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Review

Wave Energy in the Mediterranean Sea: Resource Assessment, Deployed WECs and Prospects

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Abstract: A detailed review of wave energy resource assessment and the state-of-the-art of deployed wave energy converters (WECs) in real environmental conditions in the Mediterranean Sea have been analysed in this study. 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. This paper is the first comprehensive study that overviews the recent significant developments in the wave energy sector in the Mediterranean countries. The research concludes that the advances of the wave energy sector in the Mediterranean Sea are significant. However, in order to commercialise WECs and wave energy exploitation to become profitable, more development is necessary.

Keywords: wave energy; resource assessment; WECs; Mediterranean Sea; technology maturity; wave

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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 [3–5]. 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.

This paper aims to highlight the significant developments of the wave energy sector in the Mediterranean by reviewing the main recent research findings. Section 2 provides an overview, in brief, of the recent wave energy resource assessment studies and the analysis of wave energy potential evaluation combined with other renewable energy sources. Section 3 presents the deployed WECs in real or relevant Mediterranean conditions and the academic examination of specific WECs and certain types of WEC as well as their possibility to be deployed in the basin. Section 4 provides the beneficial aspects of wave energy exploitation in Mediterranean ports and islands. Section 5 contains critical information on the status and prospects of wave energy in the Mediterranean projects and prospects of wave energy exploitation. Finally, Section 6 presents the most significant conclusions and recommendations for further work that are vital for the commercialisation of WECs. The reviewed WECs are categorised by the location of their device in (i) offshore, with water depth beyond 40 m, (ii) nearshore, with water depth between 10 m and 25 m and (iii) onshore, at the shore or swallow waters [4]. WECs are also categorised by their working principles according to the classification of the European Marine Energy Centre (EMEC) in nine types using the terms: point absorber, attenuator, oscillating water column (OWC), oscillating wave surge converter, submerged pressure differential, bulge wave, rotating mass, overtopping device and other [18].

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 [6,17,19] 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. [19], 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. [20]. Lavidas et al. [21] 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. [22] 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. [23] 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. [24], 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 [25]. 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 [25]. Paladini de Mendoza et al. [26] 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. [27] showed the eastern offshore part of Algeria, approximately 15 km from the coast, as the most energetic area. Ayat [28] 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. [29] 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 [30], 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 [31]. Jadidoleslam et al. [32] 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. [33] 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. [34] identified that Skyros has the highest significant wave heights, followed by Athos and Lemnos in the northern Aegean Sea. Foteinis et al. [35] 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. [36] 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. [37] 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. [38] found the highest value of wave energy flux, 9.1 kW/m, in northern Menorca. Additionally, in the Croatian coasts, Farkas et al. [39] 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 [40]. 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. [35]. 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	[19]
Mediterranean Sea	x	x		Entire	[20]
Mediterranean Sea	x	x		Entire	[21]
Libyan Sea	x			Eastern	[30]
Aegean Sea	x	x		Eastern	[31]
Levantine Sea	x	x		Eastern	[29]
Eastern Mediterranean Sea and Aegean Sea	x			Eastern	[28]
Aegean Sea	x	x		Eastern	[32]
Greek Coasts	x	x	x	Eastern	[33]
North Aegean Sea		x	x	Eastern	[34]
Varkiza Coasts	x	x		Eastern	[35]
Chania's Venetian harbour Coast	x	x		Eastern	[36]
North-western Sardinian Coasts	x	x		Western	[22]
Sicilian Coasts	x	x	x	Western	[23]
Tuscany, Liguria, Sardinia and Sicily Coasts	x			Western	[25]
Italian Coasts	x	x	x	Western	[17]
Sicilian Coasts	x	x		Western	[24]
Northern Latium Coasts	x	x		Western	[26]
Algerian Coasts	x	x		Western	[27]
Balearic Sea	x	x	x	Western	[38]
Croatian Coasts			x	Western	[39]

2.2. *Wave Energy Resource Assessment in Combination with Other Sources of Renewable Energy*

Thus far, several studies have investigated the potential of wave energy combined with the potential of other energy sources, such as wind and solar [41,42]. 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	[43]
Greek Coasts	-	Eastern	[41]
Greek Coasts	2001–2010	Eastern	[44]
Greek Coasts	2005–2015	Eastern	[45]
Italian Coasts	2005–2014	Western	[46]

To examine the hybrid system of wave and wind energy in the whole Mediterranean, Ferrari et al. [43] 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. [41] 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. [44] 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. [44] and Ganea et al. [45] evaluated these two renewable sources in the same regions and the most propitious sites for each source separately. Ganea et al. [45] 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. [46]. 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 [47,48]. Caloiero et al. [48] 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. [49] 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	[50]
Coasts of Calabria	1979–2017	x	x			Western	[48]
Italian Coasts	1979–2018	x	x	x		Western	[49]
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	[47]
North-western Mediterranean Sea	1971–2000 and 2071–2100 [1]	x	x		x	Western	[51]

[1] Except for Max-Planck-Institut fur Meteorologie data, for which the first period is 1981–2010 based on the authors [51].

