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A 35 year High-Resolution Wave Atlas for Nearshore Energy Production and Economics at the Aegean Sea

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Abstract

The study enhances the coastal resource knowledge and discusses opportunities for wave energy in the Aegean Sea. A fine-resolution numerical wave model is utilised to provide results for the Greek coastal regions. The model ran for 35 years (1980-2014) estimating wave characteristics, and quantifying the wave energy potential in coastal areas. The results deliver the energy potential, variability, and site characterisation for the Aegean Sea.

The dataset is coupled with wave energy converters power matrices to provide for the first time a long-term analysis of expected power production. Performance of devices is highly dependent on matching the power matrix to the local resource, suitable devices can obtain capacity factor up to 20% and favour operation for low wave heights and high frequencies.

Based on energy analysis data, an economic performance and payback period of a hypothetical wave farm is examined. With little information on wave energy in the region, this preliminary cost-to-benefit analysis shows the viability of wave converters. Even with high capital expenditure associated with novel technologies, certain scenarios achieve amortisation periods at 7.5 years for a properly selected converter. Results are comparable with previous renewable schemes aimed at increasing the cumulative installation of other early stage technologies.

Keywords: Aegean Sea, Numerical Wave Model, Wave Climate, Wave Power, Energy Economics

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1. Introduction

The Mediterranean Sea is a semi-enclosed basin with small water boundaries, to the West at the Straits of Gilbratar, North-East a channel connects Northern Aegean with the Marmara Sea, finally at the South-East the Nile river connects the Egyptian Sea with the Suez Gulf and the Red Sea. External wave boundaries are not significant for the Mediterranean Sea, but the high distribution of islands around the Mediterranean increases the difficulties for wave estimates.

Study of the Mediterranean area has been indicated [1] for wave climate analysis and wave energy quantification. The past years studies have been conducted, with some drawbacks on temporal and/or spatial attributes. Spatio-temporal limitations are either focused on either very small areas [2] or encompass a limited duration period of analysis [3, 4, 5]. Such studies provided significant improvements in understanding of the regional wave climate, limitations in time duration, scale, and level of resolution are important to note.

To date most long term studies are associated with the Mediterranean Sea, amongst the first in 2004 a consortium of several insitutions delivered 10 yea Wind-Wave Atlas for the region, based however on a coarse oceanic model [6]. Ratsimandresy et.al [7] used the same coarse oceanic model to provide a 44 years ocean and atmospheric hindcast for the Western part of the Mediterranean. Recent studies by Mentaschi et.al. [8] and Ponce de Leon et.al. [9] presented Mediterranean wave power potential for 35 and 29 years respectively. The first study focused on Italy [8] and the second in the Balearic Sea [9], both of them using an oceanic model. Majority of studies are based on oceanic models with spatial resolution hindering extrapolation of results to coastal areas, as discussed in Canellas et.al. [10]. Usual spatial resolution utilised for numerical wave models in the region are between 0.1^o ($\approx 11Km$) and 0.04^o ($\approx 4.4Km$) [11, 12, 3, 13, 6, 8, 7, 14].

Concerning the Aegean Sea, most recent long-term and up-to-date wave climate analysis (42 years) is by Zacharioudaki et.al.[15], using the oceanic model WAM and assessed wave climate from $1960 - 2001$, dynamically downscaled winds at 50 Km and a spatial resolution of 0.1^o. The outcome assessed wave height variations and return periods, after an application of correction factors [15]. Emmanouil et.al. [16] used the same oceanic model forced by 3 hourly winds from the SKIRON model, and provided a 10 year hindcast on the wave content of the region (2001-2010). The study utilised spectral discretisation of 25 frequencies and 24 direction, with a spatial resolution of 0.05^o, and assessed several key statistical indices over the domain. Additionally, studies using unstructured meshes offered wave power resource estimates for the Aegean, using a 15 years hindcast [17, 18]. Prior to them a wind and wave Atlas 10 years in duration was presented by Soukissian et.al.[14] utilising an oceanic model. A summary of studies focused in the Aegean region are presented in Table 1, with information on models used, durations, and outcomes.

Table 1: Implementation of Aegean Models

Region	Study	Model	Period (years)	Spatial Resolution	Parameters
Aegean	[14]	WAM	10	$0.1^o x 0.1^o$	Waves
Aegean	[19]	WAM	1	$0.06^o x 0.06^o$	Waves
Aegean	[17]	MIKE21	15	Unstructured	Wave Power
Aegean	[20]	SWAN	1	$0.1^o x 0.1^o$ & $0.025^o x 0.025^o$	Waves, Wave Power
Aegean	[15]	WAM	42	$0.1^o x 0.1^o$	Waves, Extremes
Aegean	[18]	MIKE21	15	Unstructured	Wave Power
Aegean	[16]	WAM	10	$0.05^o x 0.05^o$	Waves, Wave Power

For the Aegean majority of studies use oceanic models with coarser resolution, this study aims to contribute and fill in the gap of fine-resolution information on the wave power resource for the Aegean Sea. The finer resolution with tuning of nearshore components, delivers detailed long-term energy estimates and allow to assess the opportunities for wave energy converters.

The temporal length of the datasets allows us to establish a comprehensive database of wave energy and device performance in the Aegean Sea. This is of major importance to decide on energy performance indices and outline the potential benefits for the Greek energy system. Results go further than just a wave climate analysis and contribute to energy assessment of wave converters in the milder waters of the Aegean Sea. The results are quantified per region and technology, allowing estimations concerning wave energy converters and deliver an up-to-date resource and techno-economic assessment.

The study is separated in the following sections, Section 2 presents the datasets, numerical wave model calibration, buoy validation, and comparison with recent studies. Section 3 quantifies and examines the wave resource in the coastal Aegean Sea and site classification. Section 4 presents the energy results obtained and classifies the utilised wave energy converters, according to their performance in the Aegean Sea. Section 4.2 provides preliminary information, concerning payback periods of potential wave energy applications, considering current and past schemes of renewable energy frameworks in Greece. Finally, Section 5 presents a summary of results and discusses future work.

2. Material and Methods

2.1. Model set up and Areas of Investigation

Simulating WAves nearshore (SWAN) is a third generation spectral phased-average model used for wave studies [21]. The wind input is provided by NCEP and the Re-Analysis package of the CFSR dataset with 1-hour time intervals [22]. The model used a two way nesting for the Mediterranean and Aegean Seas, with a duration of 35 years from 1980–2014 for all domains, see Fig. 1. Buoy and additional selected locations for the Aegean Sea are given in Fig. 2.

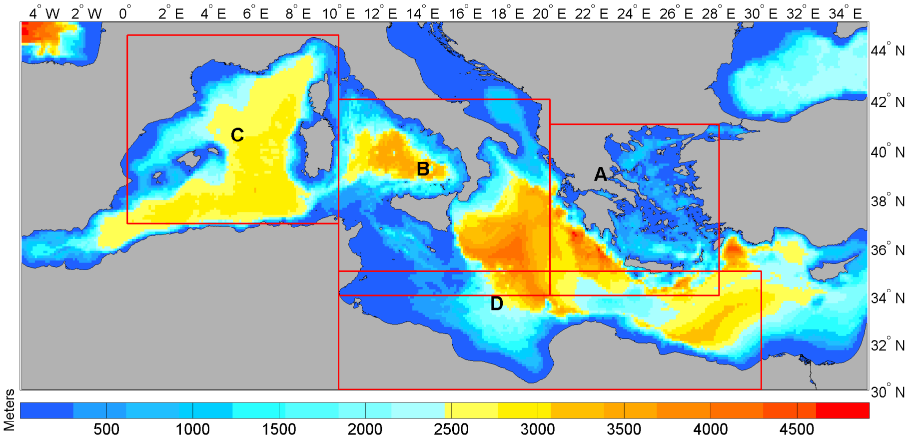
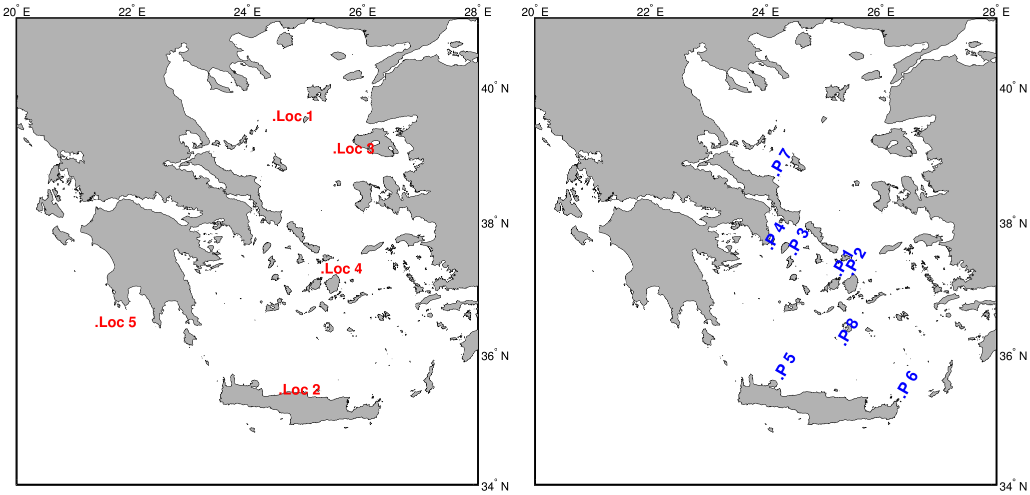


Figure 1: Initial domain utilised and subsequent nestings, A: Aegean Sea B: Tyrrhenian Sea, West Ionian, C: Balearic Sea, D: Libyan Sea (colorbar depth in meters)

The Mediterranean mesh was used to provide boundaries, the coarse resolution of the domain is 0.1^o. The Aegean was a nested domain and has a spatial resolution of 0.025^o. The resolution in combination with all nearshore source terms activated allows for a better representation of coastal waters, increasing the confidence of results in comparison with oceanic models [23, 24].

Direction has been subdivided into 25 intervals and the frequency is discretised in 30 bins, highest wave frequency is set to 28 seconds, the lowest



(a) Buoys (b) Additional Locations

Figure 2: Buoys: Loc 1-5, Athos, E1mea, Lesvos, Mykonos, Pylos (panel a). Locations: P 1-8, Paros, Naxos, Kythnos, Attika, Crete1, Crete2, Euboia, Santorini (panel b)

is 2 seconds and are distributed logarithmically ($\Delta f = 0.1f$). Selection and range of frequency and directional bins, have a direct effect on computational resources, with an increase in the parameters (frequency and directional bins) not always delivering improved performance [25]. The coordinates are Spherical and have been extracted from ETOPO-1 [26] and bathymetry domains were constructed, using bi-linear interpolation.

The wind scheme is based on formulations by Komen [27] with a linear growth coefficient activated [28]. Bottom friction, depth breaking, refraction, diffraction processes all are used to account for wave interactions. Triads are solved with the Elderky method [28], and quadruplets are activated in a semi-implicit way. Due to the orography and sudden depth changes of Mediterranean region, a backwards step and time propagation scheme is used to ensure stability. Finally, all hindcast years where initiated with a ”warm” start configuration, i.e. hindcast computations start prior to the year of investigation to avoid warm up errors in the model.

2.2. Calibration/Validation of Model

In the Mediterranean Sea, level of available buoy measurements information varies. Italy’s and Spain’s buoy networks are one of the most detailed with buoy measurements going back 20 years. For the Aegean Sea we have considered the buoys provided by Hellenic Centre for Marine Research (HCMR) [29]. The POSEIDON network buoys by HCMR [29] are publicly available, while Spanish and some Italian buoys are not publicly available.

Discussion on problems in buoy operation and other recording methods can be found in Cavaleri et.al. [30]. Availability of satellite data is known to the authors, due to temporal restriction as indicated by other studies we have not considered them. The fact that recordings have large gaps between passing of the satellites, 10 or 30 days apart, prompted to the decision. Another limitation is their spatial coverage, satellite do not offer wave recordings at the nearshore, but provide data further away usually at approximately $20Km$ off coastlines [27, 30, 31, 32, 33]. Even with the inherit problems of buoys and measurement gasps, their positioning especially at nearshore waters offer reliable considerations nearshore assessments.

