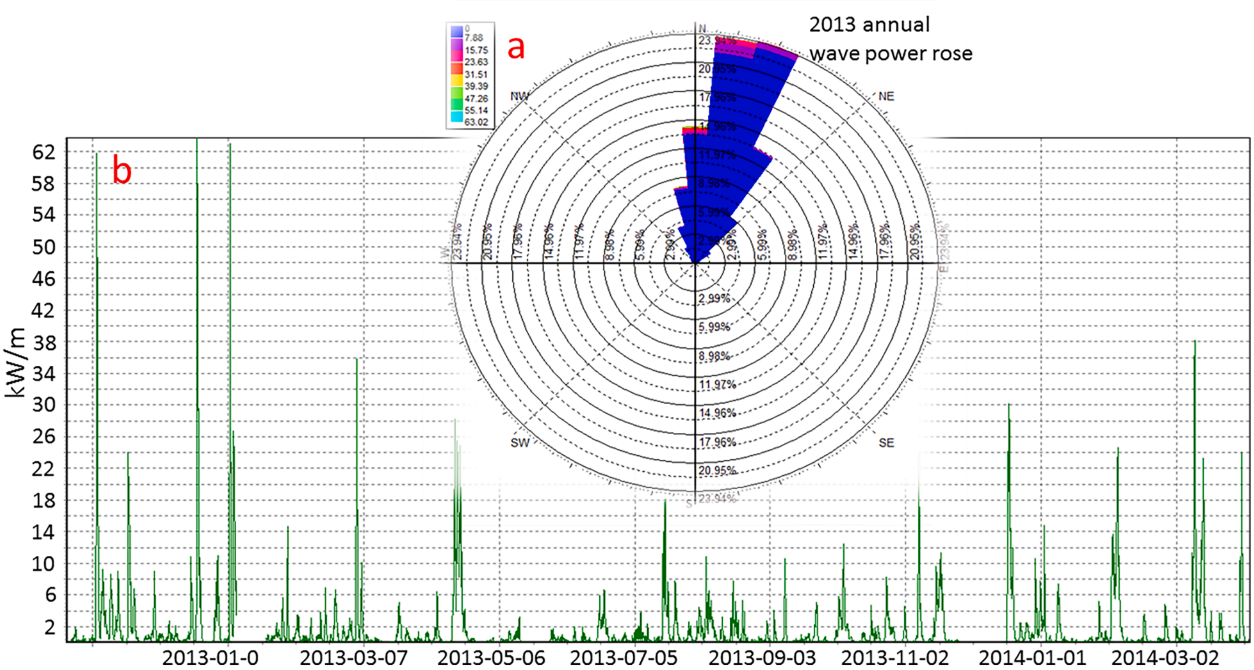

Fig. 5. Wave power estimates at Gerani, Gulf of Chania, Crete, from 26 October 2012 to 3 April 2014 (mean water depth ~20 m, missing data ~9.74%): a) annual wave power (kW/m) rose; and b) gross wave power potential (kW/m) time history.

Table 1
Wave power data (hourly mean values) for Agia Kyriaki and Gerani, Gulf of Chania, Crete.

	September	October	November	December	January	February	March	April	May	June	July	August	All
Agia Kyriaki (12/2010 – 03/2012)													
Data count	720	720	720	1 138	1 488	1 368	964	720	744	720	744	744	10,790
P_{mean} (kW/m)	1.41	2.86	5.52	1.70	4.32	4.33	4.72	3.34	0.85	0.60	0.54	1.56	2.87
SD	2.03	3.82	11.16	4.28	8.76	10.51	12.80	5.58	1.66	1.07	0.64	1.78	7.48
COV	1.44	1.34	2.02	2.52	2.03	2.43	2.71	1.67	1.95	1.78	1.19	1.14	2.61
Gerani (10/2012 – 04/2014)													
Data count	719	873	1297	744	430	672	649	720	446	720	744	744	8 758
P_{mean} (kW/m)	0.65	1.11	2.74	2.56	3.36	1.07	1.31	2.3	0.43	0.69	1.31	1.29	1.62
SD	1.28	1.71	6.2	7.81	7.62	1.62	3.58	5.06	0.47	1.1	2.43	1.65	4.36
COV	1.97	1.54	2.26	3.05	2.27	1.51	2.73	2.20	1.09	1.59	1.85	1.28	2.69