The impact of climate change on the wave parameters in the north-western Mediterranean was examined by Casas-Prat et al. [51], 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. [47] 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. [50] 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 [52], social-economic benefits [53], acoustic impact [54] and desalination [55,56]. Bergillos et al. [52] examined both WECs and coastal protection from erosion in the Guadalfeo deltaic coast. Moreover, Molina et al. [57] 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. [56], 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. [53], 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. [58] 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. [55] 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 [59]. Corsini et al. [59] detected the application of nearshore WECs as having a low environmental impact when producing energy on the island of Ponza, Italy.

3. Wave Energy Converters (WECs) in the Mediterranean Sea

3.1. Prototypes Deployed in Operational or Relevant Environmental Conditions

Over the past seven years, considerable advances in the deployment of WECs have occurred [60] wave energy seems promising for some Mediterranean countries [6] because of extensive coastlines [17,61] (Table 4, Figure 1).

Although there is a considerable number of different WECs, several of them are missing tests under real conditions [9,14,60]. In the Mediterranean, there are 10 major cases of WECs that have reached technology readiness level (TRL) equal to or higher than 6 and have been tested in the sea [14,62,63].

The establishment of the first case of an off-grid WEC was by Eco Wave Power in the Jaffa Port, Israel, in 2014 and belongs to the category of point absorbers [64]. In 2015, the second case was that of the deployment of H24, a WEC developed by 40South Energy Italia Srl power in Marina di Pisa, Italy [65]. H24 was connected to the Italian grid three years later and remains the only remarkable nearshore WEC in the Mediterranean tested under real conditions (TRL 7) [65]. Furthermore, a notable feature of this converter is that it can exploit wave and tidal energy [14,65]. The same year, the University of Campania Luigi Vanvitelli installed an overtopping WEC, named Overtopping Breakwater for Energy Conversion (OBREC), in the existing breakwater of the Port of Naples, Italy. OBREC combines energy production and port protection, and the demonstration of the prototype was in a relevant environment, TRL 6 [14,66,67].

The following year, two WEC installation projects were completed. The Polytechnic of Turin and Wave for Energy Srl developed a WEC rotating mass device, named the Inertial Sea Wave Energy Converter (ISWEC), with nominal wave power offshore of the island of Pantelleria [14,68]. In parallel, Eco Wave Power installed 100 kW WECs in Gibraltar to supply power. Additionally, Eco Wave Power installed photovoltaic panels on Wave Clappers in the port of Jaffa and Gibraltar in order to test the possibility of photovoltaic panels installation in their future WECs [14,69].

The largest Mediterranean wave power facility, until now, has been in the port of Civitavecchia since 2017, with installed wave power of 2500 kW [14]. The Mediterranean University of Reggio Calabria in cooperation with Wavenergy.it constructed a REWEC3 in the breakwater of the port, which constitutes the first integrated OWC WEC into the breakwater of a Mediterranean port [14,70]. Wavenergy.it has further announced two new projects, which include the integration of REWEC3 in the breakwaters of the Italian ports of Salerno and Roccella Jonica.

Table 4. Deployed WECs in the Mediterranean Sea.