The buoy data underwent a filtering process to exclude missing intervals and outliers. The validation process was repeated for all available years, Table 2 sums the validation of the model with buoy data. The indices used have been presented in a previous investigation by the authors for the region [20, 34]. The use of various statistical indices assist in the interpretation of results, allowing better confidence in the models [35, 36].

Prior to Aegean domain validation, calibration based on wind scheme was performed. Two wind schemes are considered, first scheme was presented in Komen et.al. [27] and denoted WAM3, while the second was adapted by the theory provided by Janssen and [37, 38, 39] denoted as WAM4.

Both solutions are options of the wind input source term of SWAN, and dictate the evolution and wind interactions with waves. Difference of wind schemes lay to some extent on wind coefficients, and especially the drag coefficient at $10m$ height. Both formulations are based on Miles [40], although basic difference are with the determination of wind drag coefficient and its effects on fetch limited seas. More information on the difference of used schemes can be found [41, 42, 39]. The selection of appropriate scheme has to depend on the wind product used, since they provide the different temporal and spatial information [43, 44, 22, 45], some alterations in the behaviour of waves are expected. Increasing the temporal resolution of the wind input has been reported to affect numerical wave performance by reducing underestimations [46].

WAM3 was activated with whitecapping coefficient (2.36^{-5}) and linear wind growth. The WAM4 adaptation also had activated a linear growth, and whitecapping coefficient set to 4.5.

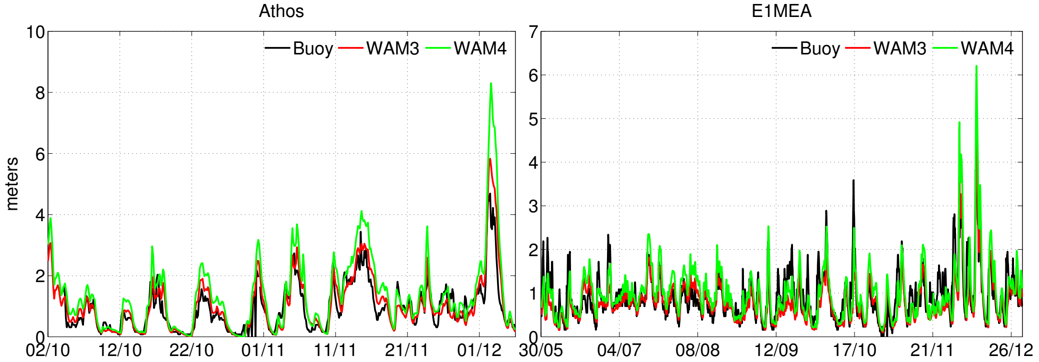


Figure 3: Hindcast under the wind schemes, with available 2013 H_{sig} buoy measurements

As seen in Fig. 3, both solutions offer good generation trends, with the WAM4 driven model recording higher peaks. More specifically for location E1MEA the comparison of available data and buoy measurements yields a correlation coefficient for H_s of 0.88 for WAM3 and 0.86 for WAM4. The bias in this case is much closer for the WAM4 scheme nearly zero ($0.014m$), while WAM3 under-estimates by $-0.17m$. The root-mean-square errors (rmse) are significantly lower for WAM3 ($0.4m$) while WAM4 acquires a value of $0.48m$. At Athos location, both models provide good correlation coefficient of 0.95, both over-estimating the results. In case of WAM3 the over-estimation is $0.1m$, while for WAM4 the over-estimation is $0.45m$. The rmse is much lower for WAM3 with $0.4m$ while WAM4 has $0.76m$.

Performance of models for wave periods, peak period (T_{peak}) has a correlation coefficient of 0.80 (WAM3) and 0.78 (WAM4) for the E1MEA locations. Both models over-estimated the period by $\approx$ 1 sec, scattering is less for (WAM4) 0.34 and 0.36(WAM3). For the Athos location, correlation coefficient are similar, 0.80 (WAM3) and 0.82 (WAM4). Both model over-estimate slightly with WAM3 (0.27 sec) and WAM4 (0.4 sec), the scatter index is 0.32 (WAM3) and 0.31 (WAM4).

From the comparison, WAM3 was considered as a physical solution, since it offered a high correlation and more representative wave heights in terms of magnitude, see Fig. 3; over-estimations can be attributed to the temporal resolution of re-analysis dataset .

After wind scheme selection, the coarse model run for 35 years to provide spectral (2-D) boundary information to the nested domain with a temporal

Table 2: Overall Validation indices for buoys considered in the nested mesh (H_{sig} in meters, T in seconds)

	Athos(2000-2014)			Lesvos(2000-2012)			Mykonos(2002-2012)			Pylos(2007-2014)		
	H_s	T_{peak}	T_{m02}	H_s	T_{peak}	T_{m02}	H_s	T_{peak}	T_{m02}	H_s	T_{peak}	T_{m02}
R	0.95	0.87	0.92	0.93	0.86	0.92	0.87	0.67	0.77	0.9 3	0.91	0.93
rmse	0.34	1.11	0.74	0.39	1.05	0.64	0.52	1.68	0.87	0.38	1.06	0.73
MPI	0.98	0.90	0.92	0.98	0.90	0.93	0.98	0.89	0.92	0.97	0.85	0.89
Average buoy	0.81	4.56	3.66	0.76	4.57	3.53	1.00	4.82	3.63	0.98	5.83	4.36
Average SWAN	0.82	4.45	3.24	0.89	4.45	3.25	0.87	4.70	3.26	0.99	5.59	3.96
Bias	0.01	-0.11	-0.42	0.13	-0.12	-0.28	-0.13	-0.12	-0.37	0.01	-0.24	-0.40
SI	0.41	0.24	0.20	0.52	0.23	0.18	0.52	0.35	0.24	0.39	0.18	0.17

step of 6 hours. Results from one year are presented in Fig 4. Table 2 provides the statistical validation of buoys with the longest recordings.

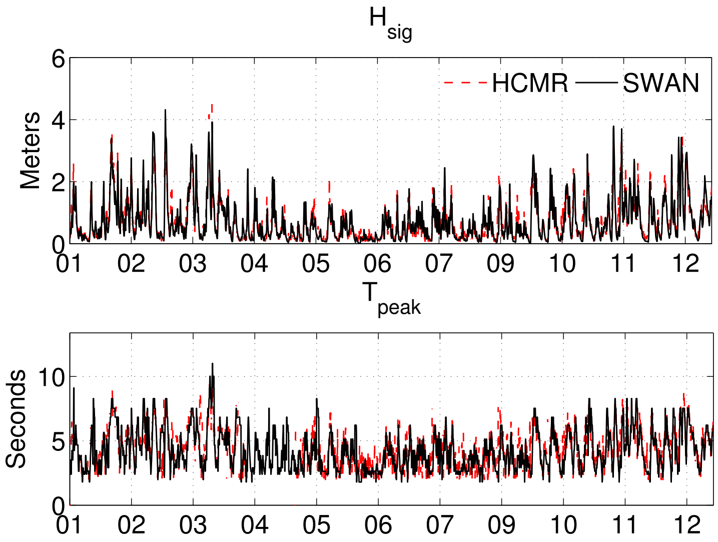


Figure 4: Validation of one of the datasets, for the year 2007 (12 months) Athos location (buoy HCMR)

Results are comparable with the latest study published by Zacharioudaki et.al. [15], reporting similar values even by utilising a different wind dataset and model. Scattering in our and the aforementioned study, present similar correlation coefficients, biases and rmse values are similar for all locations with some improvements in the Athos comparisons by our model. Lesvos presents over-estimations on H_s and at Mykonos small H_s under-estimations.

Our dataset also shows good agreement, with a nearshore model using a unstructured mesh by Jadidoleslam et.al. [18]. In same buoys locations we record improvements in all correlation coefficients for both H_s and T_{peak}. The aforementioned model offers less biases followed by consistent resource under-estimations. In terms of wave periods our modelled data show lower biases. The results provide confidence in our dataset and additional points are extracted based on the wave power spatial distribution, see Fig. 2.

3. Theory and Calculations

3.1. Wave Climate Variability Analysis

Due to the nature of waves, intermittent behaviour is expected, evaluation of seasonal and intra-annual changes provides with information concerning variations. Short hindcast of just few years are not able to assess and identify trends, at least 10 years of hindcast required for robust estimates are suggested [24, 47, 48]. Variability is for renewable energy projects. Without considerations on long-term fluctuations, confidence decreases for energy estimates [49].

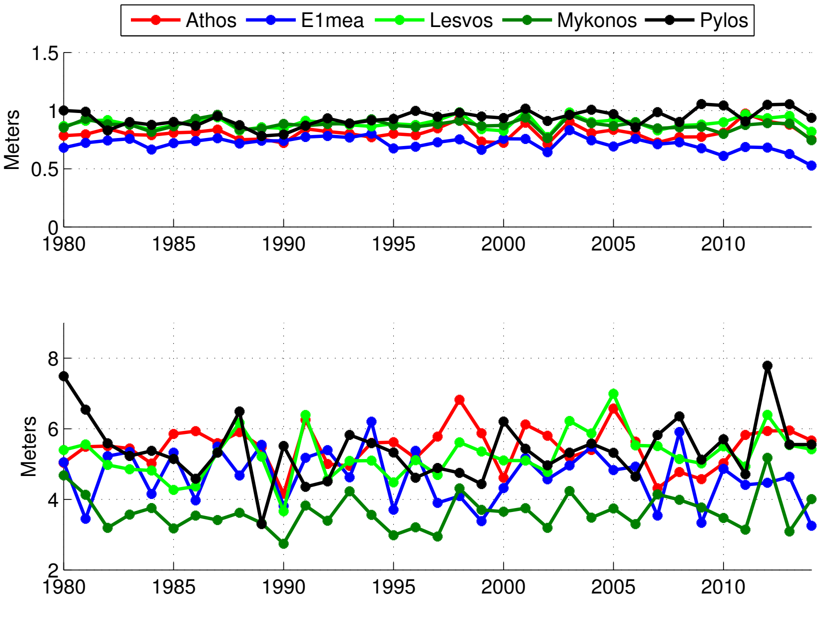
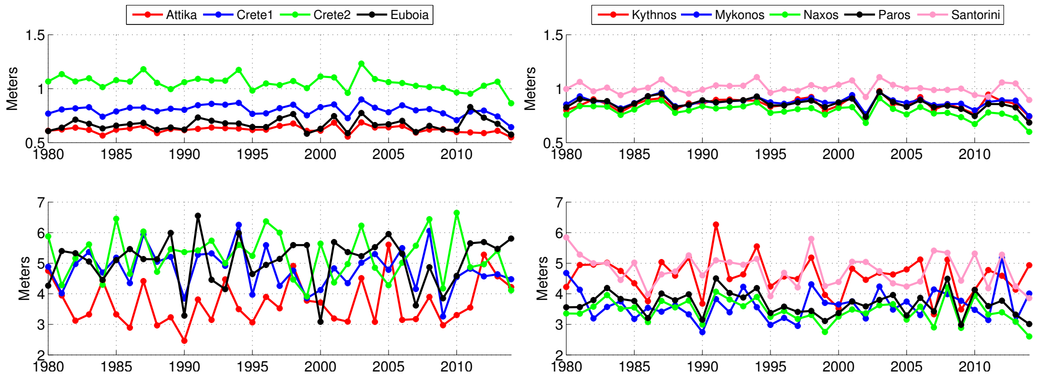


Figure 5: Annual mean (upper) and max (lower) H_s



(a) Central & Crete (b) Mean and Max Islands

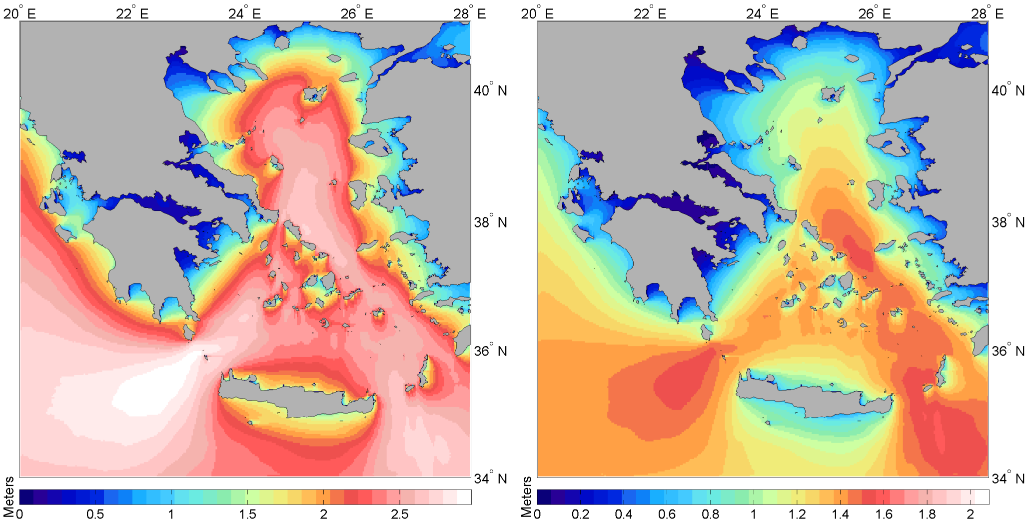
Figure 6: H_s mean (top row panels) and max (bottom row panels)

Throughout the hindcast, Athos and Pylos present high maximum values, with mean values almost consistent for Mykonos and Lesvos, see Fig 5. Slightly higher magnitudes are recorded at Pylos that is located at deep waters and exposed to swell components travelling from the West Mediterranean.

