# Wave Energy in the Mediterranean

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The installed power of the several deployed WECs in the Mediterranean Sea varies between 3–2500 kW. Ten project cases of deployed WECs in the basin are presented, with their analysis of the essential features. Five different types of WEC have already been tested under real environmental conditions in Italy, Greece, Israel and Gibraltar, with Italy being the Mediterranean country with the most deployed WECs. The main questions of the relevant studies were the ongoing trends, the examination of WECs in combination with other renewable sources, the utilising of WECs for desalination, and the prospects of wave energy in the Mediterranean islands and ports.

wave energy resource assessment WECs Mediterranean Sea technology maturity wave

## 1. Introduction

The current European Union target to accomplish climate neutrality by 2050 and the new European Union Climate Law for decline of greenhouse gas emissions at least 55% until 2030 in comparison with 1990 levels, have led scientific research more intensively to alternative sustainable energy sources [1]. Several types of source are used commercially today, such as solar, wind, biomass, geothermal, and hydropower; however, in order to address climate change and ensure a sustainable future, the renewable share in the power mix is required to increase significantly [2].

There is a growing body of literature that recognises wave energy as a promising, less exploited source that could contribute to the energy mix and reduce the need for fossil fuels [3][4][5]. It is an issue that has received considerable research attention in the last decades [6], with a variety of different wave energy converters (WECs) having already been developed [7] and deployed in several areas worldwide [8]. Wave energy is an endless and sustainable source that can make coastal countries less energy-dependent and provide essential benefits [9].

In recent years, several studies have shown that theoretical wave energy potential is considerable [10]. According to Mork et al. [11], the gross resource is counted as 3.7 TW globally. Cornett [12] also evaluated the seasonal and monthly variability globally and proved that the wave energy potential is considerable in some areas. Many countries, characterised by significant wave energy resources, have already recognised the potentiality of wave energy to the energy demands [13]. In Europe, most research projects are located on the Atlantic coast, such as the coasts of the United Kingdom, Portugal and Ireland [14] due to the high wave energy flux that characterise these regions. Kalogeri et al. [15] assessed the wave power density in Europe and concluded that north-western

European coasts are defined by the highest values. In particular, Mattarolo et al. [16] estimated that the wave energy flux is 70 kW/m in the western coast of Ireland and the north-western coast of Scotland, and 50 kW/m in Cornwall, United Kingdom, and the western coast of Brittany, France. Although high energy flux characterises these areas, the survivability of WECs is a real challenge due to storms and extreme conditions which can damage WECs during their operation [10][13]. As reported by Liberti et al. [17], less energetic seas such as semi-enclosed regions could be the solution to survivability, and the deployment of WECs in these seas could be financially viable projects. The Mediterranean is a semi-enclosed sea, with a medium wave energy power compared with the Atlantic coasts. According to Besio et al. [6], several researchers have already attempted to evaluate the wave energy potential of areas with lower energy flux than open seas.

# 2. Wave Energy in the Mediterranean Sea

## 2.1. Wave Energy Resource Assessment

A rich literature has been published on wave energy assessment in the Mediterranean Sea [6][17][18] focusing on specific areas or the whole area. Significant analysis of the wave energy evaluation in the whole basin was presented by Arena et al. [18], who investigated the most energetic locations and the areas in which it is possible extreme events will occur. They identified the north-western Mediterranean Sea as the most energetic location with mean wave power up to 15.1 kW/m in the area of Alghero, Italy, and considerable wave energy potential in northern Tunisia, Italy, western Crete (Greece), southern Sicily (Italy) and the southern Ionian Sea (Greece) with mean wave power 11.1 kW/m, 8.5 kW/m, 8.2 kW/m and 7.3 kW/m, respectively. Furthermore, Besio et al. [6] analysed 35-year data and detected the powerful regions, which are in the western Mediterranean among Sardinia, Corsica, northern Algeria and the Balearic Islands with a mean wave energy potential of relatively 10 kW/m. They found that the wave energy power is intermediate in the eastern and central Mediterranean, about 6–7 kW/m and the wave energy potential varies significantly during the seasons in the whole basin. These results agree with Pelli et al. [19]. Lavidas et al. [20] detected that the highest wave energy potential areas are in the north-eastern and southern Italian coastline, on the coasts of Libya and Egypt, in the north-eastern Spanish coastline, and the complex of islands in central Greece.

