Wave potential of the Greek seas

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Abstract

Most of the energy resources used worldwide comes from non-renewable sources such as fossil fuels. The wasteful and inappropriate use of such energy sources has led to adverse environmental effects; at the same time, there is an emerging and urgent need for pollution-free power generation. The exploitation of renewable energy sources (RES) is now a sustainable and technologically feasible solution). EU leaders agreed that by 2020, 20% of the energy of the Member states should be produced from renewable energy sources. One of the most promising renewable energy sources are sea waves. In Europe, intensive research and development of wave energy conversion began in 1973 and since the mid 1990's there has been a real renaissance in the field. This work presents a first attempt for a detailed assessment of the wave potential of the Greek seas, using data from numerical wave simulation models of high spatial and temporal resolution in combination with in-situ wave measurements. The hindcast data are in the form of time series and cover the period 1995–2004. It is also anticipated that the obtained wave energy results will provide a basis for selecting the most appropriate family of wave energy converter devices.

Keywords: wave energy, wave potential, Greek seas.

1 Introduction

The main energy source worldwide is fossil fuels. However, fossil fuels are being exhausted in such a rate that in the near future, reserves may not be adequate to meet prospective demands. At the same time, the intensive use of such energy sources has caused negative impacts to the quality of the environment. The need for immediate reduction of non-renewable energy sources is urgent; owing to this, European Union leaders agreed that by 2020

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20% of the energy of Member States should be produced from Renewable Energy Sources (RES).

Sea waves are considered to be a premium quality RES since they are characterized by the highest energy density among all other RES (Clement et al. [1]). However, sea wave energy has hardly ever been systematically exploited up to now though it attracts most of the advantages that characterize RES. Some of these advantages are: weak indicators of pollution, the decentralization of energy production, reduction of the imports of fossil fuels, prospects for economic development in remote areas, new job initiatives, etc. Considering the environmental effects from the deployment of wave energy converters such as noise or visual disturbances, impacts on the marine flora and fauna, etc., these are considered to be mild (Clement et al. [1], Iglesias et al. [4]). Moreover, the persistence of sea waves is, usually, longer than the wind persistence while waves may propagate in the form of swell far from their fetch area. The above characteristics of sea waves can be an occasional advantage regarding: i) the partial independence of the operation of wave energy converters from local weather conditions and ii) the development of hybrid (wind and wave) systems. The main difficulties in the exploitation of wave energy emerge from specific drawbacks of the respective technologies concerning high operating and construction costs. Besides, the randomness of sea waves, regarding their size, phase and direction, restricts a single device from achieving maximum efficiency over the range of ocean waves' excitation frequencies (Clement et al. [1]); this renders the choice of the most appropriate family of wave energy converter devices a difficult decision.

The best wave resource is presented in the temperate zone between latitudes 30 and 60 degrees in both hemispheres with wave power between 20-70 kW/m of wave front or even higher (CRES [5]). The technically exploitable wave potential of the Greek seas was estimated to vary between 4 and 11 kW/m (Clement et al. [1]).

This paper deals with this relatively new and unfamiliar in Greece renewable energy source which simultaneously has significant potential for exploitation in the near future worldwide. Greece, with an approximately 16000 km long coastline, has a high wind potential over the Aegean Sea which gives rise to relatively intense wave activity. Though the wind fetches are not so long due to the presence of island complexes, the channeling effect forms some hot-spots where wave power reaches high values.

This work presents a first attempt for a detailed assessment of the wave potential of the Greek seas, using data from numerical wave simulation models in combination with in-situ wave measurements. The hindcast data are of high spatial and temporal resolution and cover a period of 10 years (1995–2004) and are published in the form of a Wind and Wave Atlas (Soukissian et al. [6], Soukissian et al. [7]). The exploitation of the available wave potential could contribute to the country's demand of electricity from RES.

2 Wave power

Wave power is the rate at which wave energy is transmitted in the direction of wave propagation (normally expressed in kilowatts per metre of wave crest length) and the capture of that energy can be successfully used for electricity generation. The wave potential is determined from the amplitude of wave heights and wave period propagating across the sea surface. Compared to tides, the wave resource is more difficult to predict due to the “random” behaviour of the meteorological driving conditions.