Country	Company	Year of Deployment	Device Name	TechnologyReadiness Level (TRL)	Type of WEC	Location	Power (kW)	Area of Deployment	Sea of Deployment	Part of the Mediterranean Sea
Italy	40South Energy Italia SRLpower	2015	H24	7	Other	Nearshore	50	Marina di Pisa	Ligurian Sea	Western
	data University of Campania Luigi Vanvitelli	2015	Overtopping Breakwater for Energy Conversion (OBREC)	6	Overtopping	Onshore	8	Port of Naples	Tyrrhenian Sea	Western
	Polytechnic of Turin and Wave for Energy Srl	2016	Inertial Sea Wave Energy Converter (ISWEC)	7	Rotating mass	Offshore	100	Coast of Pantelleria	Strait of Sicily	Western
	Mediterranean University of Reggio Calabria in cooperation with Wavenergy.it	2017	REWEC3	7	Oscillating Water Column (OWC)	Onshore	2500	Port of Civitavecchia	Tyrrhenian Sea	Western
	Ocean Power Technologies	2018	PB3 PowerBuoy	7	Point absorber	Offshore	3	Ravenna	Adriatic Sea	Western
	Polytechnic of Turin and Wave for Energy Srl	2019	ISWEC	7	Rotating mass	Offshore	50	Ravenna	Adriatic Sea	Western
Greece	Sinn Power	2018	SP WEC 3rd Gen	7	Point absorber	Onshore	18	Port of Heraklion	Cretan Sea	Eastern
	Sinn Power	2019	SP WEC 4th Gen	7	Point absorber	Onshore	36	Port of Heraklion	Cretan Sea	Eastern
Israel	Eco Wave Power	2014	Wave clapper	7	Point absorber	Onshore	-	Port of Jaffa	Levantine Sea	Eastern
Gibraltar	Eco Wave Power	2016	Wave clapper	7	Point absorber	Onshore	100	Gibraltar	Alboran Sea	Western

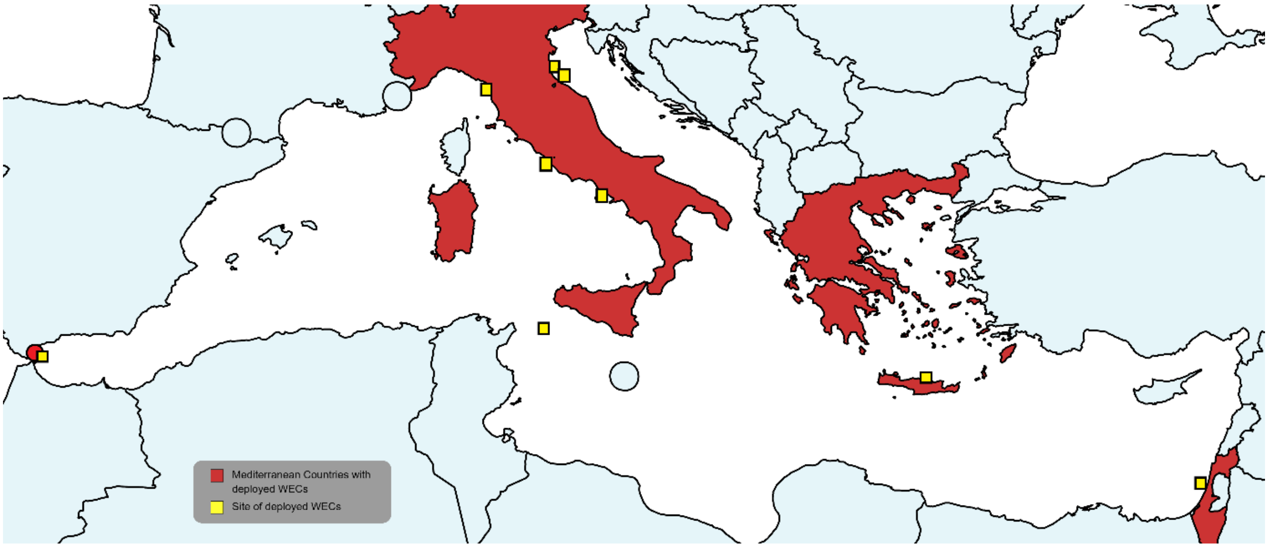

Figure 1. Mediterranean map with the deployed sites of wave energy converters (WECs) (developed on https://mapchart.net/, accessed on 7 June 2021).

Moreover, in Italy, and specifically offshore of Ravenna, the WEC PB3 PowerBuoy of Ocean Power Technologies was deployed by Eni in 2018 [63]. The purpose of this deployment is the suitability demonstration of WECs in gas and oil operations. PB3 PowerBuoy has wave power 3 kW and is a WEC that provides both communication and energy [14,63].

In the port of Heraklion, Crete, Sinn Power completed the installation of their first devices in 2018 [62]. In particular, two SP WEC 3rd Gen were installed in the breakwater of the port of Heraklion, with 18 kW per unit [62]. One year later, the same company placed two new devices in the breakwater of Heraklion. Their new technology is named SP WEC 4th Gen, with wave power 36 kW per unit. The aim of the four-device placement in the breakwater was to test their technology [62]. After their successful tests, Sinn Power carried their next project forward; the Ocean Hybrid Platform (OHP), which includes the construction, deployment and assessment of a hybrid platform that combined the exploitation of wave, wind and solar energy. OHP is currently in process in the port of Heraklion and will be completed in the following years [14,71].