We have to note that maximum values show some variance, mean values of wave height do not deviate much until 1998. However, maximum events have significant differences, with Mykonos location having lower values, this can be attributed to its location in the Cycladic island complexes, where coastlines reduce incoming waves.

For the additional locations selected, annual behaviour is also examined. Because they are closer to coastlines, variation expected is less than deeper locations. Fig. 6 displays the regions at Cycladic islands and near Central Greece, results have similar magnitudes of resource and trends in annual means. Locations at Cyclades, Naxos and Paros, show similar values and trends. In both cases maxima values are significant reaching $\approx 6.5m$ at Crete 1-2, while locations closer to island complexes have consistent values of over $\approx 4.5m$, with the exception of Kythnos.

Similar to measurements, the magnitude of 95^{th} and 75^{th} percentiles exhibit higher values at South Aegean, West of Crete. The Central belt of the Aegean (Cyclades-Central Greece) and near the mainland coastlines has low values for both percentiles, while the island complexes attain higher values. Percentiles for the Northern coasts of the Aegean have smaller wave heights as expected. Deep water locations above the central region see higher the values, with the resource significantly diminished as it propagates towards the Macedonian coastline.



(a) 95^{th} H_s

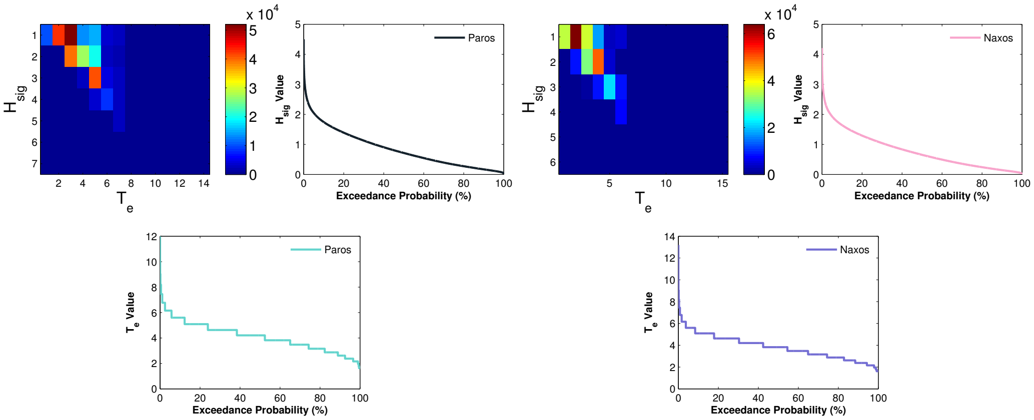
(b) 75^{th} H_s

Figure 7: 95^{th} panel (a) and 75^{th} panel (b) percentiles in meters

The joint distribution (bivariate) gives the number of instances that wave height (H_s) and energy period (T_e) occur, providing with the dominant resource characteristics. They can aid significantly in selection of appropriate wave converters. Current state-of-the-art wave energy converters are classified according to their operational principles (see also Section 3.4) installed capacity and range of operation [50]. The joint distribution data allow for an initial dissemination and selection of potential appropriate device in terms of operation conditions. This can be considered as a feasibility investigation stage for converter selection.

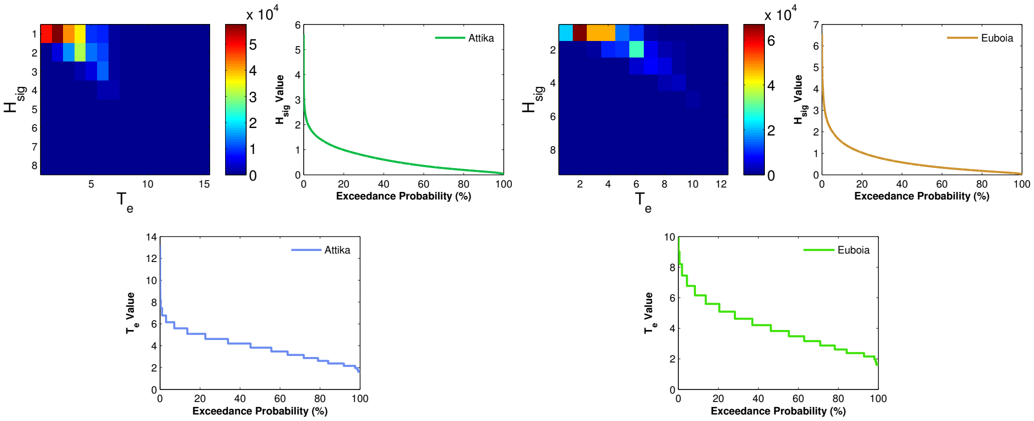
The joint distributions utilise all 35 years of hindcast parameters to examine the dominant seastates that occur at each location. The number of occurrences (recorded instances), are shown in each cell. The classification of every state corresponds to set interval of 1 sec (T_e) and 1 meter (H_s), while this can be reduced to 0.5 due to the amount of data within the dataset the previous classification was chosen for display purposes only.

For locations near central Greece dominant conditions in Attika are expressed from 0.5-4 sec and H_s up to 1.5 meters. Euboia has a slightly higher minimum value from 1.5-4 sec and similar wave heights, see Fig. 8. Locations at Crete (Crete 1 and 2), have a wider range of periods (2-7 sec) and frequent wave heights from 1.5-4 meters. The Cycladic locations (points Paros and Naxos), have higher occurrences at periods (3-6 sec) and wave heights from 1.5-5 meters, see Fig.9.



(a) Attika (b) Euboia

Figure 8: Number Occurrences and Exceedance (%), H_s in meters and T_e in seconds



(a) Paros (b) Naxos

Figure 9: Number Occurrences and Exceedance (%), H_s in meters and T_e in seconds

Kythnos, Mykonos, and Santorini have similar maximum height (≈ 7 meters), they also have similar joint distributions with periods of 2-6 secs and most commonly met H_s of 1.5-3.5 meters. Athos, Pylos and Lesvos show H_s from 1.5-4 meters and a wider period range from 2-9 sec. The overall characterisation of the Aegean Sea, can be subsequently classified as favouring operational WECs that have a higher production yields at small wave heights and low periods (high frequencies).

3.2. Wave power resource

Estimated resource is based on the form of wave energy for irregular waves, with energy contained expressed in W/m, which corresponds to the energy per crest unit length. In SWAN energy components are computed with a formulation appropriate for the realist representation of resource, over the summation different wave numbers frequencies (f) and directions (θ).

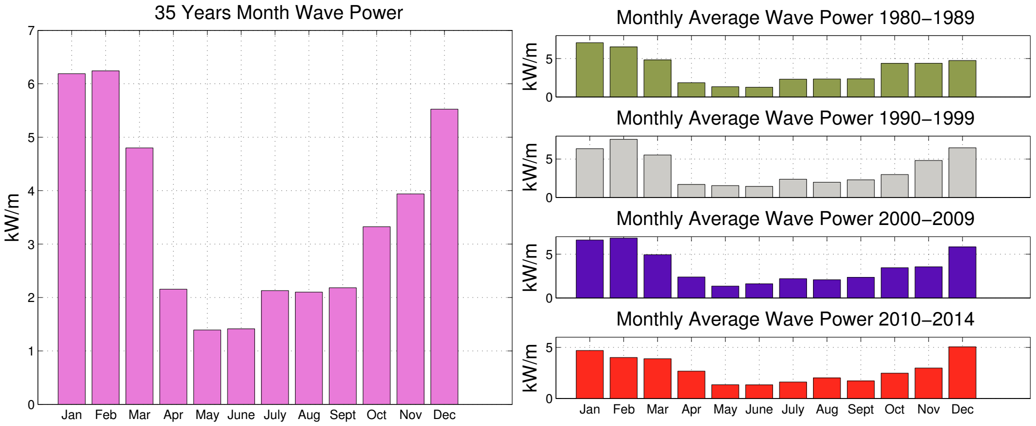
$$P_x = \rho g \int \int C_{gx} E(f, \theta) df d\theta \tag{1}$$

$$P_y = \rho g \int \int C_{gy} E(f, \theta) df d\theta \tag{2}$$

where $E(f, \theta)$ the energy density spectrum over an x (longitude) y (latitude) system, C_g are the components of absolute group velocities, water density (ρ), g gravitational acceleration. Total wave power is estimated in W/m or kW/m:

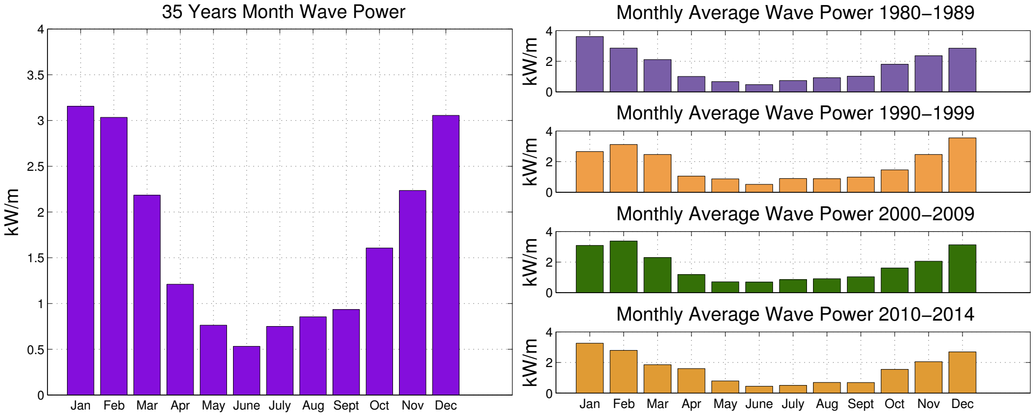
$$P_{wave} = \sqrt{P_x^2 + P_y^2} \tag{3}$$

All locations are examined annually and per month, providing with mean wave power estimates assessing the fluctuation of encountered energy levels. Indicatively content locations are displayed in Figs. 10-11. The highest levels of energy, as expected, are distributed over the winter months December-January-February showing similar trends for all locations. During summer months most locations have a significant reduction wave energy levels, see Figs. 10-11. However this is not the case always for all locations, from data which are not showed here the content of the Crete2, Naxos, Paros and Mykonos, seem to have a relative slight increase during July and August. The expected fluctuations of energy are less in ”encapsulated” coastal areas in contrast to open seas, with propagated wave heights having ”smoother”/lower magnitude due to reduction by bottom and coastline interactions.