2.1 Energy of linear waves

According to the linear wave theory, for a progressive monochromatic wave of crest amplitude a, wave height $H = 2a$ and circular frequency ω, propagating over an infinitely deep ocean, the total energy per unit of surface area is:

$$E = \frac{1}{2}\rho g a^2 = \frac{1}{8}\rho g H^2, \tag{1}$$

where ρ is the water density (1025 kg/m^3), g is the acceleration of gravity (9.81 m/s^2) and H is the wave height (m). The quantity E (J/m^2) is called wave energy density. A wave resource is typically described in terms of power per meter of wave front (or wave crest). This quantity can be calculated by multiplying the energy density by the wave celerity c_g (wave group velocity), i.e.,

$$P_{wave-front} = c_g E = nc\frac{1}{8}\rho g H^2, \tag{2}$$

where

$$n = \frac{1}{2}\left[1 + \frac{2kd}{\sinh(2kd)}\right], \tag{3}$$

c (ms^{-1}) is the phase velocity

$$c = \frac{\lambda}{\mathrm{T}} = \frac{\omega}{k} = \sqrt{\frac{g}{k}\tanh(kd)}, \tag{4}$$

d (m) is the water depth, $k = 2\pi/\lambda$ is the wave number (m^{-1}), ω is the radian frequency (s^{-1}), λ (m) is the wave crest length and $P_{wave-front}$ is expressed in W/m. For deep water $d \to \infty$, $n \to 1/2$, $c \to \sqrt{g/k}$ and eqn. (2) can be rearranged as follows:

$$P_{wave-front} = nc\frac{1}{8}\rho g H^2 = \frac{1}{16}c\rho g H^2 = \frac{1}{16}\rho g H^2\sqrt{\frac{g}{k}} = \tag{5}$$
$$= \frac{1}{16}\rho g H^2\sqrt{\frac{g^2}{\omega^2}} = \frac{1}{16}\rho g^2 H^2\frac{T}{2\pi} = \frac{1}{32\pi}\rho g^2 H^2 T,$$

where T (s) is the wave period. In this case, the energy is transported at half the phase velocity.

2.2 Energy of sea waves

In a real seaway, i.e., for irregular sea conditions and for deep water the wave power for a given sea state is given by the following relation:

$$P = \frac{\rho g^2}{64\pi}H_{m_0}^2 T_P \approx \left(0.5\frac{kW}{m^3 s}\right)H_{m_0}^2 T_p, \tag{6}$$

where P (kW/m) is the wave energy flux per unit of wave-crest length. In the above relation $H_S = H_{m_0}$ is the significant wave height (m), $T_P = 2\pi/\omega_p$ is the spectral peak period (s), ω_p (s^{-1}) is the peak radian frequency of the spectrum, ρ is the water density (1025 kg/m^3) and g is the acceleration of gravity (9.81 m/s^2). Another equation for the wave power for a given sea state is

$$P = \frac{\rho g^2}{64\pi}H_{m_0}^2 T_e \approx \left(0.5\frac{kW}{m^3 s}\right)H_{m_0}^2 T_e, \tag{7}$$

where now T_e (s) is the wave energy period. The significant wave height and energy period are defined as functions of the spectral moments. The significant wave height is defined as

$$H_{m_0} = H_S = 4\sqrt{m_0}, \tag{8}$$

the energy period is given by

$$T_e = \frac{m_{-1}}{m_0}, \tag{9}$$

and the mean zero up-crossing period is given as

$$T_{m_{02}} = 2\pi\sqrt{\frac{m_0}{m_2}}, \tag{10}$$

where m_0 is the zeroth moment (the variance) of the wave spectrum, m_2 and m_{-1} the second and -1 order wave spectral moments, respectively.