except June and July when no major storm occurred. Moreover, the large COV(P) values suggest unsteady wave power. In terms of P_{mean}, November was the most energetic month at Agia Kyriaki, with energetic seas also observed from January to April. For Genari (26 October 2012 to 3 April 2014) the data count is higher only in November, while SD is, in general, lower but the COV(P) values are fairly similar to the ones of Agia Kyriaki. Finally, results also suggest high wave power intra-annual (seasonal) variability.

Wave power assessment for the Gulf of Chania

Spatio-temporal differences occur in the gross wave power (Fig. 6) and its direction at the three locations of interest in the Gulf of Chania, even though the sites are all in close proximity. M_{dir} is NNW (Agia Kyriaki) to N (Venetian Harbour) at the eastern end of the embayment, and NNE (Gerani) near the center of the gulf. M_{dir} is affected by the Acrotiri and Rodopou peninsulas, which shield the east and west ends of the gulf.

Seasonal and annual P_{mean} values also vary, even between locations in close proximity. Differences can be attributed to the shielding of Venetian Harbour by the Rodopou peninsula from NW waves and to the local bathymetry at Agia Kyriaki, which might promote wave refraction. Moreover, Fig. 6 shows that gross wave power at these locations also differs substantially even when AWAC measurements are available at both locations. For Agia Kyriaki and the Venetian Harbour, four storms with $P_{\text{max}} > 35$ kW/m, another one with $P_{\text{max}} > 15$ kW/m and several other events with $P_{\text{max}} > 10$ kW/m all coincided. For the low energy seas and for a storm with $P_{\text{max}} < 15$ kW/m, the results from both deployment locations were in good agreement. Nevertheless, during the four higher-energy storms P_{max} was usually lower at Agia Kyriaki than Venetian Harbour. For example, during the most energetic storm, P_{max} was ~30% lower at Agia Kyriaki than at Venetian Harbour (Fig. 6). The lower values at Agia Kyriaki can be partly attributed to wave shielding, the slightly greater deployment depth at Venetian Harbour, and differences in the local seabed topography. It should be noted that the estimated P_{mean} values at Agia Kyriaki and Venetian Harbour were in good agreement for the four storms.

Wave data for the single storm recorded simultaneously at Venetian Harbour and Gerani provide estimates of P_{max} about 32% lower in the latter location, about 11 km east of Venetian Harbour (Fig. 6). The difference can be attributed to spatio-temporal variations of the original storm-induced waves, wave shielding, and possibly local bathymetric effects. The annual (2011, 2013) estimates of P_{mean} and P_{max} at Agia Kyriaki and Gerani, where ample data were available, differ significantly and cannot be solely attributed to local bathymetric effects. These differences, which cannot be accurately captured by hindcast estimates for the offshore, highlight the need for long-term measurement campaigns to justify sustainable wave energy harnessing.

Furthermore, the P_{max} for the Gulf of Chania reached 133 kW/m and this is similar to the P_{max} value (133 kW/m) reported in a nearshore area (15 m depth) in west Sicily [19]. The P_{mean} values are also similar to the ones reported for nearshore (15 m depth) northern (0.85 to 2.61 kW/m) and central (0.29 to 2.61 kW/m) Tuscany, but significantly lower from nearshore (15 m depth) Sardinia (3.09 to 10.18 kW/m) [43]. Therefore, the observed P_{mean} and P_{max} values can be considered typical for relatively sheltered areas of the Mediterranean Sea.