Most of the research was carried out by studying specific locations and not the entire region. Liberti et al. [17] recommended as the most energetic areas of the Italian Seas western Sardinia and between southern and north-western Sicily. Vicinanza et al. [21] investigated the area of north-western Sardinia and concluded that the western coasts of the island, especially Porto Alabe and Torre del Porticciolo, are amongst the most promising areas in the Mediterranean. In Sicily, Italy Iuppa et al. [22] found that the locations with the highest wave energy potential are the western parts of the island and the Strait of Sicily, with wave energy flux 8 kW/m and 4–6 kW/m, respectively. Their main scope was to examine the insular wave energy potential in order to locate the probable spots for wave energy exploitation by WECs. The wave energy potential of Sicily was also studied by Monteforte et al. [23], who concluded that the most energetic region is the Aegadian Islands (western Sicily). The coasts of Sicily, Sardinia, Liguria and Tuscany were the study regions of Vannucchi and Cappietti [24]. The wave power and the variability were estimated in nearshore and offshore spots of these four areas, and their findings proved that the nearshore area of Argenteria (depth of 20 m) is the most energetic hotspot [24]. Paladini de Mendoza et al. [25] defined as a suitable spot for harvesting wave energy, the northern Italian coasts with low environmental consequences, considerable energy flux, and viable access is the region onward the breakwater of Civitavecchia.

A wave energy potential assessment of the Algerian coast conducted by Amarouche et al. [26] showed the eastern offshore part of Algeria, approximately 15 km from the coast, as the most energetic area. Ayat [27] examined the wave power potential of the Aegean Sea and the eastern Mediterranean and identified that the central-eastern Mediterranean and the Aegean Sea have the highest values, approximately 5 kW/m. He further indicated that this region has substantial seasonal variability, except for the area between the islands of Karpathos and Crete, which is characterised by lower differences. Zodiatis et al. [28] identified the locations with the highest wave energy potential in the Levantine Basin: the western coastline of Cyprus and the coasts of Alexandria, Lebanon and Israel.

The Libyan Sea's wave energy resources were examined by Lavidas and Venugopal [29], indicating that the wave energy flux fluctuates between 8–10 kW/m in winter and the wave energy potential is higher in the western part of the Libyan Sea. They claimed that some area parts are suitable for wave energy extraction due to the low wave energy variability. These researchers also assessed the Aegean Sea's wave energy potential and suggested that the most energetic areas are southern and eastern of Crete with a mean wave energy flux of about 8 kW/m, in contrast with central Aegean's lower values of approximately 5–6.5 kW/m [30]. Jadidoleslam et al. [31] also evaluated the wave power of the Aegean Sea and detected that the regions between Mykonos-Ikaria and Crete-Casos have the highest wave heights, and the wave energy flux surpasses the 5.2 kW/m. They further stated that the regions with fewer islands have higher wave energy potential in the Aegean Sea.

Zacharioudaki et al. [32] evaluated the wave resource of the entire Greek sea area and demonstrated that the most energetic regions are in the western and eastern Crete. Kaldellis et al. [33] identified that Skyros has the highest significant wave heights, followed by Athos and Lemnos in the northern Aegean Sea. Foteinis et al. [34] assessed a specific area of Greece, Varkiza, and indicated that with the present technology, the exploitation of wave energy is not an economically feasible solution. Foteinis et al. [35] determined the functionality of WECs in the Venetian harbour of Chania, Greece. They calculated that the mean wave power is close to 4.8 kW/m and proposed that future installations of WECs in the harbour breakwater could be a feasible solution. Lopez-Ruiz et al. [36] detected substantial temporal wave power variation and recognised the nearshore region of Punta del Santo, Italy, as a region with the highest significant wave height.