3 Wave data

3.1 The wind and wave models

The wave data used in this work consists of time series of wave spectral parameters for the time period 1995–2004. The data have been obtained from the WAM-Cycle 4 numerical wave simulation model with a spatial resolution of 0.1°x0.1° and temporal resolution of 3 hours. Such a resolution is fairly appropriate for a general description of the wind and wave climate of the entire Mediterranean, as well as the Aegean Sea, which is a semi-closed basin with peculiarities such as a complex bathymetry with abrupt changes and many insular groups. Utilizing hindcasts produced by numerical models of high spatial and temporal resolution is the only way to represent as precisely and accurately as possible the main characteristic features of the wave climate of the Greek seas. The hindcast data have been calibrated by using collocated in time and space wave measurements obtained by the POSEIDON buoy network (Soukissian et al. [8]).

The atmospheric forcing for the WAM wave model was produced by the non-hydrostatic weather model SKIRON-Eta (Kallos et al. [9]). The vertical structure of the SKIRON-Eta model consists of 38 levels stretching from the surface up to the model top (at 15800 km). The meteorological input used for defining the initial and boundary conditions of the model was obtained from the analysis fields, produced by the European Center for Medium-Range Weather Forecasts (ECMWF). The input data are available at a 0.5°x0.5° resolution and 16 standard pressure levels (1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 hPa) every 6 hours (at 00, 06, 12, and 18 UTC). The input concerning the ground temperature and humidity at 4 ground layers (defined at the depths of 7 cm, 28 cm, 100 cm and 255 cm), as well as the temperature of the sea surface, was also derived from ECMWF at a 0.5°x0.5° resolution. The corresponding analysis fields, produced during the operational use of ECMWF and obtained through MARS-Meteorological Archive and Retrieval System,

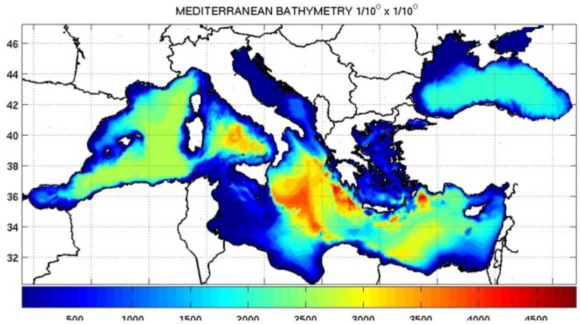


Figure 1: Implementation area of the weather and wave model and bathymetric map used in the wave model.

were used. The application area of the model, shown in Fig. 1, extended from 7° W to 42° E and 30.25° S to 47.25° N, and the spatial resolution was set to 0.1°x0.1°.

The wave model used for the generation of the hindcast wave data was based on the 3rd generation model WAM-Cycle 4. WAM-Cycle 4 (or simply WAM for brevity) calculates the spatial-temporal evolution of the wave spectrum, taking into account wave generation due to the wind forcing, wave diffraction due to change of bathymetry and/or presence of currents, transformation of energy due to non-linear quadruplet wave interactions and energy absorption due to white capping and bottom friction. The model was modified in order to be effective (concerning both accuracy and computing power aspects) for applications of high spatial resolution and to give successful forecasts at coastal areas, where wave breaking is important.

The application area of the model is the same as for SKIRON-Eta, see Fig. 1. The particular geographical coverage is considered adequate for the proper development and propagation of waves in the two basins (Mediterranean and Black Sea). The bathymetry was adapted to the spatial resolution of the grid through bilinear interpolation of the worldwide bathymetry/topography ETOPO 2 with spatial resolution of $2'$ and vertical accuracy of 1 m. In the cases of deficiency of the above database (in shallow water areas of the two basins), corrections were introduced based on the nautical charts of the Hellenic Navy Hydrographical Service (HNHS). The spectral frequency resolution of the model was set according to the logarithmic distribution $\omega_{i+1} = 1.1\omega_i$, where the minimum frequency was set to $0.05\,\text{Hz}$ and the maximum frequency to $0.793\,\text{Hz}$ (30 frequency sectors in total). The significant wave height, the mean wave period and the mean wave direction are obtained as integrated products of the wave spectrum, while the spectral peak period and the wave energy corresponding to the low-frequency and the high-frequency part of the spectrum are derived from the distribution of the spectrum. For an analytic description of the SKIRON-Eta and the WAM model set-up see (Soukissian et al. [7]).

It is worth noting that both the weather and the wave model have the same spatial resolution (0.1°x0.1°) and nearly the same land-sea masks, avoiding in this way multiple linear interpolations for the calculation of wind parameters at the grid points of the wave model.