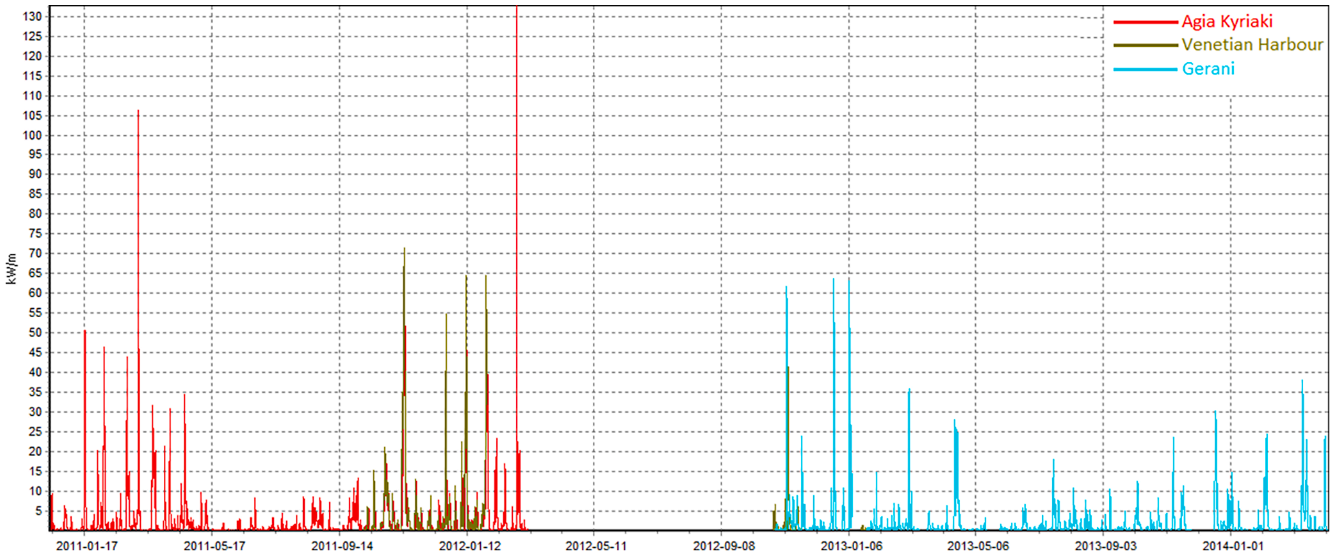

Fig. 6. Time histories of gross wave power potential (kW/m) at Agia Kyriaki, Venetian Harbour, and Gerani, in the Gulf of Chania from 15 December 2010 to 3 April 2014. The deployment depth ranges from around 20 to 24.5 m.

Moreover, the large COV(P) values observed across locations indicate a relative unsteady wave power resource. A strong intra-annual (seasonal) variability of the wave power was observed, also reported in the Black Sea [44]. However, some future projections for the end the century, suggest that in central Mediterranean P_{mean} could decrease up to 30% during fall and winter but only 5% during spring and summer [31]. In such scenarios, wave energy's temporal variability in the Gulf of Chania area may decrease, which will be beneficial for future wave energy harnessing projects, but the total wave energy resource could also decrease.

Downscaling of existing wave energy technology and accounting for the unsteady conditions

Wave power presently has a much higher levelised cost of electricity (LCOE) than other renewable energy sources, such as wind and solar power [29]. Given the calmer conditions that prevail in the Mediterranean Sea compared to the north Atlantic, it is hardly surprising that the estimates of P_{mean} for the Gulf of Chania are significantly lower than those along the coast of Western Europe, where P_{mean} averages close to 40 kW/m [5]. For example, P_{mean} values of 30 – 50 kW/m during winter months and $<$ 10 kW/m during summer months have been predicted using the SWAN wave model for sites to the north and west of Orkney, Scotland, where WECs have been deployed [45]. As a result, existing technology has been developed for more energetic wave climates [30].

Fig. 7 shows the annual wave power matrix for Agia Kyriaki, where different intervals of wave height and period combinations (energy bins) are shown, along with the estimated wave power resource (colour gradient). This was used to estimate the CFs of two typical devices, i.e., Oyster and Pelamis. Specifically, the Oyster is a flap type oscillator WEC that had mainly been proposed for shallow waters (10 to 15 m depth) [23] and has been found promising for nearshore areas (e.g., in Oman Sea) [19]. Pelamis is an attenuator type WEC [20] that had been designed for deep waters [31], but it has also been redesigned (downscaled) for lower energy seas such as Xiamen Bay, China [43] and has also been assessed in Portuguese continental nearshore [46] and the NW Iberian Peninsula [47]. Using the occurrence of the corresponding energy bin, the performance of Pelamis (750 kW, attenuator type) and Oyster (315 kW, flap type oscillator) WEC technologies were analysed [22].