(a) (b)

Figure 10: Crete 1 Wave Power, panel (a) overall monthly distribution, panel (b) monthly distribution per decade

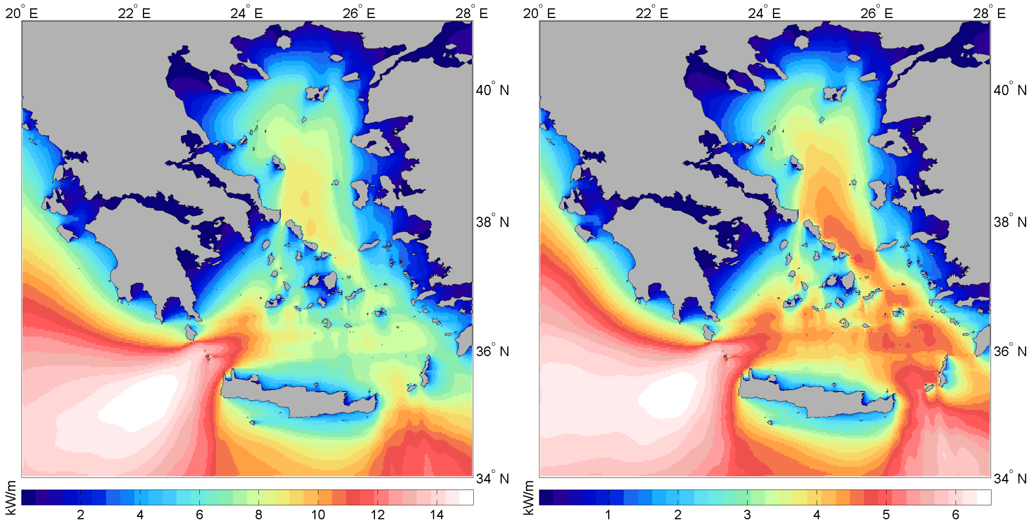


(a) (b)

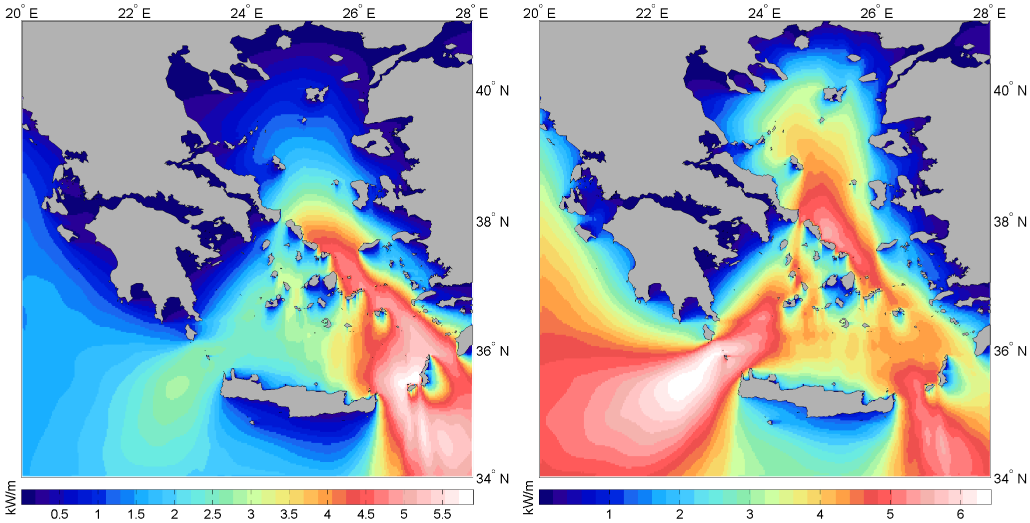
Figure 11: Attika Wave Power, panel (a) overall monthly distribution, panel (b) monthly distribution per decade

Annual maps of the Aegean present the wave energy (kW/m) for every year (i.e. 1980 from January 00:00 to 1st January 1981 00:00) and map the wave energy spatial distibution in the area. The seasonal separation of wave power resource has followed the established method: with winter December-January-February (DJF), Spring March-April-May (MAM), Summer June-July-August (JJA) and autumn September-October-November (SON), i.e. the seasonal resource of 1981 constitutes DJF: December 1980-January 1981-

February 1981 etc.



(a) DJF (b) MAM



(c) JJA (d) SON

Figure 12: Seasonal Resource (kW/m) for the hindcast dataset

The seasonal resource assessment indicates that Southern parts of the Aegean are exposed to higher resources. Especially, waters around Crete and central island belt. Analysis of both maps and locations (annual and seasonal) indicate that highest resource are achieved through out DJF, SON months with levels reaching up to 15-25 kW/m, while lowest months are JJA with values closer to 6-8 kW/m. Fig. 12 display the seasonal wave power levels from the hindcast, with DJF having the highest mean power flux. Similarly, high energy is attained in MAM and SON months, although most Cycladic areas have a higher resource levels throughout SON. Wave energy "builds up" from November till March, see also Figs. 10-11. In general terms the North Ionian, Central and South Aegean Seas acquire highest levels, with North Aegean having low values throughout.

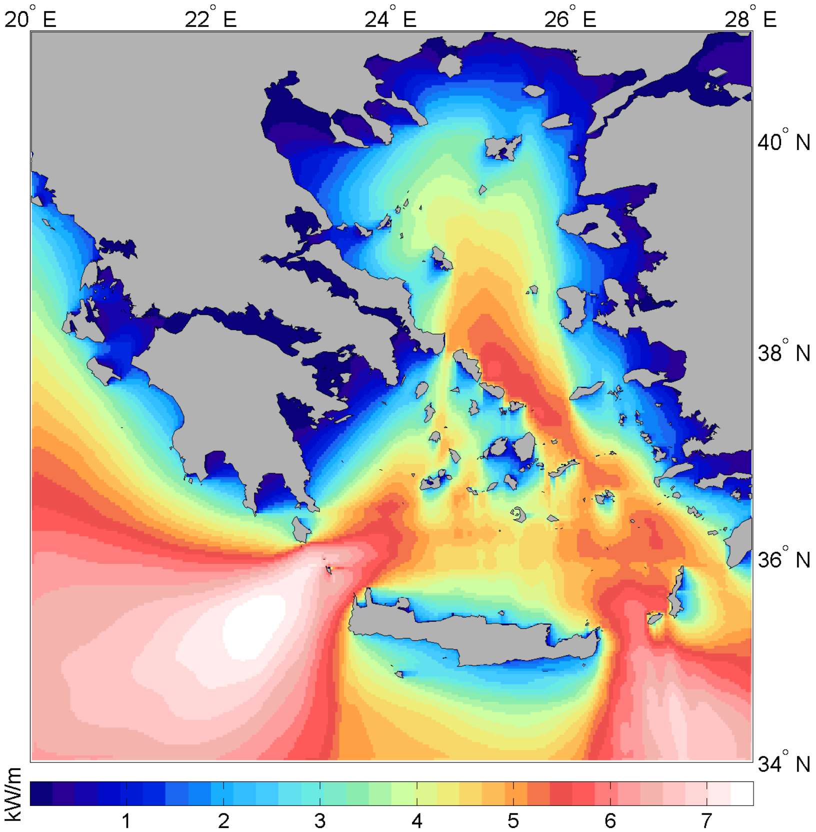
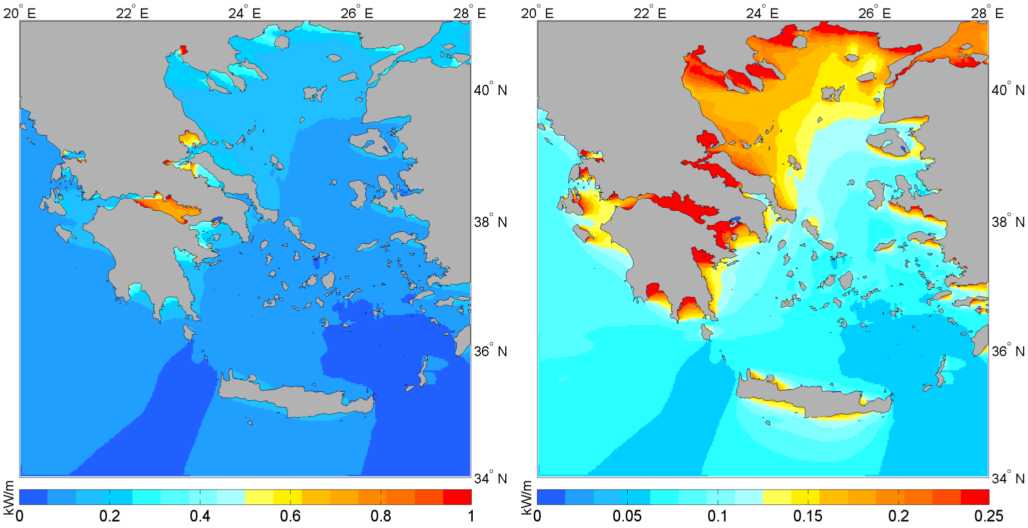


Figure 13: Wave Power (kW/m) 35 years dataset

The mean energy content of the region is presented in Fig. 13, with higher energy content is met at East and South of Crete with $\approx$ 8 kW/m. The Cyclades have $5 - 6.5$ kW/m, although between the islands the resource is reduced. Northern coastlines have lower resource as also indicated by the seasonal analysis. North West part of the Ionian islands encounter similar levels of wave power as the ones met in central regions.

With wave energy being a renewable resource, variability is a factor that affects production. Coefficient of variation (CoV) reveals most volatile areas of change, meaning that variation levels are higher in those regions leading to greater uncertainty. Coefficient of variation (CoV) (σ/μ) is associated with the mean (μ) and standard deviation (σ) of sampled data. If the CoV is 0, then the values do not present fluctuations, on the other hand if CoV is 1 then strong variations exist and may affect performance [13]. Coefficient of variation over a long period of time, ensures the inter-annual fluctuations are incorporated into examination of the variability levels in the region.



(a) Normal Scale

(b) Reduced scale

Figure 14: Wave Power (kW/m) coefficient of variation for the Aegean Sea with the 35 years dataset

Due to the interaction of propagated resource with bathymetric changes and major coastlines, CoV is higher at nearshore locations such as the Cycladic islands, see Fig. 14. Highest levels are located in the straits of Korinthos between Peloponnesus and Central Greece, followed by the Pagasetic Gulf and Malian Gulf. The first location is exposed to locally wind generated waves with, as the location closely resembles encapsulated area with low depths. As stated depths variations around Greece are quite sudden with the majority of having values close to shore around 60 meters, while sudden changes lead to extremely deep waters of more than 500 meters [26, 51] and

Fig. 1. These sharp changes add to the complexity of wave breaking due to bottom interactions, shoaling and diffraction. Similarly the North regions coastal of Macedonian (Thermaikos Gulf) and Thrace (Thrakiko Pelagos), while exposed to lowest resources their annual variations presents a high variance level.

Cycladic island many coastline profiles reducing wave heights which affects the resource levels. Crete presents levels slightly higher after the presence of small Peninsulas, for example at the Chania Peninsula. The South region of Attika is freely exposed to the Aegean Sea and has higher variation. Locations at the coast of Central Euboia have high deviations, partially due to resource dependence on coastal and bathymetry characteristics.

As expected, winter months are the most energetic with lowest resources given constantly throughout the years for summer months. The regions, especially at the Central Aegean, incorporates a difficult bathymetric environment but has an almost consistent energy flow, with small variations. These reductions are generally encountered to areas for which the coastal environment is involving complex shorelines and multiple obstacles (land masses), Southern part of the Cyclades which is exposed to larger fetches has a better resource and smaller variations.

3.3. Wave Energy Development Index (WEDI)

Mean ($\overline{P_{wave}}$) and maximum (J_{wave}) wave power are important for identification of promising locations. Use of multiple indices aids in the dissemination of the local resource. The coefficient of variation revealed the potential changes in the energy resource for the region. Expanding upon that, the Wave Energy Development Index (WEDI) considers the interactions and severity of the resource at locations. A low WEDI with a high mean resource index can prove beneficial for WECs, when considering resource interactions, accessibility, and availability for energy production.

$$WEDI = \frac{\overline{P_{wave}}}{J_{wave}} \tag{4}$$

The index is the ratio of annual average wave power to the maximum storm wave power that every offshore device or structure will absorb. Devices are usually placed based on mean power content distribution, however depending on both the mean and maximum power potential influences of waves at the location can measure and penalise areas with a high index as discussed in Hagerman [52].