Finally, the most recent deployed WEC, in real environmental conditions, is that of ISWEC in the offshore area of Ravenna [14,68]. The Polytechnic of Turin and Wave for Energy Srl deployed their technology for a second time in 2019. However, their second device has half of the wave power of the first-deployed one. Furthermore, the ISWEC that was deployed offshore of Ravenna was integrated with photovoltaic panels on the roof, combining the exploitation of solar and wave energy [14,68].

Generally, in the Mediterranean Sea, five different types of WEC have been deployed which belong to the categories of point absorber, OWC, overtopping, rotating mass and other. In Figure 2a, the installed power of the five different types of WEC is presented, with no trend of installed power to be observed, and the installation of the most powerful Mediterranean project was noted in 2017, with installed power 2500 kW. Most of the devices were installed onshore, and only one WEC device nearshore and two offshore (Figure 2b). In addition, the point absorber is the most deployed type of WEC, with half of the devices belonging to this type (Figure 2c).

3.2. Academic Research

Several studies have been published investigating a particular type of WEC or a specific developed device in a distinct location. The studies evaluated the WECs and reported significant features of the devices, with various research to pertain to the Italian seas. Miquel et al. [72] designed a WEC in accordance with the wave characteristics of the Mediterranean Sea. Moreover, using wave data from the wave climate of Mazara del Vallo (Sicily) and Alghero (Sardinia), the device was installed. Lavidas et al. [73] examined the exploitation of wave energy by OWC in the port of Genova, Italy. They evaluated the possibility of installing an OWC in the port, estimating the payback period, the levelized cost of electricity (LCoE), the technical and economic capabilities, as well as the pollution that would be avoided due to the decreased consumption of fossil fuels. The probability of the deployment of an OWC in an Italian port was also investigated by Naty et al. [74]. They studied the embedding of an OWC in the breakwater of the Giardini Naxos harbour, which is an area with low wave energy potential. Notably, they optimised the device and assessed the noise and financial feasibility. Another Italian port that the positioning of an OWC has been examined is Civitavecchia's [75]. Arena et al. [75] investigated the REWEC3, a device that had already been deployed in the harbour. They exhibited the operation of the device of two chambers in the port of Civitavecchia in November 2015. Arena et al. [75] further calculated that absorption of the incident wave power was on average between 76% and 96%.