According to the measurements, the Pelamis and the Oyster WEC will be idle 69.28 % and 55.12 % of the time, respectively. Furthermore, when the local wave regime is able to drive these WECs, they will both operate well below their potential, producing only a small amount of electricity. Specifically, when using the data for 2011 in Agia Kyriaki, Pelamis would operate for ~2,691 h, producing ~240 MWh and yielding a CF = 3.65%, and would not even have reached its rated power output (750 kW) under the local wave regime. As far as the Oyster WEC technology is concerned, under the local wave climate it would operate for ~3,931 h in 2011, producing ~264 MWh and yielding a CF 9.57%. The results are in line with the literature, where reported CF for Oyster ranged from 3.44 to 19.58% and for Pelamis from 0.87 to 16% under the Mediterranean wave regime [30]. The better performance of the lower rated power output WEC (Oyster) that was observed in the Gulf of Chania was expected, since the annual wave power matrix of Agia Kyriaki (Fig. 7) mainly comprises low energy bins (combinations of low wave periods and heights). The very low CFs of the typical WEC technologies examined herein further imply that relative to other renewables the LCOE of wave energy harnessing in the Mediterranean nearshore is very high.

Furthermore, the COV(P) values (2.61 in Agia Kyriaki and 2.69 in Genari, Table 1) indicate a relative unsteady wave power resource. In the southern coasts of Chile, South Africa, Tasmania, and New Zealand near-coast COV(P) values range between 0.85 and 0.9, suggestive of only moderately unsteady resources; while indicative values for the Northern hemisphere are in Ireland (~1.5); Portugal (~1.4); Iceland (1.4–1.6); Norway (1.5–1.6); Newfoundland (1.2–1.4); Vancouver Island (~1.3); Oregon (~1.2); Aleutian Islands (~1.4); and Kamchatka (~1.5) [36]. The Gulf of Chania COV(P) values are well above those of near-coast areas in oceans. This can be explained by the interplay between maritime and continental air masses, leading to tropical-like cyclones in the Mediterranean (known as Medicanes) and the complex topography of the enclosing land masses, which can create katabatic winds (known as fall winds since they flow downhill and are often referred to as meltemia in Greece) that, in turn, lead to higher waves [46].

Therefore, it is inferred that, given the low P_{mean}, the high COV(P) values, and the current state and economic cost of WEC technology, wave power generation from the Gulf of Chania is currently economically unattractive. In Mediterranean, wave heights are generally smaller and wave periods shorter than along open oceanic coasts, and this is also reflected in the results of this study. In this regard, Hutcheson et al also concluded that Pelamis emplaced in the Ionian Sea, Greece would also be unprofitable [48].

Overall, results suggest the need to downscale existing wave energy technology to fit mild and variable local wave, and in general, the mild Mediterranean wave regime, as has also been suggested by Bozzi et al [49]. This is also the case for other low energy seas such as the Black Sea