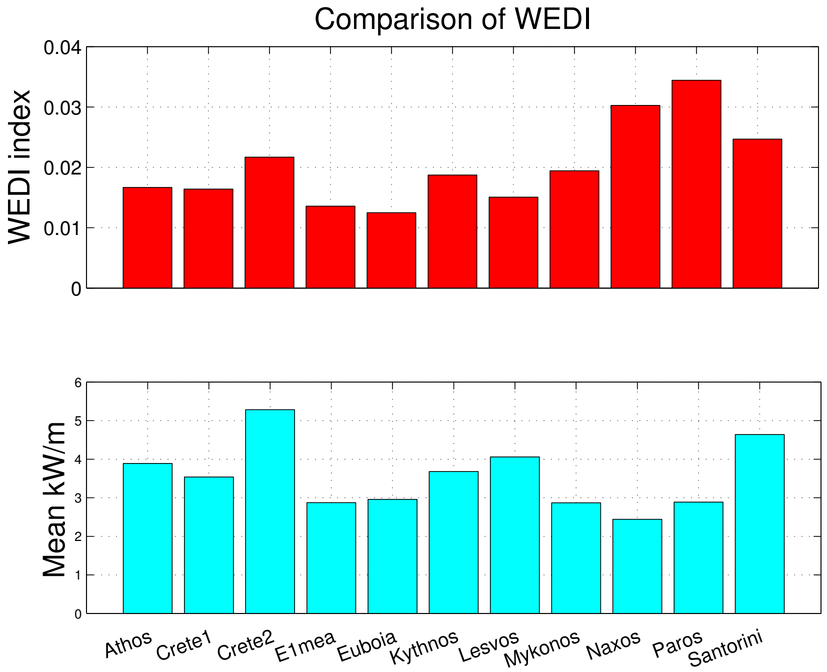


Figure 15: WEDI Locations for 35 years

WEDI takes into account the maximum extreme (storm) values of power and assigns a corresponding level index that can be translated into potential increase/decrease of maintenance and operation [53, 54]. The higher the WEDI then locations will potentially require more capital expenditure for infrastructure. Suggesting that potential sites should not only be consider for their mean content, but also as a ratio of the maximum content. Covariance and the interaction of the resource though WEDI can reduce the level of uncertainties concerning the survivability of converters, minimizing CAPEX, OPEX, and achieve consistent operation.

WEDI at the Cyclades islands is amongst highest ranked region of the Aegean indicating, that the location resource is affected by storm events. These findings have to be taken into account for structural and economic considerations for development of wave farms.

Overall, from studies completed by the authors at various regions and especially the energetic coastlines of Scotland and the United Kingdom [55], the WEDI expressed in the Aegean region is far more consistent and less variant. This comes in expense of energy production, but survivability and operation of the devices is expected to obtain a more constant production rate.

3.4. Wave Energy Converters Application

Wave converters produce energy based on local characteristics of wave height and period. This joint distribution provides the representation of sea occurrences in an area. While many technologies exist, not all of them are appropriate for every wave environment. Studies suggest that application of WECs should always consider the wave climate of locations. In milder regions regions such as the Mediterranean countries suggestions for hydrodynamically scaling devices down to match the local wave environment have been proposed [56, 57, 58, 59, 60].

Several devices are coupled with locations via power matrices as found in various studies [61, 50, 62]. These are used to indicatively assess the energy performance of multiple WECs for several coastal locations, as identified by the resource assessment. WECs selected for each location have been based on the depth characteristics of areas and proposed practices [24]. The WECs used in the study represent both deep and shallow water technologies, although no coastal applications are taken into account. More detail discussions on technical characteristics of WECs are discussed in several studies [50, 63, 58, 62, 64, 65].

Power matrices account for the production of the extractable energy by a WEC based on joint wave distribution. Though, other ways exist in order to calculate the energy levels, power matrices are the most commonly used. For a more detail analysis on the production in case of multiple devices and their wave-wave interaction [50, 66], discusses alternative computational fluid dynamic models (CFD).

As seen in Figs. 16-20 the characteristic periods (T) and H_{sig} are different for each converter. From a first glance we expect that the local environment will favour converters which tend to have a cut-in operation and maximum output at lower wave heights i.e. WaveStar, see Fig. 20. The devices are classified according to existing literature to shallow and deep (mid-depth less than $\leq 150m$). Obviously, not all of them are applicable at the locations, see Table 3.

We have examined the production levels at all coastal and nearshore

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[1] WaveStar based on its operation can be deployed at higher depths [50, 66, 67]

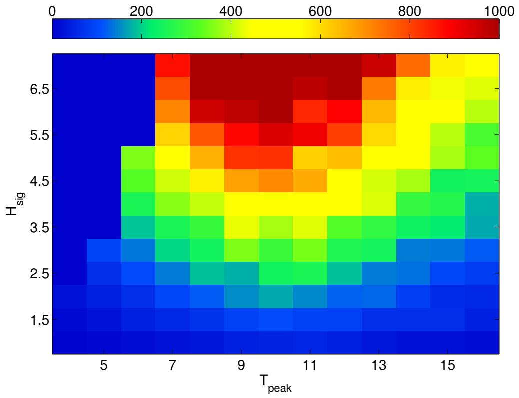


Figure 16: F-2HB power matrix (kW)

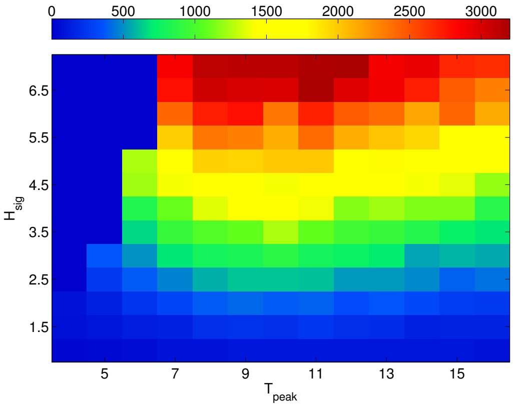


Figure 17: BOF power matrix (kW)

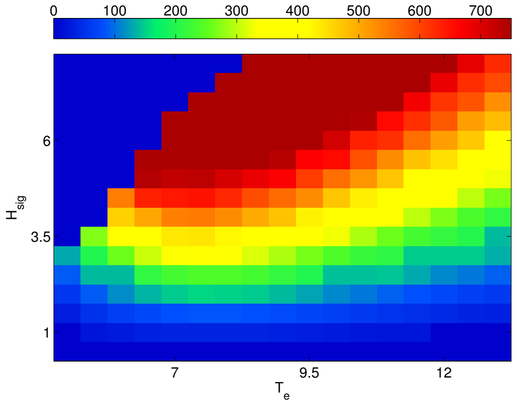


Figure 18: Pelamis power matrix (kW)

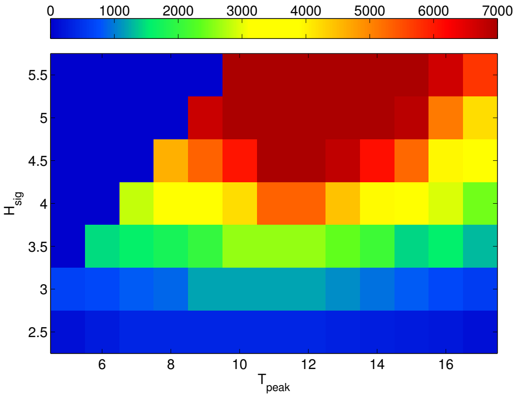


Figure 19: WaveDragon power matrix (kW)

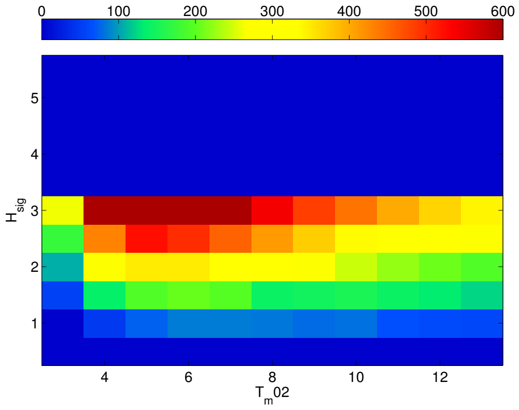


Figure 20: WaveStar power matrix (kW)

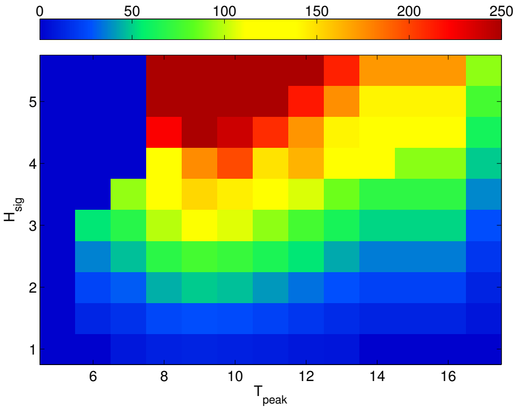


Figure 21: AquaBuoy power matrix (kW)

Table 3: Device classification according to depth

Wave Energy Converter (WEC)	Nearshore	Deep	Operational Depth (h)
Bottom Oscillating Flap (BOF)	X		$h \leq 50m$
WaveStar[1]	X		$h \leq 50m$
Floating two body heave converter (F2HB)	X		$h \leq 50m$
Pelamis		X	$h \geq 50m$
WaveDragon		X	$h \geq 50m$
AquaBuoy		X	$h \geq 50m$

locations, for over a period of 35 years. As installed capacity of each device, the maximum allowed power production was taken into account, similar to when examining other renewable technologies i.e. wind turbines.

The use of multiple devices in the selected locations reveals not only the compatibility of each device for the wave environments but also levels of expected production by bigger array of devices. Because the Aegean Sea is exposed to almost three times less the average energetic wave resource in comparison to the oceanic coastline, device selection has to account dominant conditions to maximise the energy production, selecting a WEC should not only rely upon installed capacity (kW) but also on characteristics of operation.

The power matrices utilized in this study have not been scaled down to match the specific areas, but provide a first glance on the feasibility and best applicable devices. Downscalling can be performed either through applying a Froude criterion and re-estimating the power matrices as seen in Luppa et.al. [68], or by utilising hydrodynamic models with specified input conditions appropriate to the local seas (as taken from the database) and constructing the scale power matrices as seen in Babarit et.al. [50] and Bozzi et.al. [58].

Estimating production with long-term data series allows for for a robust estimation of capacity factors (CF) for all devices in the region. Based on available recordings, final estimations of production and CF by a device is not only based on annual data, but on the overall 35 years. Data used are extracted from the nested higher resolution domain and correspond to one hourly wave parameters, annual total time is ≈ 8760 hours (except for leap years) with overall datasets per location including $\approx 306,000$ hours. This implies that final proposed capacity factors per area are extensive, include intra-annual variations, and downtimes due to storms or very mild seas, though no consideration on the required maintenance hours is considered.

However, concerning downtime for maintenance is not expected to alter the results significantly, since most of the times maintenance work is carried out on very mild sea states, which are indirectly taken into account.

Estimation of capacity factors offers an improvement to the perception of WEC performance in the areas, and exhibit that even without hydrodynamical downscaling, devices are able to produce amounts of energy and can easily compare to other mature and technically advanced technologies such as photovoltaic and onshore wind. Some studies have suggested that by specifically creating a more ”generic” device adapted to the Mediterranean Sea is expected to boost performance and capacity factors enhancing the energy production and potential decrease of costs [58, 5, 69].

4. Results

4.1. Wave Energy at the Aegean Sea, the case of Greece

The electricity system in Greece can be classified in two distinct ways as the central connected region (continental), and dispersed non-connected electrical networks (islands). This arises the opportunity for wave energy to be considered in combination with other renewable energies for the vast number of de-centralized islands. The locations and spatial wave maps analysis (see Figs 12-13) represent a thorough and robust energy quantification of the opportunities for wave energy applicability.

Extracted additional locations give focus on decentralized islands, and examine the potential contribution by wave energy. The authors would like to point out that although average annual and seasonal maps for wave energy, wave height, and period are constructed, due to publication limitations, the present analysis uses overall mean maps. With a variety of monthly, annual and seasonal products developed and accompanying our database.