In general, the WAM model underestimates the high values of the significant wave height and the spectral peak period; part of this error could be attributed to corresponding errors between the weather model output and the real values of the wind speed (Soukissian and Prospathopoulos [10]).

The wave hindcast results were calibrated using in-situ wave measurements and classical linear regression. The final relationships used for the correction of the model significant wave height H_S and the spectral peak period T_P are the following:

$$\hat{H}_{S,WAM} = 1.15 H_{S,WAM} \tag{11}$$

$$\hat{T}_{P,WAM} = 1.07 T_{P,WAM}, \tag{12}$$

where $\hat{X}$ variables denote the corrected values and X variables denote the initial ones.

4 Wave power in the Greek seas

The study area is defined by the following points: (42.25° N, 19.00° E), (42.25° N, 30.00° E), (30.25° N, 19.00° E), (30.25° N, 30.00° E). The area has been divided into a grid with resolution 0.1°x0.1°. For each grid point, 10-year long time series of the main wave spectral parameters, with 3 hours frequency, was obtained from the WAM wave model. The wave hindcast data are used to derive the spatial distribution of the wave power in the Greek seas. To this end, the iso-energy contours have been produced; each contour represents the loci of points with the same values of wave energy.

The study of spatial distribution of wave power over the Greek seas was elaborated on seasonal and annual basis. The seasons examined are winter (December, January, February), spring (March, April, May), summer (June, July, August), and autumn (September, October, November).

At first, wave power, P_i (W/m), for each sea state (H_{Si}, T_i) of the 10 years time series, was estimated, eqn. (13).

$$P_i = \frac{\rho g^2}{64\pi} H_{S_i}^2 T_i, \quad i = 1, 2, \ldots, N, \tag{13}$$

where ρ is the water density, g is the acceleration of gravity, H_{S_i} the significant wave height and T_i the peak period of the i th sea state. Then, the mean seasonal and annual wave power $\overline{P}$ can be easily obtained as follows:

$$\overline{P} = \frac{\sum_{i=1}^{N} P_i}{N}, \tag{14}$$

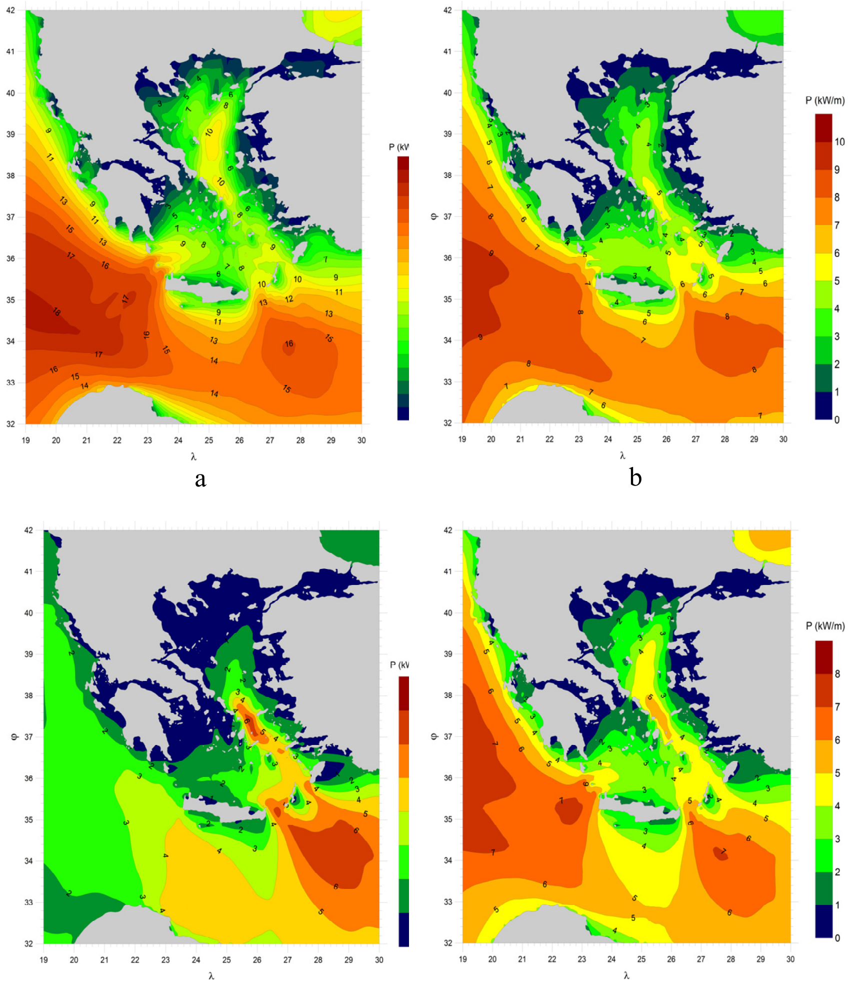
where N is the total number of sea states in the examined time period.