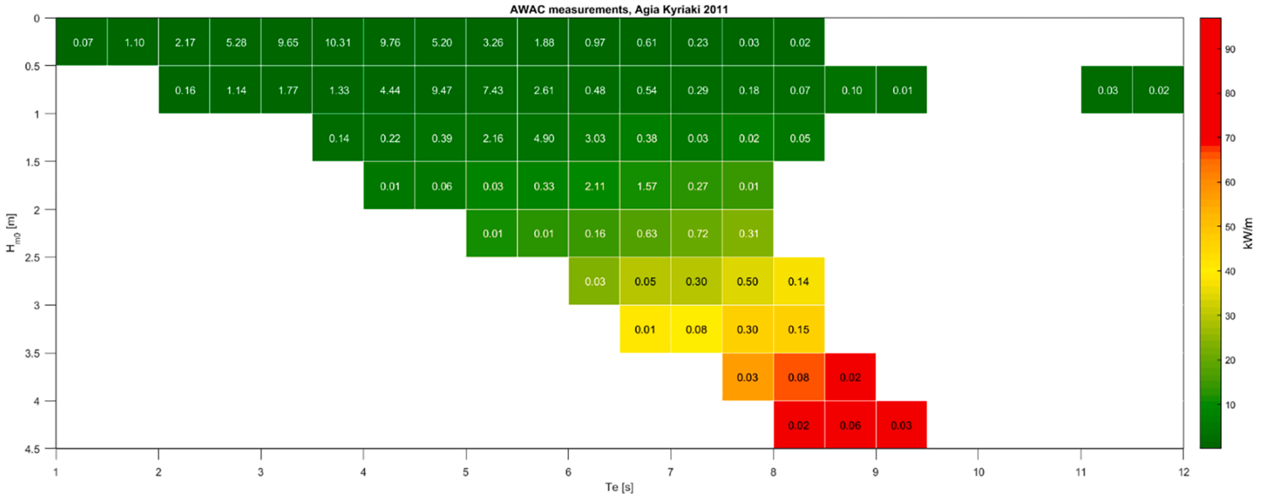

Fig. 7. Wave power matrix in Agia Kyriaki, Crete Greece, indicating the joint occurrence (%) of wave height and period combinations for the reference period 01/01/2011–31/12/2011 (missing data ~0.27%).

[15,44,50], where downscaling has also been suggested for sustainable wave energy harnessing. Specifically, due to improved accessibility and WEC survivability, the Mediterranean nearshore can be an excellent candidate location to introduce sustainable wave energy harnessing technology [30]. To this end, it has been suggested that more WEC technologies should be deployed and tested in the Mediterranean nearshore [14]. It is for this reason that comprehensive descriptions of the full set of local wave characteristics, such as the ones provided herein, rather than hindcast estimates, should be available underpin the success of such ventures.

Finally, future research should first focus on identifying promising nearshore locations for wave energy in the Mediterranean nearshore (e.g., using hindcast data) and then long-term measurements of the actual wave regime should be undertaken to account for nearshore effects such as shoaling, refraction, and focusing. Furthermore, geospatial analyses could inform on locations where support infrastructure is already in place or nearby and identify areas that are prone to or are actively eroding. By doing so, cost-sharing opportunities between wave energy harnessing and coastal protection could be also realized [29]. Research should also focus on WEC farms layout optimisation [51], downscaling of existing technology [30], and the introduction of new WEC concepts and designs that can harvest energy from low energy seas [52,53]. Policy makers in the EU should encourage nearshore WEC deployment and testing, since wave energy can promote the EU Blue Growth strategy for sustainable growth in the marine and maritime sectors [54] and assist in achieving greenhouse gas emissions neutrality, which is the EU's strategic long-term vision for climate neutral economy by 2050 [55].

Conclusions

The nearshore wave energy resource of the Gulf of Chania, Crete, Greece, a typical nearshore Mediterranean locale, was estimated using actual field measurements rather than hindcast estimates for the offshore. Specifically, two 600 kHz Nortek AWAC acoustic Doppler current profilers (ADCPs) were deployed, from 2010 to 2014, in three nearshore locations in the Gulf of Chania. The maximum wave power ($P_{\max}$) over the entire reference period was 133 kW/m at ~20 m; while at the eastern end (Agia Kyriaki) and near the center (Gerani) of the Gulf of Chania the annual mean wave power (P_{mean}) was 2.57 kW/m in 2011 and 1.50 kW/m in 2013, respectively, suggestive of high inter-annual variability. Generally, shorter duration storms occurred during autumn, winter, and spring. In the intervals between storms, and during the summer, calm seas were observed, with very low P_{mean} values. As a result, wave power's coefficient of variation (COV(P)) was large, exhibiting values well above 2; on a monthly base COV(P) values ranged from as little as 1.09 to as high as 3.05, indicating high intra-annual (seasonal) variability and that the local wave power resource is relatively unsteady. For context, in the more energetic oceanic coasts the COV(P) values are significantly lower, even reaching values below unity, for example in South Africa and New Zealand the COV(P) ranges between 0.85 and 0.9.