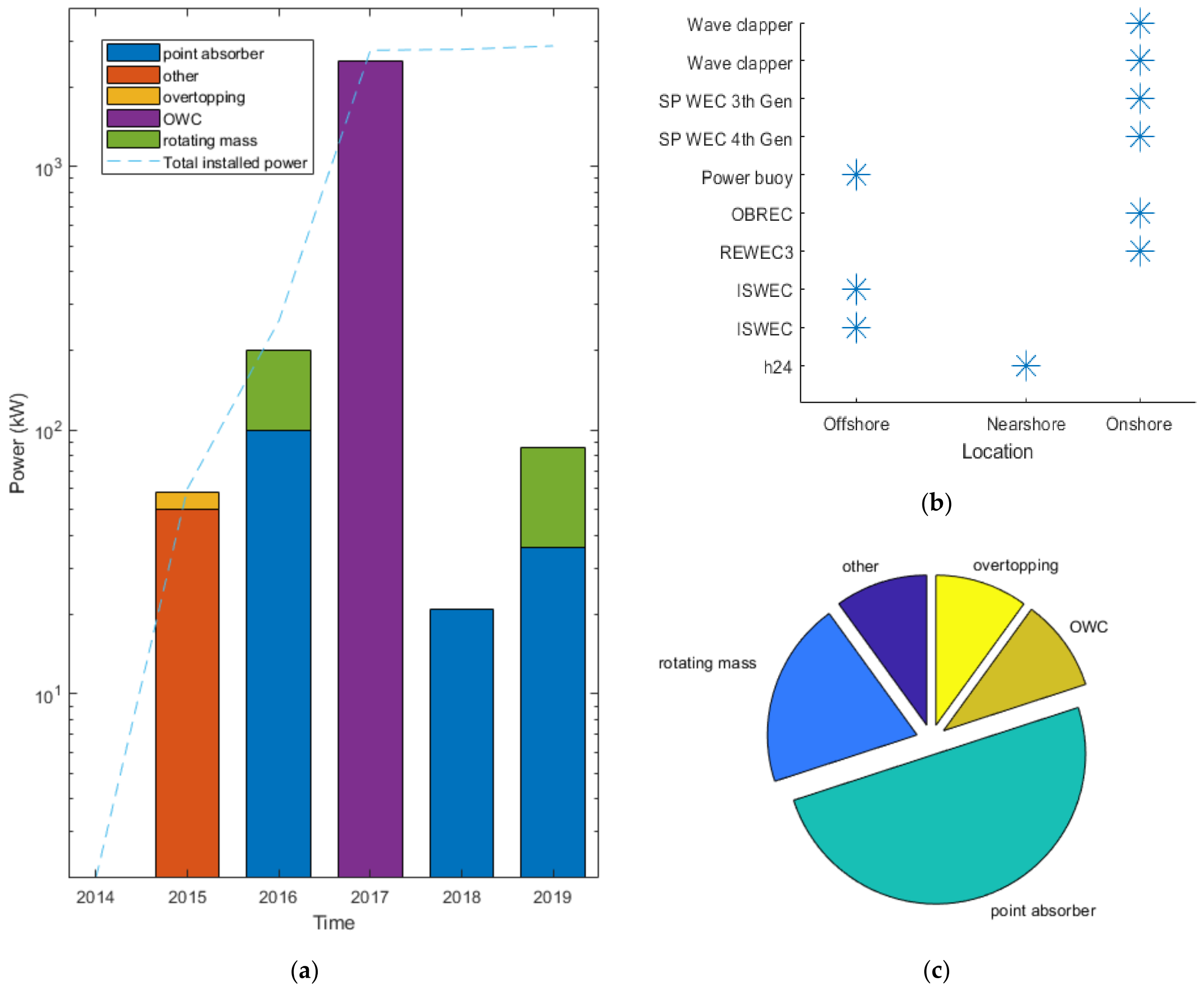

Figure 2. (**a**) Installed power of the five different types of WECs in the Mediterranean Sea; (**b**) location of deployed WECs in the Mediterranean Sea; (**c**) pie chart of the deployed types of WEC in the Mediterranean Sea.

Moreover, detailed scientific research has been conducted in order to detect the hydraulic performance [76] and the wave loadings [77] of the deployed WEC OBREC that have been installed in the port of Naples. In this regard, reliable estimation of time distribution of input flow was calculated through new methods introduced by Iuppa et al. [78]. Furthermore, such methods allow the prediction of the energy produced in parallel with the characteristics of the device. Cavallaro et al. [79] used those methods, proposed a numerical model for the OBREC performance optimisation, and applied their proposed model in the breakwater of Pantelleria island, Italy. Palma et al. [80] examined the structural and hydraulic performance of OBREC by analysing field data of the device operation in the port of Naples and by using a numerical model. Contestabile et al. [81] carried out a research describing a set of experiments performed on a physical model of OBREC. The goal of that research was to show how changing the geometrical shape of a mounted nose on the top of the OBREC's vertical crown wall can help mitigate the consequences of the sea level rise by 2100. In addition, Contestabile et al. [67] reviewed the research on OBREC in recent years. Their study encompassed unpublished aspects of the power-take-off system and geometry of OBREC and focused on the description/information of the device installation in the port of Naples, Italy. An innovative vertical breakwater with an overtopping WEC was presented by Lauro et al. [82] who investigated its stability response and hydraulic operation.

A creative solar/wave hybrid device was suggested by Viola et al. [42]. Their research focused on the assessment of solar and wave potential of Sardinia in order to choose the optimal siting of wave/solar farms, and thus, they selected Alghero. Franzitta et al. [83] proposed and analysed a scenario to install 12 farms of DEIM WECs in the western sea area of Malta and Gozo. They calculated the yearly energy production and the CO_2 emissions avoided due to the operation of these solar/wave farms. The feasibility of DEIM for the wave energy extraction of the area of the Pantelleria island, Italy, was evaluated by Franzitta et al. [61]. Konispoliatis et al. [84] analysed the wind and wave climate of two potential Mediterranean installation areas (east of Crete and south-west of Sicily) to investigate the wind/wave hybrid offshore floating platform (with three OWC devices and one wind turbine) platform's dynamic response under combined wave and wind loadings.