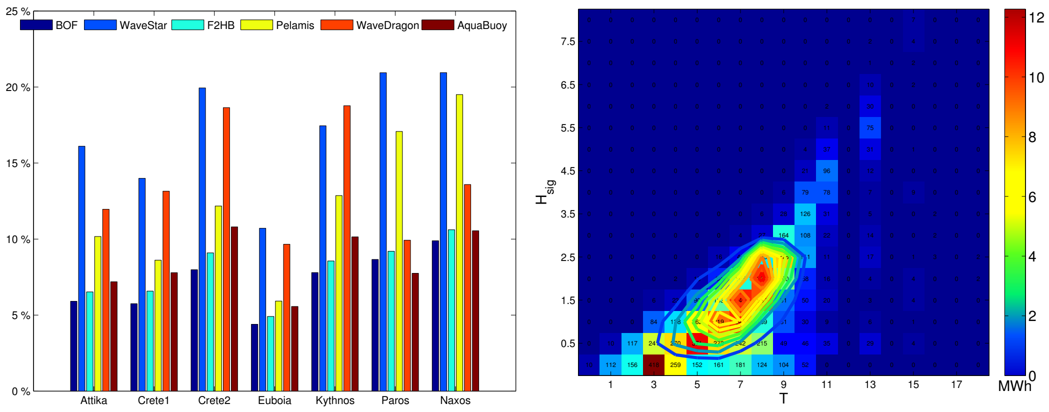
A long-term hindcast allows for characterization and estimation of potential power production. Indicative locations have considered one device installed. Although, the same results can be used to extend in nearby areas for consideration of wave energy farms with multiple same devices.

Production is estimated in expected GWh per year, see Table 4, with capacity factors given per technology and location. Identifying the exploitable energy content and quantify expected production by-off-the-self technologies.

On absolute energy production terms WaveDragon dominates the results followed by BOF. Remainder WECs have similar levels of production, with the lowest expressed by AquaBuoy. WaveDragon has rated capacity (7MW)

Table 4: Expected Production ($\approx GWh$)

	Crete 1	Crete 2	Kythnos	Paros	Naxos	Attika	Euboia
BOF	1.61	2.24	2.19	2.77	2.43	1.66	1.23
WaveStar	0.74	1.05	0.92	1.10	1.10	0.85	0.56
FH2B	0.58	0.80	0.75	0.93	0.81	0.57	0.43
Pelamis	0.57	0.80	0.84	1.28	1.12	0.67	0.39
WaveDragon	8.06	11.43	11.51	8.33	6.09	7.34	5.92
Aquabuoy	0.17	0.24	0.22	0.23	0.17	0.16	0.12



(a) Capacity Factor

(b) Matched production

Figure 22: (a) Capacity factors by various WECs, (b) matched production with occurrences for Crete2 in 2000

and was expected that production levels would be significantly greater. This though is not coming without a cost, since the higher the rated capacity then capital expenditure is increased.

Even so, the goal is to obtain the best performance i.e. energy production with lowest cost. Robust identification of capacity factors is a crucial component for the determination of most suitable device for the region. Extensive simulation analysis allows to estimate the annual expected energy extracted by each device, and indicative numbers of capacity factors that can be of use throughout the Greek region.

In Fig. 22 the corresponding capacity factors over the aggregated period, for such resources the most useful operated device is the WaveStar, with significant less rated power (600kW) than WaveDragon which provided highest energy yield. Pelamis also attained consistent production throughout South-

Table 5: Capacity factor per Device and region

Device/Locations	Crete	Central Aegean	Central Greece
BOF	7%	9%	5%
WaveStar	17%	20%	13%
F2HB	8%	9%	6%
Pelamis	10%	16%	8%
WaveDragon	16%	14%	11%
Aquabuoy	9%	9%	6%

ern regions. F2HB, BOF and Aquabuoy present similar performances for all areas under 10%. In panel (b) of the same figure the annual number of occurrences are correlated with the production of WaveStar. The coloured contour represent the energy production of the WEC, while the background coloured box plot present the number of occurrences. The lowest operational characteristics of WaveStar match and favour enery production as this is expressed in higher capacity factors.

As mentioned, not all devices are suitable for all locations though we chose to effectively assess all devices and explore couple WEC production. Exact depths are not easy to calculate, due to spatial limitations when constructing the bathymetry profile, wave energy resources are expected to be similar at nearby coastal locations. The elaborated sharp changes of the Greek territory also suggest that distances from shore will be very small, even for depths of 150 m underlining careful consideration of area selection.

As the study focused on several locations, we can consider capacity factors per device and region as follows in Table 5. The area with highest potential levels of utilisation is the Southern and Central Aegean. With suitable to resource WECs presenting CF over $\approx 10 - 20\%$.

From generation information, capacity factors, distribution, and resource levels it is obvious that low wave height and high frequency devices operate much better, due to the low resource expressed in the areas. Components which comprise wave energy resource in the Aegean, indicate that WECs with lower operational ranges are highly favoured. This is directly correlated to the availability of resource, devices which achieve higher CF have nominal power at lower H_s and high frequencies (short second periods), see Figs. 16-21.

Specifically, Wavestar is more suitable because it achieves peak production at lower wave heights ($\leq 3m$) and shorter periods (high frequencies), matching dominant lower resource conditions better. We have to underline the fact that energy quantification is based on publicly available power matrices, which entail levels of uncertainty in production from $\pm 20 - 40\%$ [50].

Another issue potential affecting WECs is effect of directionality, although such information concerning the power matrices are not available publicly. Swell direction is not involved in our computing power analysis, it is important to emphasize that it can be a parameter to consider when installing a power converter at a specific site, since many of them use the most frequent direction as a design parameter, like the Pelamis. A future custom site selected analysis is required to determine the "shadow" effects and diffusion of energy by wave farms. Such analysis can be achieved by coupling focused hydrodynamic modelling, and wave farm interactions analysis. This can also lead to the determination of a hydrodynamically downscaled converters suitable for the resource, reducing capital expenditure and increasing performance.

4.2. Preliminary Economic Evaluation with Regional Adaptation

Currently in Greece all renewable installations are provided with a Feed-In-Tarrif (FIT) from the Greek government based on region and contribution to system (centralized or decentralized). Higher FITs are provided to island regions in order to maximize the use of RE and reduce energy dependency by fossil fuels. So far the consideration of the Greek State have been solely based on the development of wind, photovoltaic, solar and some level of biomass, no consideration or appropriate pricing exists for the development of innovative technologies in the region such as wave energy [70].

In addition, current investment schemes provide some level of subsidization activities including energy production; latest developments have excluded photovoltaics and wind. The authors believe the proposed installation of WECs can be classified as an investment of highly technical and skilled nature allowing it to be included in the umbrella of the legislation [71].

The above legislative framework separates the region of Greece into subdivisions allowing higher levels of potential subsidies in the island regions of the Aegean, where as shown in the previous sections the wave energy potential is greater [71]. These subsidies may vary from $30\% - 50\%$, with current FITs subdivided according to technology, selling prices of electricity by offshore wind is 105Euro/MWh, and island based photovoltaic $260 - 290$ Euro/MWh regardless of installation capacity. RE produced electricity is sold at priority to the Greek electrical operator. This ensures that the investment of green technologies is allowed priority grid penetration, while selling electricity price if guaranteed for 20 years of contract (10+10 years). Considering the innovative nature of the technology and the fact that is located offshore, the authors considered a range of proposed prices spanning from 150-250 Euro/MWh, as is the case for de-centralized connected photovoltaics [70].

Apart from energy generation estimation, the investigation of adapted cost is imperative for the areas, providing with preliminary results of associated costs and levels of amortization periods. Costs for wave energy are mostly associated with Northern European countries for which wave energy has been looked at a much higher degree. Here associated CAPEX and OPEX are based on a scaled down approach of cost, taking into account the milder seas and conditions that are encountered. Infrastructure and initial work cost associate relevant areas and their extreme values by assigning a proper percentage for maintenance and operation taking into account local environment and infrastructure.

Studies that have examined the cost of wave energy converters, though at initial stages suggest that WEC sost should always be considered based on the device chosen [72, 63, 73, 74, 75, 76]. Studies suggest cost of the power-take-off (PTO) of a device ranging from $2,000,000$ up to $3,500,000$ Euros/MW. This corresponds to devices using material and structural considerations based on far higher energetic Seas (i.e. Atlantic exposed coastlines), the authors consider them as CAPEX ex-works cost. It is logical to expect that adaptation of a device in the milder Aegean environment will require less CAPEX, thus one can consider (depending on technology) that the cost will start at $1,750,000$ to $2,000,000$ Euros/MW, with less need for mooring strengthening and other infrastructure cost reduced in comparison with the reported for the European Atlantic costs.

The lifetime of a wave farm taken as 20 years, while indicative consideration on operational costs and infrastructure (works costs) examined and presented. However, some assumptions are made in terms of the economic indices, the energy estimations are improved in comparison to previous studies with capacity factors based on a thorough energy assessment.

The authors have considered that the CAPEX cost has the highest influence. In Table 6 all financial considerations of the scenarios are given, with CAPEX representing the ex-works costs, installation ($inst_{cost}$) and maintenance costs (m_{cost}) being a specific percentage of CAPEX. Selling price of electricity considers inflation (g), rate of return (i), energy escalation (e), potential subsidy (γ), and capacity factor (CF) are assigned constant values. The CAPEX has been assigned in a range of 1.5-3.5 million Euros/MW, and is incrementally increased by 500,000 Euro.

Table 6: Financial considerations on the cost of a wave energy farm

	CAPEX	$inst_{cost}$	m_{cost}	c_o	g	i	e	γ	CF	P_o
Scenario 1	1.5 mE	22%	5% per annum	220 E/MWh	2%	10%	3%	40%	15%	10
Scenario 2	2 mE	22%	5% per annum	220 E/MWh	2%	10%	3%	40%	15%	10
Scenario 3	2.5 mE	22%	5% per annum	220 E/MWh	2%	10%	3%	40%	15%	10
Scenario 4	3 mE	22%	5% per annum	220 E/MWh	2%	10%	3%	40%	15%	10
Scenario 5	3.5 mE	22%	5% per annum	220 E/MWh	2%	10%	3%	40%	15%	10

Additional revenues are expected for RE by introduction of CO_2 permits sold through the Emission Trading Scheme (ETS), for the avoided cost of carbon used in electricity production. While this can be a significant added revenue stream, it has not been taken into account. WEC downscaling using hydrodynamic modelling for the region is expected to reduce overall CAPEX, and shortening the payback period significantly. The energy calculated and annual revenue stream for financial estimations are based on the proposed method by Kaldellis [77]. With initial capital (CAPEX) including the I_{Cn}, works cost ($inst_{cost}$) and installed capacity for every MW installed (P_o).

$$I_{Co} = [(I_{Cn} \cdot inst_{cost}) + I_{Cn}] \cdot P_o \tag{5}$$

The fixed annual cost for $M\&O$ (m_{cost}) calculated by the assigned percentage of maintenance, and values are estimated for current money prices, over years (n). The annual fixed cost (FC_n) expenditure allows to calculate the cost to benefit (C_n) of the wave farm.

$$FC_n = m_{cost} \cdot IC_o \cdot \left[\frac{1+g}{1+i} + \cdots + \left(\frac{1+g}{1+i}\right)^n\right] \tag{6}$$

$$C_n = IC_o + FC_n \tag{7}$$

Annual revenues are estimated by adapting the CF with installed capacity over one year period providing the annual energy (E_o), with the finalized earnings of each year adapted to current prices.

$$R_n = E_o \cdot c_o \cdot \left[\frac{1+e}{1+i} + \cdots + \left(\frac{1+e}{1+i}\right)^n\right] \tag{8}$$

The final amortization periods, i.e. "break-even" scenarios, are estimated by accumulated gains of each years adjusted to current prices R_n, and the C_n of the wave farm.