Furthermore, even though the AWAC deployment sites were in close proximity, significant differences were observed in $P_{\max}$, P_{mean}, and mean wave direction (M_{dir}). This can be attributed to wave shielding and from nearshore effects such as shoaling, refraction, and focusing which can greatly affect the nearshore wave regime. Such differences cannot yet be accurately captured by hindcast estimates that typically refer to the offshore. As such, for the sustainable sitting of future wave energy ventures in the Mediterranean nearshore long-term measurement campaigns of the local wave climates are required and remain the golden standard. More studies on the wave regime of the nearshore Mediterranean as well as more case studies of actual WEC emplacement on the Mediterranean nearshore are required to underpin the feasibility and showcase the sustainability of wave energy ventures in the Mediterranean and further afield.

Overall, results suggest that wave power extraction from the Gulf of Chania is currently uneconomical, given: i) the present state of WEC technology, ii) the much higher levelized cost of electricity (LCOE) relative to other renewables, and iii) the very low-capacity factors (CFs) of typical WEC technologies, i.e., Pelamis (3.65%) and Oyster (9.57%). For this reason, future research and development should focus on sustainably downscaling and redesigning existing wave energy technology to account for milder and relatively unsteady wave energy resource of the Mediterranean nearshore (including the Gulf of Chania), compared to the oceans. Finally, the successful harnessing of wave energy in the Mediterranean can assist in meeting EU's carbon–neutral 2050 goals and underpin EU's Blue Growth strategy and therefore should be amongst the EU policy priorities.

CRediT authorship contribution statement

Spyros Foteinis: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Visualization. **Costas Emmanuel Synolakis:** Data curation, Resources, Investigation, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] Musial W. Status of wave and tidal power technologies for the United States. In: Innovation for our energy future. Golden, Colorado: National Renewable Energy Laboratory; 2008. p. 16.

[2] Gunn K, Stock-Williams C. Quantifying the global wave power resource. Renew Energy 2012;44:296–304.

[3] International Energy Agency. Key World Energy Statistics. In: Agency IE, editor. 9 rue de la Fédération 75739 Paris Cedex 15; 2014.

[4] Mollison D. Wave climate and the wave power recourse. In: Evans AFdOFD, editor. Hydrodynamics of ocean wave-energy utilization. IUTAM Symposium, Lisbon; 1985. p. 133–56.

[5] Mollison. Assessing the wave energy resource. In: Turkman VBKF, editor. Statistics for the environment 2. Wiley; 1994. p. 205–20.

[6] Falcão AFO. Modelling of wave energy conversion. Tech. rep. Instituto Superior Técnico, Universidade de Lisboa; 2014. p. 38.

[7] Leishman J, Scobie G. The development of wave power. A techno-economic study. Economic assessment unit, national engineering laboratory (NEL), Glasgow, Scotland; 1976.

[8] Drew B, Plummer AR, Sahinkaya MN. A review of wave energy converter technology. Proc Inst Mech Eng, A: J Power Energy 2009;223(8):887–902.

[9] Glendenning I. Ocean wave power. Appl Energy 1977;3(3):197–222.

[10] Neill SP, Hashemi MR. Wave power variability over the northwest European shelf seas. Appl Energy 2013;106:31–46.

[11] Kim CK, Toft JE, Papenfus M, Verutes G, Guerry AD, Ruckelshaus MH, et al. Catching the right wave: evaluating wave energy resources and potential compatibility with existing marine and coastal uses. PLoS One 2012;7(11):e47598.

[12] Lo Re C, Manno G, Basile M, Ciraolo G. The opportunity of using wave energy converters in a Mediterranean hot spot. Renew Energy 2022;196:1095–114.