Moretti et al. [85] assessed an innovative WEC in the port of Civitavecchia, Italy. The WEC is a combination of two innovative concepts that have been tested in a mild environment; the data of this test were analysed, and the results illustrated their performance, which is similar to other technologies. In the port of Valencia, Spain, Cascajo et al. [86] considered the most suitable type of WEC for deployment that is also used as a breakwater. They estimated the wave power potential of the study region and concluded that the overtopping device is the optimal option.

Shehata et al. [87], using real data for the Egyptian area, evaluated simultaneously the Well turbines for wave energy extraction and breakwater. In addition, Bozzi et al. [88] assessed the performance of different WECs in the offshore areas of the Mediterranean Sea. In particularly, the assessed WECs were AWS, Wavebob, AquaBuOY, SeaPower, OE buoy, Pontoon, Langlee, and Pelamis. All the referred research and the main characteristics of the studied WECs are illustrated in Tables 5 and 6.

Academic research has provided important information on mooring systems. In fact, Sirigu et al. [89] carried out experiments on a 1:20 scaled ISWEC model in a towing tank and examined its mooring system while focusing on the influence of extreme events occurring on the system. The design of the examined mooring system was based on this particular device of ISWEC which has been deployed in Pantelleria island, Italy.

Table 5. Academic research on specific WECs.

Geographical Area	Name of WECs	Types of WEC	Location	Part of the Mediterranean Sea	Authors
Entire Mediterranean Sea	MoonWEC, AquaBuOY, Archimedes Wave Swing (AWS), OE buoy, Langlee, Pelamis, Pontoon, SeaPower and Wavebob	Other, Point absorber, Oscillating wave surge converter, Oscillating water column (OWC) and Attenuator	Offshore	Entire	[72,88]
Port of Civitavecchia	REWEC3	OWC	Onshore	Western	[75]
Maltese Coasts	DEIM (Department of Energy, Engineering Information and Mathematical Models (DEIM)	Point absorber [1]	Offshore	Western	[83]
Sardinian Coasts	DEIM	Point absorber [1]	Offshore	Western	[42]
Port of Naples	Overtopping Breakwater for Energy Conversion (OBREC)	Overtopping	Onshore	Western	[67,76–81]
Pantelleria island	DEIM	Point absorber [1]	Offshore	Western	[61]
Sea area of eastern Crete and north-west of Sicily	Renewable Energy Multi-Purpose Floating Offshore System (REFOS)	OWC [2]	Offshore	Eastern and Western	[84]

[1] hybrid system—WEC integrated with photovoltaic panels. [2] hybrid system—Floating platform with three OWC devices and one wind turbine.

Table 6. Academic research on particular types of WEC.

Geographical Area	Type of WEC	Location	Part of the Mediterranean Sea	Authors
Egyptian Coasts	Oscillating water column (OWC)	Onshore	Eastern	[87]
Port of Giardini Naxos	OWC	Onshore	Western	[74]
Port of Civitavecchia	OWC	Onshore	Western	[85]
Port of Valencia	Overtopping	Onshore	Western	[86]

4. Advantageous Aspects of Wave Energy Exploitation in the Mediterranean Sea

There is a notion that wave energy exploitation in ports and islands could be remarkably beneficial [56,90]. In the case of the ports, a large sector of the academic and business communities agree on wave energy suitability for sustainability improvement in ports [91]. This notion is mainly due to the processes to construct, install and maintain WECs in the less complicated breakwaters, with lower costs in opposition to the respective offshore WECs [90,92]. Hence, up to date, innovative concepts have been designed in such a way that WECs can easily be integrated into the breakwaters of ports, providing both energy and safety [92]. Moreover, there is a growing body of literature that revealed the advances of these integrations [90–92] and focused on the assessment of WECs in the breakwaters of ports [73,82]. In the case of islands, energy safety is a vital issue, and renewable extraction has growing importance [93]. Therefore, wave energy harvesting is assumed that could contribute to the energy mix of renewables and assist in addressing energy safety concerns due to its easy predictability and low variability [56].

4.1. Mediterranean Ports

In the Mediterranean, there are thousands of ports. The installation of WECs in ports, where wave energy potential is operational, seems to have a great prospect for increasing the contribution in their energy mix [91]. Several recent studies have been conducted in order to examine the prospects of WECs and estimate the exploitable wave power in the Mediterranean ports [74,75,86]. The main types of WEC that have theoretically been analysed are the OWC, point absorbers and overtopping devices. Some of these devices have been tested in real environmental conditions.