In the Balearic Sea, Ponce de Leon et al. [37] found the highest value of wave energy flux, 9.1 kW/m, in northern Menorca. Additionally, in the Croatian coasts, Farkas et al. [38] stated that the mean wave power fluctuates between 1.959 kW/m and 2.784 kW/m, and the region with the highest value is south-eastern Lastovo. **Table 1** illustrates the geographical areas of the conducted research for the wave energy assessment in the Mediterranean Sea and the type of data examined to carry out the research. The wave data were classified into three types: numerical wave models, satellite remote sensing and in situ measurement, according to [39]. It is significant to note that in some studies in situ measurements were used for model validation, such as the studies of Besio et al. and Liberti et al. [6][17] and others for the analysis, as in the case of Foteinis et al. [34]. Several of the numerical wave models implemented in the resource assessment studies are presented in Supplementary Material Table S1.

**Table 1.** Wave energy resource assessment studies in the Mediterranean Sea and type of examined data.

| Geographical Area | Data | | | Part of the Mediterranean Sea | Authors |
|---|---|---|---|---|---|
| | Numerical Wave Models | In Situ Measurements | Satellite Data | | |
| Mediterranean Sea | x | x | | Entire | [6] |
| Mediterranean Sea | x | x | | Entire | [18] |
| Mediterranean Sea | x | x | | Entire | [19] |
| Mediterranean Sea | x | x | | Entire | [20] |
| Libyan Sea | x | | | Eastern | [29] |
| Aegean Sea | x | x | | Eastern | [30] |
| Levantine Sea | x | x | | Eastern | [28] |
| Eastern Mediterranean Sea and Aegean Sea | x | | | Eastern | [27] |
| Aegean Sea | x | x | | Eastern | [31] |
| Greek Coasts | x | x | x | Eastern | [32] |
| North Aegean Sea | | x | x | Eastern | [33] |
| Varkiza Coasts | x | x | | Eastern | [34] |
| Chania’s Venetian harbour Coast | x | x | | Eastern | [35] |
| North-western Sardinian Coasts | x | x | | Western | [21] |
| Sicilian Coasts | x | x | x | Western | [22] |
| Tuscany, Liguria, Sardinia and Sicily Coasts | x | | | Western | [24] |
| Italian Coasts | x | x | x | Western | [17] |
| Sicilian Coasts | x | x | | Western | [23] |
| Northern Latium Coasts | x | x | | Western | [25] |

| Geographical Area | Data | | | Part of the Mediterranean Sea | Authors |
|---|---|---|---|---|---|
| | Numerical Wave Models | In Situ Measurements | Satellite Data | | |
| Algerian Coasts | x | x | | Western | [26] |
| Balearic Sea | x | x | x | Western | [37] |
| Croatian Coasts | | | x | Western | [38] |

able

l of other energy sources, such as wind and solar [40][41]. The epicentre of recent studies is based on wind–wave hybrid systems, with fewer studies focusing on other forms of renewable energy source (**Table 2**).

**Table 2.** Wave and wind energy resource assessment in the Mediterranean Sea.

| Geographical Area | Period | Part of the Mediterranean Sea | Authors |
|---|---|---|---|
| European Coasts | 2001–2010 | Entire | [15] |
| Mediterranean Sea | 1979–2016 | Entire | [42] |
| Greek Coasts | - | Eastern | [40] |
| Greek Coasts | 2001–2010 | Eastern | [43] |
| Greek Coasts | 2005–2015 | Eastern | [44] |
| Italian Coasts | 2005–2014 | Western | [45] |

To examine the hybrid system of wave and wind energy in the whole Mediterranean, Ferrari et al. [42] determined that the most advantageous area for combined harvesting of wind and wave energy is the Algerian coast. In their process of assessing the entire offshore European area, Kalogeri et al. [15] indicated that the most promising areas for the hybrid harvest of wave and wind energy are the Strait of Sicily, offshore of the coasts of Sardinia, offshore north-west of the Balearic Islands, the Gulf of Lions and certain parts in the Aegean Sea.

Vasileiou et al. [40] showed that the most suitable areas in Greece are considered the area east of Crete, the offshore region of south-eastern Mykonos and the north-western Crete. Emmanouil et al. [43] also evaluated the Greek wave and wind potential, underlying the highest wave power potential in the western Cretan Sea and the southern Ionian Sea, almost 7 kW/m. Both Emmanouil et al. [43] and Ganea et al. [44] evaluated these two renewable sources in the same regions and the most propitious sites for each source separately. Ganea et al. [44] characterised the south, north and south-east area of Crete as the most energetic ones for wave energy exploitation, with mean wave power 2.9–3 kW/m.