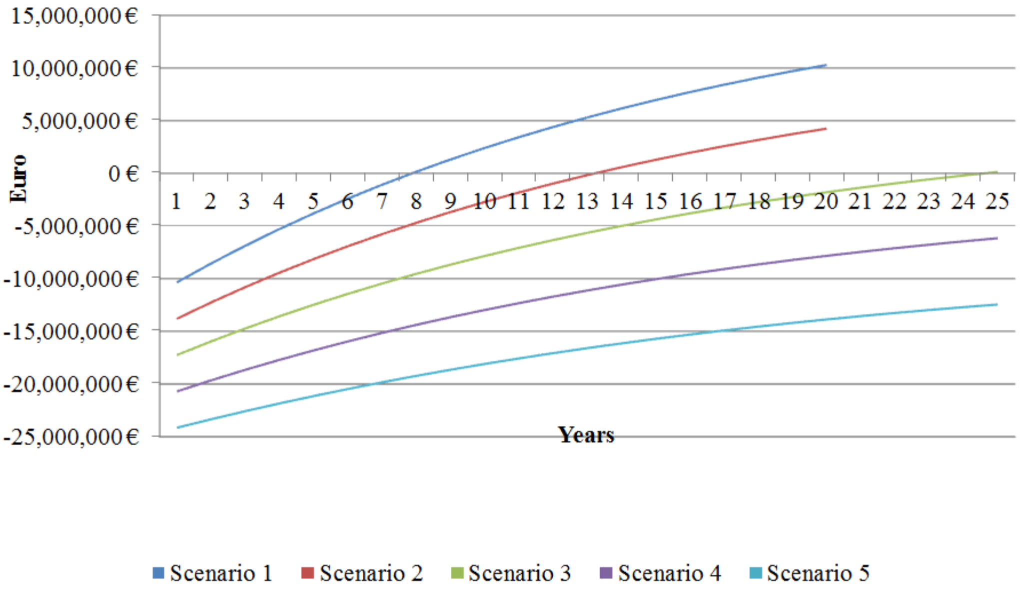


Figure 23: Payback Period for Scenarios, with y-axis monetary terms and x-axis the years of operation

The preliminary considerations on wave energy amortization periods show the potential payback for such an investment concerning different scenarios, see Fig. 23. Based on the assumptions Scenario 1 offers amortization within 7-8 years, Scenario 2 requires 12-13 years, Scenario 3 requires ≈ 22.5[1], while Scenarios 4-5 never break even.

Of course as explained there is not a specific legislative framework supporting wave energy in the region, thus assumptions taken into account especially the electricity selling price and investment subsidization are expected to affect the results. Based on previous experience with other technologies applied in the Greek Market through $2000 - 2008$, first stage PV park installations were given 50% subsidies while the FIT (for a then immature technology) was 450 Euro/MWh.

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[1] Extended to 25 years to observe whether break-even is achieved

Another important factor is the economic uncertainty, especially of CAPEX, associated with such pre-commercial technologies. Sensitivity of the payback period depends highly on CAPEX, thus a further investigation on reducing CAPEX by exact specifications of materials and costs used in a hydrodynamically downscaled WEC may accelerate the technology.

Initial findings show that the adaptation of wave energy can lead to investment considerations even Technology Readiness Levels (TRL) of such new technology, with additional improvements and clarifications in the regulatory and legal frameworks required. Although, as shown in the analysis for wave energy, variability of capacity factors and generating performance is heavily dependent on the selection of the appropriate device to be implemented and scaled to the location.

Thus, this extensive study has allowed a long-term estimation for the indicative technologies and their utilization rates for Greeece. The authors would also like to repeat that energy estimations are based on published power matrices; by obtaining more detailed information available by developers, we expect a better understanding of the opportunities.

5. Conclusions

In this study the wave environment of the Mediterranean and Aegean region was hindcasted for 35 years, from 1980-2014, with a nearshore fine resolution model that used nested domains. Previous studies, have expressed considerations about the limitations of larger models used in terms of their capabilities to resolve coastal and complex orographic regions. In addition, the selected wind dataset provides with a high temporal input in an attempt to reduce under-estimations, as this is one of the most common problems in wave models.

So far, there has not been a long-term fine-resolution coastal wave energy atlas for the region. Our dataset is validated compared with buoy measurements, and allowed a detail spatial characterisation of the Greek Seas for wave energy and dominant conditions. The wave climate of the region is examined in terms of the seasonal and annual variation of its parameters with an extensive scope for wave energy sites.

Subsequently our resulted dataset is coupled with available published power matrices provided, to deliver for the first time a detail production assessment and performance of WECs for the Greek Seas. Electrical production estimates show that significant contributions can be achieved by

WECs that can benefit the many islands in the Greek Seas. The levels of potential power per device vary according to location as expected, with most favourable WECs operating at low H_s and high frequencies that match the resource characteristics of the Aegean.

A preliminary financial sensitivity analysis provides insight for wave energy in the Aegean, for the first time, based on expected production and available schemes promoting RE in Greece. The results show that the uncertainty and large range of capital expenditure affects the amortisation periods. Feasible payback periods vary from 7.5 to 13 years, with larger CAPEX leading to not viability under the current assumptions. Although the initial expenditure is high the milder conditions and smaller variability levels provide consistent resource, these conditions can reduce costs and accelerate proof-of-concepts. Acting as a catalyst to assist potential energy contribution by RE to the de-carbonisation of the heavily dependent Greek island system.

Based on the results of the study, further analysis can be developed. Firstly, based on disseminated areas a dedicated and even higher resolution assessment can be used to model the wave interactions of WEC farms. The current hindcast dataset can be used for hydrodynamic downscaling analysis of ”generic” converters. Long-term wave characteristics of high temporal resolution can aid in sizing WEC operation at the region much more effectively. Such custom to resource devices will have lower capital and operational expenditures, accelerating the proof-of-concept and providing better economical considerations.

6. Acknowledgements

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7. References

[1] A. Clément, P. McCullen, A. Falcão, A. Fiorentino, F. Gardner, K. Hammarlund, G. Lemonis, T. Lewis, K. Nielsen, S. Petroncini, M. T. Pontes, P. Schild, B. O. Sjöström, H. C. Sørensen, T. Thorpe, Wave energy in Europe: Current status and perspectives, Renew. Sustain. Energy Rev. 6 (5) (2002) 405–431. doi:10.1016/S1364-0321(02)00009-6.

[2] K. Guizien, Spatial variability of wave conditions in the gulf of lions (NW Mediterranean Sea), Vie Milieu 59 (3-4) (2009) 261–270.

[3] G. Korres, A. Papadopoulos, P. Katsafados, D. Ballas, L. Perivoliotis, K. Nittis, A 2-year intercomparison of the WAM-Cycle4 and the WAVEWATCH-III wave models implemented within the Mediterranean Sea, Sci. Mediterr. Mar.

[4] T. H. Soukissian, A. M. Prospathopoulos, C. Diamanti, Wind and Wave Data Analysis for the Aegean Sea - Preliminary Results, J. Atmos. Ocean Sci. 8 (2-3) (2002) 163–189. doi:10.1080/1023673029000003525.

[5] D. Vicinanza, L. Cappietti, P. Contestabile, Assessment of Wave Energy around Italy, 8th European Wave and Tidal Energy Conference (2009) 256–262.

[6] Medatlas Group, Wind and Wave Atlas of the Mediterranean Sea, Tech. Rep. April, Western European Union (2004).

[7] A. W. Ratsimandresy, M. G. Sotillo, J. C. Carretero Albiach, E. Álvarez Fanjul, H. Hajji, A 44-year high-resolution ocean and atmospheric hindcast for the Mediterranean Basin developed within the HIPOCAS Project, Coast. Eng. 55 (11) (2008) 827–842. doi:10.1016/j.coastaleng.2008.02.025.

[8] L. Mentaschi, G. Besio, F. Cassola, A. Mazzino, Performance evaluation of Wavewatch III in the Mediterranean Sea, Ocean Model.doi:10.1016/j.ocemod.2015.04.003.

[9] S. Ponce de Leon, A. Orfila, G. Simarro, Wave energy in the Balearic Sea. Evolution from a 29 year spectral wave hindcast, Renewable Energy 85 (2016) 1192–1200. doi:10.1016/j.renene.2015.07.076.

[10] B. Cañellas, A. Orfila, F. Méndez, M. Menéndez, J. Tintoré, Application of a POT model to estimate the extreme significant wave height levels around the Balearic Sea (Western Mediterranean), J. Coast. Res. Spec. Issue 50 (50) (2007) 329–333.
URL http://costabalearsostenible.com/PDFs/ICS2007{_}final3{_}.pdf

[11] L. Bertotti, L. Cavaleri, Wind and wave predictions in the Adriatic Sea, J. Mar. Syst. 78 (2009) S227–S234. doi:10.1016/j.jmarsys.2009.01.018.

[12] G. Contento, G. Lupieri, M. Venturi, T. Ciuffardi, A medium-resolution wave hindcast study over the Central and Western Mediterranean Sea, J. Mar. Sci. Technol. 16 (2) (2011) 181–201. doi:10.1007/s00773-011-0122-5.

[13] L. Liberti, A. Carillo, G. Sannino, Wave energy resource assessment in the Mediterranean, the Italian perspective, Renew. Energy 50 (2013) 938–949. doi:10.1016/j.renene.2012.08.023.

[14] T. H. Soukissian, A. Prospathopoulos, G. Korres, A. Papadopoulos, H. Maria, K. Maria, A new wind and wave atlas of the Hellenic Seas, in: Proc. ASME 2008 27th Int. Conf. Ocean. Arct. Eng. OMAE2008, ASME, Estoril,Portugal, 2008, pp. 1–9.

[15] A. Zacharioudaki, G. Korres, L. Perivoliotis, Wave climate of the Hellenic Seas obtained from a wave hindcast for the period 1960-2001, Ocean Dyn. 65 (6) (2015) 795–816. doi:10.1007/s10236-015-0840-z.

[16] G. Emmanouil, G. Galanis, C. Kalogeri, G. Zodiatis, G. Kallos, 10-year high resolution study of wind, sea waves and wave energy assessment in the Greek offshore areas, Renew. Energy 90 (2016) 399–419. doi:10.1016/j.renene.2016.01.031.

[17] B. Ayat, Wave power atlas of Eastern Mediterranean and Aegean Seas, Energy 54 (2013) 251–262. doi:10.1016/j.energy.2013.02.060.

[18] N. Jadidoleslam, M. Özger, N. Araliolu, Wave power potential assessment of Aegean Sea with an integrated 15-year data, Renew. Energy 86 (2016) 1045–1059. doi:10.1016/j.renene.2015.09.022.

[19] N. Mazarakis, V. Kotroni, K. Lagouvardos, L. Bertotti, High-resolution wave model validation over the Greek maritime areas, Nat. Hazards Earth Syst. Sci. 12 (11) (2012) 3433–3440. doi:10.5194/nhess-12-3433-2012.

[20] G. Lavidas, V. Venugopal, D. Friedrich, Investigating the opportunities for wave energy in the Aegean Sea, in: 7th Int. Sci. Conf. Energy Clim.

Chang. 8-10 Oct. 2014 Athens, PROMITHEAS The Energy and Climate Change Policy Network, Athens, 2014.

[21] T. Delft, SWAN User Manual Cycle III version 41.01 (2014).

[22] S. Saha, S. Moorthi, H. L. Pan, X. Wu, J. Wang, S. Nadiga, P. Tripp, R. Kistler, J. Woollen, D. Behringer, H. Liu, D. Stokes, R. Grumbine, G. Gayno, J. Wang, Y. T. Hou, H. Y. Chuang, H. M. H. Juang, J. Sela, M. Iredell, R. Treadon, D. Kleist, P. Van Delst, D. Keyser, J. Derber, M. Ek, J. Meng, H. Wei, R. Yang, S. Lord, H. Van Den Dool, A. Kumar, W. Wang, C. Long, M. Chelliah, Y. Xue, B. Huang, J. K. Schemm, W. Ebisuzaki, R. Lin, P. Xie, M. Chen, S. Zhou, W. Higgins, C. Z. Zou, Q. Liu, Y. Chen, Y. Han, L. Cucurull, R. W. Reynolds, G. Rutledge, M. Goldberg, The NCEP climate forecast system reanalysis, Bull. Am. Meteorol. Soc. 91 (8) (2010) 1015–1057. `doi:10.1175/2010BAMS3001.1`.