Notably, the Italian ports are at the epicentre of research. For instance, the installations of two different OWC devices have been investigated in the port of Civitavecchia. Moretti et al. [85] assessed a U-oscillating water column equipped with a dielectric elastomer generator power take-off system, and Arena et al. [75] evaluated the REWEC3 device. An OWC device was also investigated in detail in the Port of Giardini Naxos [74]. Furthermore, the overtopping OBREC device, which has been installed in the port of Naples, has been assessed [66,76,77].

Apart from Italian ports, efforts have been conducted in other Mediterranean ports. For example, in the port of Valencia, Spain, different types of WECs were examined, and the authors concluded that the overtopping devices are the most suitable [86]. In Greece, the installation of four point absorbers has been tested and evaluated by Sinn Power in the port of Heraklion [62]. Similarly, Eco Wave Power installed their technology in the port of Jaffa in Israel in order to test their point absorbers devices [64].

Hence, the integration of WECs has prospects that have already been acknowledged in the Mediterranean Sea. Recently, researchers and companies are trying to study and assess different devices that have possibilities to be operational in the breakwaters of ports, providing both safety and electric energy.

4.2. Mediterranean Islands

Significant efforts have been carried out in researching wave energy exploitation in the Mediterranean islands mainly on the Italian islands. In particular, the island of Sicily has been investigated extensively, concentrating on wave energy assessment of the island [17,19,23], evaluation of hybrid systems [15], desalination of water by WECs [55,58] and ongoing trends of wave energy [49].

However, wave energy research has attracted not only the large islands of the Mediterranean basin but also smaller ones, such as the island of Pantelleria, Italy. The island is considered one of the most suitable locations for wave energy exploitation [94], with high wave energy potential [61]. Different studies have evaluated the potential of the area and the possibilities of a WEC installation. Furthermore, Pantelleria island is one of the deployed WECs in real environmental conditions in the Mediterranean. The device ISWEC was deployed offshore the island in 2016, and the purpose of this deployment was to test the device in that sea environment [68].

Crete is an island where WECs have also been installed. Sinn Power installed devices in the port of Heraklion, Greece, to examine their technology [62]. Upon successful completion of the tests, the team moved their next project forward; the assessment of a hybrid platform, where wind turbines, solar panels and WECs are integrated. The tests have also been carried out in the sea off Heraklion [71].

In addition, many other islands in the basin have been investigated theoretically as single cases, such as Sardinia [22,42], Malta [83] and Menorca [5]. Significant attempts have recently been made to investigate the suitability of wave energy exploitation in small Italian islands: Favignana [95], Ponza [59] and Giglio [96].

5. Discussion

Mediterranean wave energy potential is characterised by low wave power density compared to the Atlantic coasts [15]. However, wave energy harvesting appears to be promising in specific Mediterranean areas, even though the exploited wave power is not as significant as in the open seas [6].

A notable characteristic of the beneficial aspects of WECs in the Mediterranean Sea is the fact that there are many islands, which complicate the decarbonisation of the Mediterranean countries. Most islands are tourist destinations with high energy land demand, so the exploitation of renewable sources, such as wind and solar, is a challenge indeed. Hence, in high or moderate wave energy potential islands, nearshore and offshore wave energy harvesting could be the solution of green energy production, increasing the contribution of the renewables in the energy mix and boosting the decarbonisation of the islands. Moreover, high solar and wind intermittency is a severe problem for the islands' energy safety. Therefore, the installation of WECs could diminish this problem due to low variability and easy predictability of wave power.

One of the most remarkable advantages of Mediterranean wave energy exploitation compared to high energetic locations (open seas) is that extreme events occur more rarely due to the moderate wave climate. The survivability of WECs in the sea during their operation is one of the most preeminent obstacles of the wave energy harvesting sector. In open seas, the possibilities of extreme events are much higher, thus the damage risk is much higher than in semi-enclosed seas. Considerable literature has been published around the theme of wave energy exploitation in the Mediterranean Sea, with many researchers focusing on extreme events and beneficial aspects of the Mediterranean moderate wave climate. A notable example is the study of Besio et al. [6], who suggested that the Mediterranean Sea is a region that appears to have promising wave energy resources despite its lower levels compared to the open seas. Moreover, Liberti et al. [17] also pointed out that in semi-enclosed seas with low wave energy potential, such as the Mediterranean, the solution of the survivability issues could be much more feasible in comparison with higher energy potential areas such as in the open seas. This occurs due to the fact that higher energy potential locations entail more extraordinary wave conditions in extreme events, posing serious design challenges of deployed WECs in these locations.