Finally, four seasonal and one annual map depicting the average iso-energy contours were developed.

4.1 Seasonal and annual wave power of the Greek Seas

The results are presented in charts of spatial distribution of the mean wave power in a seasonal (Fig. 2) and annual basis (Fig. 3). Charts illustrating the spatial distributions of mean wave energy flux per unit of wave-crest length are represented by iso-energy contours.

On seasonal basis, the mean wave power reaches its maximum values during winter (Fig. 2a). Northern of the Cyclades complex, the maximum wave power is 10 kW/m, while southern of Cyclades the wave power has a lower value, 6–8 kW/m. In the south-eastern Aegean Sea, between Crete and Kasos islands, wave power is about 10-12 kW/m while in the south-west Aegean, the value of the wave energy is about 8-10 kW/m. The highest wave potential in the Aegean Sea, ranging between 12 and 14 kW/m is observed between Crete and Kithira islands. During winter, in the Ionian Sea, the values of the wave power are higher (9–15 kW/m).



a

b

c

d

Figure 2: Mean wave energy flux in the Greek seas: a) Winter, b) Spring, c) Summer, d) Autumn.

During spring (Fig. 2b), in the north-central and southern Aegean Sea the values of mean wave energy flux do not exceed 5 kW/m. As far as the maximum of mean wave energy flux value in the Aegean Sea is concerned (7 kW/m), it occurs again at the straits between Crete-Kithira, Crete-Kasos and Karpathos-Rhodes islands. The maximum of the wave energy flux in the Ionian Sea during spring is also 7 kW/m.

In summer (Fig. 2c), the higher mean wave power values in the Greek seas occur in the central Aegean, northern of the Cyclades complex (5–6 kW/m) and at the South-eastern Aegean between Crete-Kasos (5–6 kW/m), and Karpathos-Rhodes (5 kW/m) islands. The occurrence of mean wave energy flux maxima in the straights of central and southeast Aegean Sea is due to the dominant “etesian” winds blowing from north-northwest to south-southeast in the Aegean Sea during summer.

In autumn (Fig. 2d), in north-central Aegean, the value of the wave power is 4–5 kW/m. In the southwest Aegean Sea (at the straits between Crete -Kithira islands) and southeast Aegean Sea (at the straits between Crete-Kasos, Karpathos- Rhodes) wave power is 5–6 kW/m. In the Ionian Sea, the values are slightly higher, 4–6 kW/m.

At the annual chart (Fig. 3), in the north Aegean, the value of wave power is 3–5 kW/m, while in the north-central Aegean at the Cyclades complex reach up to 6 kW/m. At the south-west Aegean Sea, the wave power is 4–5 kW/m. The highest wave energy values of the order of 6-8 kW/m, on an annual basis, occur at the straits between Crete-Kithira and Crete-Kasos Islands. At the straits between Kasos-Karpathos and Karpathos-Rhodes islands, the wave power is about 6 kW/m. For the Ionian Sea, the wave power ranges between 4–8 kW/m.