[13] Karathanasi F, Soukissian T, Sifnioti D. Offshore wave potential of the Mediterranean Sea. International Conference on Renewable Energies and Power Quality (ICREPQ'15), La Coruña (Spain); 2015.

[14] Dialyna E, Tsoutsos T. Wave energy in the mediterranean sea: Resource assessment, deployed wecs and prospects. Energies 2021;14(16).

[15] Rusu E. Study of the wave energy propagation patterns in the Western Black Sea. Appl Sci 2018;8(6):993.

[16] Giatrakos GP, Tsoutsos TD, Zografakis N. Sustainable power planning for the island of Crete. Energy Policy 2009;37(4):1222–38.

[17] Foteinis S. Coastal erosion in Greece. In: Assessment and mitigation [in Greek]. School of Environmental Engineering, Technical University of Crete, Chania; 2014. p. 255.

[18] Iuppa C, Cavallaro L, Vicinanza D, Foti E. Investigation of suitable sites for wave energy converters around Sicily (Italy). Ocean Sci 2015;11(4):543–57.

[19] Monteforte M, Lo Re C, Ferreri GB. Wave energy assessment in Sicily (Italy). Renew Energy 2015;78:276–87.

[20] Rusu L, Onea F, Rusu E. The expected impact of marine energy farms operating in island environments with mild wave energy resources—a case study in the Mediterranean Sea. Inventions 2021;6(2):33.

[21] Lavidas G, Venugopal V. A 35 year high-resolution wave atlas for nearshore energy production and economics at the Aegean Sea. Renew Energy 2017;103:401–17.

[22] Carballo R, Sánchez M, Ramos V, Fraguela JA, Iglesias G. The intra-annual variability in the performance of wave energy converters: a comparative study in N Galicia [Spain]. Energy 2015;82:138–46.

[23] Majidi Nezhad M, Groppi D, Rosa F, Piras G, Cumo F, Garcia DA. Nearshore wave energy converters comparison and Mediterranean small island grid integration. Sustainable Energy Technol Assess 2018;30:68–76.

[24] Xu X, Robertson B, Buckham B. A techno-economic approach to wave energy resource assessment and development site identification. Appl Energy 2020;260:114317.

[25] Maravelakis N, Kalligeris N, Lynett P, Synolakis CE. Case study of small harbor excitation under storm conditions, Ports 2016; 2016.

[26] Maravelakis N, Kalligeris N, Lynett PJ, Skanavis VL, Synolakis CE. Wave overtopping due to harbour resonance. Coast Eng 2021;169:103973.

[27] Synolakis C, Kalligeris N, Kalligeris G, Maravelakis N. Research for the placement of a small Marina in the Gulf of Chania [in Greek]. Chania, Greece: Technical Unveristy of Crete; 2012.

[28] Foteinis S, Tsoutsos T, Synolakis C. Numerical modelling for coastal structures design and planning. A case study of the Venetian harbour of Chania, Greece. ISSMGE Int J Geoeng Case Histories 2018;4(4):232–41.

[29] Foteinis S, Tsoutsos T. Strategies to improve sustainability and offset the initial high capital expenditure of wave energy converters (WECs). Renew Sustain Energy Rev 2017;70:775–85.

[30] Foteinis S. Wave energy converters in low energy seas: current state and opportunities. Renew Sustain Energy Rev 2022;162:112448.

[31] Lira-Loarca A, Ferrari F, Mazzino A, Besio G. Future wind and wave energy resources and exploitability in the Mediterranean Sea by 2100. Appl Energy 2021;302:117492.

[32] Wessel P, Luis JF, Uieda L, Scharroo R, Wobbe F, Smith WHF, et al. The Generic mapping tools version 6. Geochem Geophys Geosyst 2019;20(11):5556–64.

[33] Nortek AS, AWAC Introduction in Sea Technology; 2006. http://www.nortek-as.com/lib/technical-notes/awac-introduction-in-sea-technology-february-2006/view [Accessed 19.08.2015].

[34] López-Ruiz A, Bergillos RJ, Ortega-Sánchez M. The importance of wave climate forecasting on the decision-making process for nearshore wave energy exploitation. Appl Energy 2016;182:191–203.