[23] V. Venugopal, T. Davey, H. Smith, G. Smith, L. Cavaleri, L. Bertotti, L. John, Equitable testing and evaluation of Marine Energy Extraction Devices of Performance, Cost and Environmental Impact. Deliverable 2.3 Application of Numerical Models, Tech. rep. (2010).

[24] D. Ingram, G. H. Smith, C. Ferriera, H. Smith, Protocols for the Equitable Assessment of Marine Energy Converters, Tech. rep., Institute of Energy Systems, University of Edinburgh, School of Engineering (2011).

[25] S. Piche, A. M. Cornett, S. Baker, I. Nistor, Validation of the IEC Technical Specification for Wave Energy Resource Assessment, in: Proc. 11th Eur. Wave Tidal Energy Conf. 6-11th Sept 2015, Nantes, Fr., Nantes, 2015, pp. 1–10.

[26] C. Amante, B. Eakins, ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24 (2014).
URL `http://maps.ngdc.noaa.gov/viewers/wcs-client/`

[27] G. Komen, L. Cavaleri, M. Donelan, S. Hasselmann, P. Janssen, Dynamics and Modelling of Ocean waves, Cambridge University Press, 1994.
URL `www.cambridge.org/9780521470476`

[28] T. Delft, SWAN scientific documentation Cycle III version 41.01, Delft University of Technology Faculty of Civil Engineering and Geosciences Environmental Fluid Mechanics Section, 2014.

[29] H. Hellenic Centre for Marine Research, Monitoring, Forecasting System Oceanographic information for the Greek Seas (POSEIDON) (2014). URL http://www.poseidon.hcmr.gr/

[30] L. Cavaleri, M. Sclavo, A wind and wave atlas for the Mediterranean Sea, Eur. Sp. Agency, (Special Publ. ESA SP (614) (2006) 0–5.

[31] L. Cavaleri, M. Sclavo, The calibration of wind and wave model data in the Mediterranean Sea, Coast. Eng. 53 (7) (2006) 613–627. doi:10.1016/j.coastaleng.2005.12.006.

[32] I. R. Young, Seasonal variability of the global ocean wind and wave climate, Int. J. Climatol. 950 (19) (1999) 931–950.

[33] J. Vinoth, I. R. Young, Global Estimates of Extreme Wind Speed and Wave Height, J. Clim. 24 (6) (2011) 1647–1665. doi:10.1175/2010JCLI3680.1.

[34] G. Lavidas, V. Venugopal, D. Friedrich, Sensitivity of a numerical wave model on wind re-analysis datasets, Dynamics of Atmospheres and Oceans 77 (2017) 1 – 16. doi:http://dx.doi.org/10.1016/j.dynatmoce.2016.10.007.

[35] R. C. Ris, L. H. Holthuijsen, N. Booij, A third-generation wave model for coastal regions: 2.Verification 104 (1999) 7667–7681.

[36] T. Soukissian, A. Pospathopoulos, The Errors-in-Variables approach for the validation of the WAM wave model in the Aegean Sea, Sci. Mediterr. Mar. 7 (1) (2006) 47–62.

[37] P. A. Janssen, Wave - induced Stress and drag of air flow over sea waves.pdf, J. Phys. Oceanogr. 19 (6) (1988) 745–754.

[38] P. A. Janssen, Quasi-Linear theory of Wind-Wave Generation applied to wave forecasting, J. Phys. Oceanogr. 6 (1991) 1631–1642.

[39] P. Janssen, The Interaction of Ocean Waves and Wind, Cambridge University Press, Cambridge, 2009. doi:10.1017/CBO9780511525018.

[40] J. W. Miles, On the generation of surface waves by shear flows, J. Fluid Mech. (1957) 185–204doi:10.1017/S0022112057000567.

[41] L. Cavaleri, J.-H. Alves, F. Ardhuin, A. Babanin, M. Banner, K. Belibassakis, M. Benoit, M. Donelan, J. Groeneweg, T. Herbers, P. Hwang, P. Janssen, T. Janssen, I. Lavrenov, R. Magne, J. Monbaliu, M. Onorato, V. Polnikov, D. Resio, W. Rogers, A. Sheremet, J. McKee Smith, H. Tolman, G. van Vledder, J. Wolf, I. Young, Wave modelling The state of the art, Prog. Oceanogr. 75 (4) (2007) 603–674. doi:10.1016/j.pocean.2007.05.005.

[42] P. A. Janssen, Progress in ocean wave forecasting, J. Comput. Phys. 227 (7) (2008) 3572–3594. doi:10.1016/j.jcp.2007.04.029.

[43] S. Caires, A. Sterl, J.-R. Bidlot, N. Graham, V. Swail, Intercomparison of Different Wind-Wave Reanalyses, J. Clim. 17 (10) (2004) 1893–1913.

[44] D. P. Dee, S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A. J. Geer, L. Haimberger, S. B. Healy, H. Hersbach, E. V. Holm, L. Isaksen, P. Kallberg, M. Kohler, M. Matricardi, A. P. Mcnally, B. M. Monge-Sanz, J. J. Morcrette, B. K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J. N. Thepaut, F. Vitart, The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Q. J. R. Meteorol. Soc. 137 (656) (2011) 553–597. doi:10.1002/qj.828.

[45] J. E. Stopa, K. F. Cheung, Intercomparison of wind and wave data from the ECMWF Reanalysis Interim and the NCEP Climate Forecast System Reanalysis, Ocean Model. 75 (2014) 65–83. doi:10.1016/j.ocemod.2013.12.006.

[46] L. Cavaleri, Wave Modeling-Missing the Peaks, J. Phys. Oceanogr. 39 (11) (2009) 2757–2778. doi:10.1175/2009JPO4067.1.

[47] H. Smith, Best Practice Guidelines for Wave and Current Resource Assessment Task 1 . 6 of WP3 from the MERiFIC Project A report prepared as part of the MERiFIC Project ” Marine Energy in Far Peripheral and Island Communities ” (June) (2014) 1–16.

[48] B. Reguero, I. Losada, F. Méndez, A global wave power resource and its seasonal, interannual and long-term variability, Appl. Energy 148 (2015) 366–380. doi:10.1016/j.apenergy.2015.03.114.

[49] G. P. Harrison, a. R. Wallace, Climate sensitivity of marine energy, Renew. Energy 30 (12) (2005) 1801–1817. doi:10.1016/j.renene.2004.12.006.

[50] A. Babarit, J. Hals, M. Muliawan, A. Kurniawan, T. Moan, J. Krokstad, Numerical benchmarking study of a selection of wave energy converters, Renew. Energy 41 (2012) 44–63. doi:10.1016/j.renene.2011.10.002.

[51] ORECCA, Off-shore Renewable Energy Conversion platforms Coordination Action (ORECCA) (2015).
URL http://www.orecca.eu/web/guest

[52] G. Hagerman, Southern New England Wave Energy Resource Potential, in: Building Energy, no. March, 2001.

[53] M. Saglam, E. Sulukan, T. S. Uyar, Wave Energy and Technical potential of Turkey, J. Nav. Sci. Eng. 6 (2) (2010) 34–50.

[54] A. Akpinar, M. . Kömürcü, Wave energy potential along the south-east coasts of the Black Sea, Energy 42 (1) (2012) 289–302. doi:10.1016/j.energy.2012.03.057.

[55] G. Lavidas, Wave Energy Resource Modelling and Energy Pattern Identification Using a Spectral Wave Model, Ph.d thesis, University of Edinburgh, Edinburgh (2016).

[56] D. Vicinanza, L. Cappietti, V. Ferrante, P. Contestabile, Estimation of the wave energy in the Italian offshore, J. Coast. Res. (64) (2011) 613–617.

[57] S. Bozzi, P. Milano, G. Passoni, Omae2011-49372 Feasibility Study of Wave Energy Farm in the Western Mediterranean Sea : Comparison Among Different Technologies, in: Proc. ASME 2011 30th Int. Conf. Ocean. Arct. Eng. OMAE2011, 2011, pp. 1–6. doi:978-0-7918-4437-3.

[58] S. Bozzi, A. M. Miquel, A. Antonini, G. Passoni, R. Archetti, Modeling of a point absorber for energy conversion in Italian seas, Energies 6 (6) (2013) 3033–3051. doi:10.3390/en6063033.

[59] S. Bozzi, R. Archetti, G. Passoni, Wave electricity production in Italian offshore: A preliminary investigation, Renew. Energy 62 (2014) 407–416. doi:10.1016/j.renene.2013.07.030.

[60] A. de Andres, R. Guanche, C. Vidal, I. Losada, Adaptability of a generic wave energy converter to different climate conditions, Renew. Energy 78 (2015) 322–333. doi:10.1016/j.renene.2015.01.020.

[61] R. H. Hansen, M. M. Kramer, Modelling and Control of the Wavestar Prototype, Proc. 9th Eur. Wave Tidal Energy Conf. (2011) 1–10.

[62] D. Silva, E. Rusu, C. G. Soares, Evaluation of various technologies for wave energy conversion in the portuguese nearshore, Energies 6 (2013) 1344–1364. doi:10.3390/en6031344.

[63] R. Carballo, G. Iglesias, A methodology to determine the power performance of wave energy converters at a particular coastal location, Energy Convers. Manag. 61 (2012) 8–18. doi:10.1016/j.enconman.2012.03.008.

[64] J. Fernández-Chozas, N. E. Helstrup Jensen, H. C. Sørensen, J. P. Kofoed, A. Kabuth, Predictability of the power output of three wave energy technologies in the Danish North Sea, in: Proc. 9th Eur. Wave Tidal Energy Conf., Vol. 1, University of Southampton, 2011, pp. 84–98. doi:10.1016/j.ijome.2013.05.002.

[65] L. Rusu, F. Onea, Assessment of the performances of various wave energy converters along the European continental coasts, Energy 82 (2015) 889–904. doi:10.1016/j.energy.2015.01.099.

[66] A. Babarit, A database of capture width ratio of wave energy converters, Renew. Energy 80 (2015) 610–628. doi:10.1016/j.renene.2015.02.049.

[67] WaveStar, WaveStar (2015).
URL http://wavestarenergy.com/

[68] C. Luppa, L. Cavallaro, E. Foti, D. Vicinanza, Potential wave energy production by different wave energy converters around Sicily, J. Renew. Sustain. Energy 7 (6) (2015) 061701. doi:10.1063/1.4936397.

[69] M. Monteforte, C. Lo Re, G. Ferreri, Wave energy assessment in Sicily (Italy), Renew. Energy 78 (2015) 276–287. doi:10.1016/j.renene.2015.01.006.

[70] Law 3851/2010, Accelerating of Renewable Energy Sources for the avoidance of Climate Change and other themes in matters of relevance to the Greek Ministry of Environment, Power and Climate Change (In Greek), Tech. rep. (-).

[71] Law 3908/2011, Strengthening of Private Investments for the Financial Development, Entrepreneurship and Local Cohision(In Greek), Tech. rep. (–).

[72] G. Allan, M. Gilmartin, P. McGregor, K. Swales, Levelised costs of Wave and Tidal energy in the UK: Cost competitiveness and the importance of "banded" renewables obligation certificates, Energy Policy 39 (1) (2011) 23–39. doi:10.1016/j.enpol.2010.08.029.

[73] Carbon Trust, AMEC, Carbon Trust Foreword to UK Wave Resource Study ., Tech. Rep. October (2012).

[74] G. J. Dalton, R. Alcorn, T. Lewis, Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America, Renew. Energy 35 (2) (2010) 443–455. doi:10.1016/j.renene.2009.07.003.

[75] B. V. Mathiesen, H. Lund, K. Karlsson, 100% Renewable energy systems, climate mitigation and economic growth, Appl. Energy 88 (2) (2011) 488–501. doi:10.1016/j.apenergy.2010.03.001.

[76] M. O'Connor, T. Lewis, G. Dalton, Techno-economic performance of the Pelamis P1 and Wavestar at different ratings and various locations in Europe, Renew. Energy 50 (2013) 889–900. doi:10.1016/j.renene.2012.08.009.

[77] J. Kaldellis, Stand-alone and hybrid wind energy systems.Technology, energy storage and applications, Woodhead Publishing Limited, Great Abington, Cambridge CB21 6AH, UK, 2011.