Several wave energy technologies have successfully been tested in environmental conditions, supporting WECs feasibility in the Mediterranean basin. In addition, it is worth underlying the fact that five different types of WEC have already been examined without considerable problems. This means that the wave conditions allow wave energy extraction by different technologies. In particular, the Wave Clapper, which is one of the four different devices of point absorbers that have been deployed, has been installed in two different areas. Three out of four point absorber devices, Wave Clapper, SP WEC 3rd Gen and SP WEC 4th Gen were installed in the breakwaters of ports, and the fourth, PB3 PowerBuoy, was deployed offshore of Ravenna. The wave power of these point absorbers varies between 3–36 kW, with the SP WEC 4th Gen being the most powered point absorber that has been deployed in the whole Mediterranean. Furthermore, the number of installed Wave Clappers is much higher than the other point absorbers since only one PB3 PowerBouy, two SP WEC 3rd Gen and two SP WEC 4th Gen are deployed.

In terms of the other types of investigated WECs in real conditions, the project of integrated REWEC3 in the port of Civitavecchia is regarded as the most powerful. REWEC3 belongs to OWCs with installed wave power of 2500 kW, a value much higher than that of the rest of the technologies. The following more powerful device is ISWEC (100 kW) deployed in the island of Pantelleria. Two different ISWEC devices have been deployed: one has twice the power of the second. In addition, ISWEC is one of the two WEC technologies in the Mediterranean that was installed offshore. The second WEC is PB3 PowerBouy, with 3 kW, which means much lower power.

Moreover, OBREC has low power, 8 kW, and it is the only of the examined devices installed in a relevant environment, which means that the exploited wave energy is foreseeably low. One last point worth mentioning is that the onshore, nearshore and offshore WECs have been tested in the Mediterranean Sea. Undoubtedly, the cases of onshore devices outnumber them despite the operation of one nearshore WEC (H24) and two offshore WECs (ISWEC and PB3 PowerBouy).

6. Conclusions and Recommendations

A detailed review of wave energy resource assessment and an overview of the state-of-the-art of deployed WECs in real environmental conditions in the Mediterranean Sea have been presented in this study. Furthermore, several primary studies, which focused on different wave energy issues in the Mediterranean are discussed. The main focus of these studies were the ongoing trends, the examination of WECs in combination with other renewable sources, the utilisation of WECs for desalination, and the prospects of wave energy in the Mediterranean islands and ports.

To the best of the authors' knowledge, this paper is the first comprehensive study that reports recent significant developments in the wave energy sector in the Mediterranean countries. The large body of literature that was analysed illustrates the considerable efforts that have been conducted and the attempts of academic and business research to investigate the possibilities of WECs in the Mediterranean Sea. The most important conclusions are:

- Several studies have broadly assessed the wave energy potential in the Mediterranean Sea; some focused on specific locations and some on the entire basin.
- Italy is the Mediterranean country where the most WECs have been deployed. The countries with at least one tested WEC are Greece, Israel and Gibraltar.
- Some studies relate wave energy exploitation to water desalination, coastal areas protection and sustainability of the Mediterranean countries.
- The question of which WECs could benefit the Mediterranean ports and islands with moderate or high wave energy potential has been broadly investigated.
- Projects about the expansion of facilities, construction and deployment of new technologies have been announced.

As concerns the deployed WECs:

- The installed WECs fall in the categories of overtopping device, OWC, rotating mass, point absorber and others.
- The point absorber is the most commonly installed type of WEC.
- Onshore WECs account for the majority of WECs which have been tested among onshore, nearshore and offshore devices.
- The installed power of the several deployed WECs in the Mediterranean Sea varies between 3–2500 kW.
- SP WEC 4th Gen, SP WEC 3rd Gen, Wave Clappers and ISWEC have all been successfully deployed twice, with the latter two installed in a different environment the second time.
- Photovoltaics panels were integrated on the WECs Wave Clappers in Israel and Gibraltar, and ISWEC in Ravenna.

The developments on the wave energy assessment and the real environmental testing of WECs is clear. However, the current maturity of the WECs and their high constructive, operational and maintenance cost are a barrier to exploit a non-profitable yet commercial energy source in contrast to other renewable energy sources in the Mediterranean. Hence, in order for wave energy to be economically viable, broadly exploited and to contribute significantly to the energy mix of the Mediterranean countries, more developments need to occur in the wave energy sector, and more research funds should support efforts to commercialise WECs.

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