[35] Vögler A, Morrison J. Assessment of the Grid Capacity Sharing Potential for Wave and Wind Energy Conversion Systems in the Outer Hebrides of Scotland, European Wave and Tidal Energy Conference (EWTEC) 2013. Denmark: Aalborg; 2013.

[36] Cornett A. A global wave energy resource assessment. Sea Technol 2009;50(4):59.

[37] Foteinis S, Hancock J, Mazarakis N, Tsoutsos T, Synolakis CE. A comparative analysis of wave power in the nearshore by WAM estimates and in-situ (AWAC) measurements. The case study of Varkiza, Athens, Greece. Energy 2017;138:500–8.

[38] Athanassoulis GA, Stefanakos CN, Gerostathis TP, Gaillard P, Ravazzola P, Kontolios C, et al., Wind and Wave Atlas of the Mediterranean Sea, Brussels; 2004.

[39] Pastor J, Liu Y. Wave climate resource analysis based on a revised gamma spectrum for wave energy conversion technology. Sustainability 2016;8(12):1321.

[40] Guillou N. Estimating wave energy flux from significant wave height and peak period. Renew Energy 2020;155:1383–93.

[41] Sierra JPC, Mestres R, Mösso M, Lionello C, Marzo P. Impact of climate change on wave energy resource in the Mediterranean Coast of Morocco. Energies 2020;13:2993.

[42] Cavaleri L, Bajo M, Barbariol F, Bastianini M, Benetazzo A, Bertotti L, et al. The October 29, 2018 storm in Northern Italy – an exceptional event and its modeling. Prog Oceanogr 2019;178:102178.

[43] Vannucchi V, Cappietti L. Wave Energy Estimation in Four Italian Nearshore Areas. ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering; 2013.

[44] Rusu L. Evaluation of the near future wave energy resources in the Black Sea under two climate scenarios. Renew Energy 2019;142:137–46.

[45] Neill SP, Lewis MJ, Hashemi MR, Slater E, Lawrence J, Spall SA. Inter-annual and inter-seasonal variability of the Orkney wave power resource. Appl Energy 2014;132:339–48.

[46] Martinez A, Iglesias G. Wave exploitability index and wave resource classification. Renew Sustain Energy Rev 2020;134:110393.

[47] Ribeiro AS, deCastro M, Rusu L, Bernardino M, Dias JM, Gomez-Gesteira M. Evaluating the future efficiency of wave energy converters along the NW Coast of the Iberian Peninsula. Energies 2020;13(14):3563.

[48] Hutcheson J, de Andrés A, Jeffrey H. Risk vs. reward: a methodology to assess investment in marine energy. Sustainability 2016;8(9):873.

[49] Bozzi S, Besio G, Passoni G. Wave power technologies for the Mediterranean offshore: scaling and performance analysis. Coast Eng 2018;136:130–46.

[50] Majidi A, Bingölbali B, Akpınar A, Iglesias G, Jafali H. Downscaling wave energy converters for optimum performance in low-energy seas. Renew Energy 2021;168:705–22.

[51] Loukogeorgaki E, Michailides C, Lavidas G, Chatjigeorgiou IK. Layout optimization of heaving Wave Energy Converters linear arrays in front of a vertical wall. Renew Energy 2021;179:189–203.

[52] Barbarelli S, Amelio M, Castiglione T, Florio G, Scornaienchi NM. Design and analysis of a new wave energy converter based on a point absorber and a hydraulic system harvesting energy from waves near the shore in calm seas. Int J Energy Res 2021;45(1):661–90.

[53] Oikonomou CLG, Gomes RPF, Gato LMC. Unveiling the potential of using a spar-buoy oscillating-water-column wave energy converter for low-power stand-alone applications. Appl Energy 2021;292:116835.

[54] Lavidas G, De Leo F, Besio G. Blue growth development in the Mediterranean sea: quantifying the benefits of an integrated wave Energy Converter at Genoa Harbour. Energies 2020;13(16):4201.

[55] European Commission. A clean planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. COM(2018) 773 final; 2018. p. 25.