Furthermore, the wind and wave energy potential of the Italian coasts have been analysed by Azzellino et al. [45]. They detected the most promising offshore locations, considering the wind turbines are not viable in any depth, several uses of the sea areas and the vulnerability of some natural environments. These locations are south of

Elba, off the Aeolian islands (southern Tyrrhenian Sea) and Alghero (north-western Sardinia), and southern Adriatic and the Ionian Sea areas.

## 2.3. Ongoing Trends of Wave Climate

Research has also focused on the effect of climate change on wave energy resources (**Table 3**). Much of the current literature pays particular attention to the ongoing trends of wave energy parameters in the Mediterranean [46][47]. Caloiero et al. [47] showed that the wave power could rise because of the highest proportion of long waves in the Calabria coasts in southern Italy. Caloiero et al. [48] predicted the changes in wave period, power and significant height in the entire Italian sea. Their analysis indicated that all investigated seas have positive ongoing trends except for the Adriatic and the Ligurian Sea.

**Table 3.** Research on ongoing trends of the wave climate in the Mediterranean Sea.

| Geographical Area | Period | Data | | | | Part of the Mediterranean Sea | Authors |
|---|---|---|---|---|---|---|---|
| | | Significant Wave Height | Wave Period | Wave Power | Wave Direction | | |
| Mediterranean Sea | 1970–2100 | x | x | | x | Entire | [49] |
| Coasts of Calabria | 1979–2017 | x | x | | | Western | [47] |
| Italian Coasts | 1979–2018 | x | x | x | | Western | [48] |
| Coasts of Menorca | 1971–2000 and 2071–2100 | x | x | x | x | Western | [5] |
| Coasts of Morocco | 1986–2005 and 2081–2100 | x | x | x | x | Western | [46] |
| North-western Mediterranean Sea | 1971–2000 and 2071–2100 [1] | x | x | | x | Western | [50] |

The impact of climate change on the wave parameters in the north-western Mediterranean was examined by Casas-Prat et al. [50], who pointed out the differences between the future and present values of wave parameters in summer and winter. Sierra et al. [5] studied the area of Menorca, Spain, and illustrated a decline of wave energy in autumn and winter, a lower reduction in spring and changeability in space in summer, with an inclining trend in northern Menorca. In general, they detected that the distribution of direction and space of the present wave energy is similar to the future ones. Future wave projections are also accomplished by Sierra et al. [46] for the Mediterranean coasts of Morocco. They argued that in the region, the present values of wave power are similar to the future ones. Leo et al. [49] argued that wave period and significant wave height are expected to decline generally in the entire Mediterranean Sea.

### 2.4. Wave Energy and Other Variables

Wave energy has already been analysed combined with research topics such as coastal protection [51], social-economic benefits [52], acoustic impact [53] and desalination [54][55]. Bergillos et al. [51] examined both WECs and coastal protection from erosion in the Guadalfeo deltaic coast. Moreover, Molina et al. [56] studied the wave climate of the Andalusian coast and the storms that occurred during a long time period and also evaluated the wave energy flux of these storms. The combination of wave energy exploitation and the reduction of coastal erosion was further analysed by Foteinis et al. [55], who investigated different schemes that could improve the sustainability of WECs, decrease the cost of WECs and make the exploitation of wave energy possible in low energetic seas.

Furthermore, the social-economic aspects of WECs in Greece were examined by Lavidas et al. [52], aiming to promote policy considerations and the development of WECs concerning the significant opportunities of wave energy exploitation. He claimed that, although the Greek sea area is often overlooked due to its low energy potential, the lower resources mean lower possibilities for extreme catastrophic events.

Viola et al. [57] examined the use of wave energy for water desalination in Sicily, Italy. In addition, they reported the feasibility of a WEC by the Department of Energy, Engineering Information and Mathematical Models (DEIM) of University of Palermo to wave energy harvest that would integrate power generation and water desalination in Pantelleria, Italy. Hwang et al. [54] focused on the desalination plants of Sicily, the wave energy potential and the installation of point absorbers around the island to supply the water desalination plants. Wave energy combined with desalination of water was also examined [58]. Corsini et al. [58] detected the application of nearshore WECs as having a low environmental impact when producing energy on the island of Ponza, Italy.

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