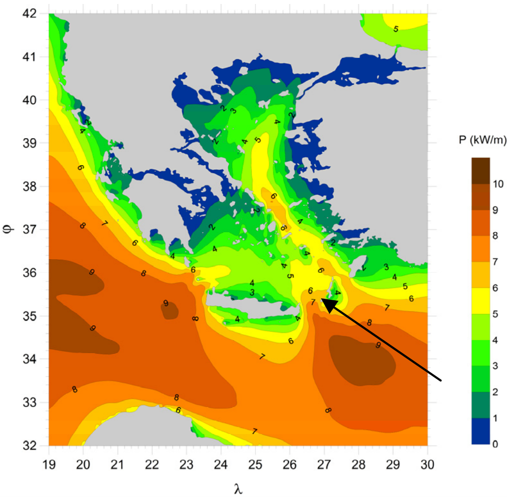


Figure 3: Annual mean wave energy flux in the Greek seas.

4.2 Local wave power

An area which could be a promising candidate for offshore wind farm installation is located at the straits between Kasos-Karpathos Islands, and is indicated by the black arrow in Fig. 3. For this area the estimated mean wave power on an annual basis is 6.4 kW/m. On seasonal basis, at the straits between Kasos-Karpathos Islands, the wave power is 4.91 kW/m in autumn, while in winter it reaches 9.58 kW/m. During spring and summer, mean wave power values are lower, 5.75 kW/m and 5.41 kW/m, respectively. The annual wave chart in Fig. 4 illustrates the distribution of the frequency of wave propagation occurrence combined with the respective significant wave heights at this region (27°.00 E, 35°45N) on annual basis. The dominant wave direction in the area is west-northwest. The most frequent wave directions, on annual basis, lie in the sector [285°, 300°] and their frequency of occurrence is about 26%. The higher values of the significant wave height, though, occur in the sector [315°, 345°]. The above results suggest that wave power can be an auxiliary RES to the available offshore wind energy for the specific area.

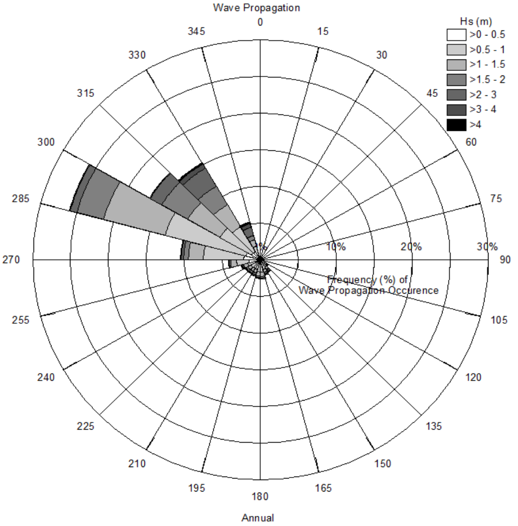


Figure 4: Annual wave chart for the area between Kasos-Karpathos islands.

5 Conclusions

In this work, the wave potential of the Greek Seas is being assessed, based on 10-year (1995–2004) hindcast data generated by the combination of the SKIRON-Eta atmospheric model and the WAM-cycle 4 wave model, implemented at a high spatial and temporal resolution.

On annual basis, the overall wave potential is relatively high compared to the available wave power of the Mediterranean Sea. Additionally, there are ‘hot spots’ where wave power reaches its higher values. That is due to channeling effects taking place in the specific areas. The higher wave energy values occur in the Ionian Sea and in the straights of Crete-Kithira, Crete-Kasos, Kasos-Karpathos and Karpathos-Rhodes islands, as well as in the central Aegean Sea, northern of the Cyclades complex. The maximum values of mean wave power range between 6-8 kW/m. On a seasonal basis, the higher wave power values along Greek Seas occur during winter. The wave potential is reduced during spring and autumn and the lower values occur in summer. The areas where the maxima occur during winter, spring and autumn are the same with those mentioned on the annual analysis. On the contrary, maxima of wave potential in summer are observed in the central Aegean Sea, at the straights of Mykonos-Ikaria Islands and in southeast Aegean Sea, between Crete-Kasos and Karpathos-Rhodes Islands.

Taking into account the spatial distribution of mean wave power on a seasonal and annual basis for the Greek Seas, there are five favorable potential areas for installing wave energy converters: the Ionian Sea, and the straights between Crete-Kithira, Crete-Kasos, Kasos-Karpathos and Karpathos-Rhodes islands.

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