Wave Energy Potential in the Mediterranean Sea: Assessment, Challenges, and Future Prospects

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As the global demand for sustainable and low-carbon energy sources intensifies, the United Nations' Sustainable Development Goals (SDGs) advocate for renewable, sustainable, and environmentally friendly energy sources. Ocean wave energy, a predictable and stable renewable resource, presents a significant opportunity to diversify the energy mix, enhance energy security, and mitigate climate change. Despite having a moderate energy flux compared to open oceans, the Mediterranean Sea offers a unique opportunity for harnessing wave energy. This is mainly attributed to the stable sea conditions, lower installation risks, and proximity to coastal populations. However, realizing this potential requires overcoming challenges related to technology durability, high capital costs, environmental impact, and fragmented regional policies. Through a qualitative synthesis of recent resource assessments, this paper provides an overview of the Mediterranean Sea's wave energy capacity, highlighting the performance and deployment of wave energy converters (WECs) in various locations within the basin. This study also explores the role of WECs, their technological advancements, integration with hybrid renewable systems, and emerging pilot projects in Mediterranean countries. The study highlights the need for regional cooperation, innovation in wave-hybrid systems, and climate adaptation strategies to harness wave energy as a viable contributor to the Mediterranean's sustainable energy transition.

Keywords: *Mediterranean Sea, wave energy resource, SDGs, WECs, assessment*

List of Abbreviations

Hs………………………………	Significant Wave Height
IPTA……………………………	Innovative Polygon Trend Analysis
ITA……………………………..	Innovative Trend analysis
NDCs…………………………...	Nationally Determined Contributions
OWC…………………………...	Oscillating Water Column
PTO…………………………….	Power Take-off
REWEC3……………………….	Resonant Wave Energy Converter 3
SDGs……………………………	Suitable Development Goals
TW……………………………...	Tera Watts
UN………………………………	United Nations
WECs…………………………...	Wave Energy Converters

Introduction

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The world's energy demand is currently expanding in order to meet the world's ambitious development goals. Between 2003 and 2030, energy consumption is expected to increase by an annual average of 2.0% (AbdElhafez et al. 2012). Since the late 1800s industrial revolution, traditional fossil fuel energy supplies, such as coal and oil, have been primarily used in development processes (Avagyan 2021). Traditional resources are responsible for over ⅓ of global greenhouse gas emissions (Mondal et al. 2022), causing catastrophic climate change. Additionally, increased demand hastens the depletion of fossil fuel reserves. The United Nations (UN) adopted the Sustainable Development Goals (SDGs) to guarantee a more sustainable future for humankind. The goals were established in 2015, and significant implementation is scheduled to be completed by 2030. The proposed SDGs aim to address the pressing global challenges of poverty, inequality, and climate change while ensuring environmental sustainability. Figure 1 displays the SDGs framework, which allows for monitoring of Agenda 2030 implementation and accomplishments. As a result, academics and politicians are interested in exploring renewable, sustainable, and environmentally friendly energy resources. Renewable energy promotes energy security in various sectors, including transportation, the environment, buildings, and industry, in line with the SDGs (Olabi et al. 2023).

Renewable energy resources include wind, sun, geothermal energy, salinity gradient, tides, ocean wave energy, biofuels, and biogas. Renewable energy systems are becoming less costly and more effective, and their share of total energy consumption is growing (Mohammed et al. 2019). Energy from renewable resources accounted for one-third of the total worldwide power capacity built in 2019 (IRENA 2020).

Wave energy, derived from the movement of ocean waves, represents an untapped potential in the renewable energy sector. Unlike solar and wind energy, which are highly variable and weather-dependent, wave energy is more predictable and stable due to its relationship with ocean currents and wind patterns. As the world moves toward decarbonisation, wave energy presents a valuable opportunity to diversify the renewable energy mix, enhance energy security, and contribute to climate change mitigation.

Among the UN-SDGs, SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) are critical, especially in the context of renewable energy. Renewable energy plays a significant role in contributing to several SDGs because it can help countries reduce their dependency on fossil fuels, promote cleaner energy, and create sustainable industries (Jaiswal et al. 2022).

As a renewable energy resource, the contribution of ocean wave to fulfilling SDGs can be highlighted in the following points according to priority:

- SDG 7: Affordable and Clean Energy

Wave energy is a sustainable and reliable source of energy for coastal and island communities. It can complement existing renewable sources, such as solar and wind energy, to offer a more consistent energy generation solution. Countries with high energy demands and reliance on imported fossil fuels can use wave energy to diversify their energy mix, improve energy security, and reduce the environmental footprint of their energy production (Falcão 2010).

Figure 1. *Sustainable Development Goals (SDGs) of the United Nations*

Source: https://www.un.org/sustainabledevelopment/blog/2015/12/sustainable-development-goals-kick-off-with-start-of-new-year/#

- SDG 13: Climate Action

Wave energy contributes to climate change action by reducing greenhouse gas emissions. By shifting from fossil fuels to renewable energy sources, such as wave energy, countries can significantly lower their carbon emissions. The integration of wave energy converters (WECs) into the energy grid also supports the global effort to meet the targets of the Paris Agreement on climate change by enabling cleaner, more sustainable energy generation (IEA-OES 2021).

- SDG 9: Industry, Innovation, and Infrastructure

The development of wave energy technologies has promoted innovation in energy systems, manufacturing, and infrastructure. Investments in WECs drive technological advancements, creating new industries, provide employment opportunities, and foster economic growth in regions with significant wave energy potential (IEA-OES 2021).

- Wave energy also aligns with SDG 14: Life Below Water because it offers an opportunity for low-impact energy generation that minimizes harm to marine ecosystems (Fallah Shayan et al. 2022).
- Furthermore, exploring wave energy resources supports SDG 8: Decent Work and Economic Growth by creating opportunities for jobs in the manufacturing, installation, and maintenance of WECs (Foteinis 2022).

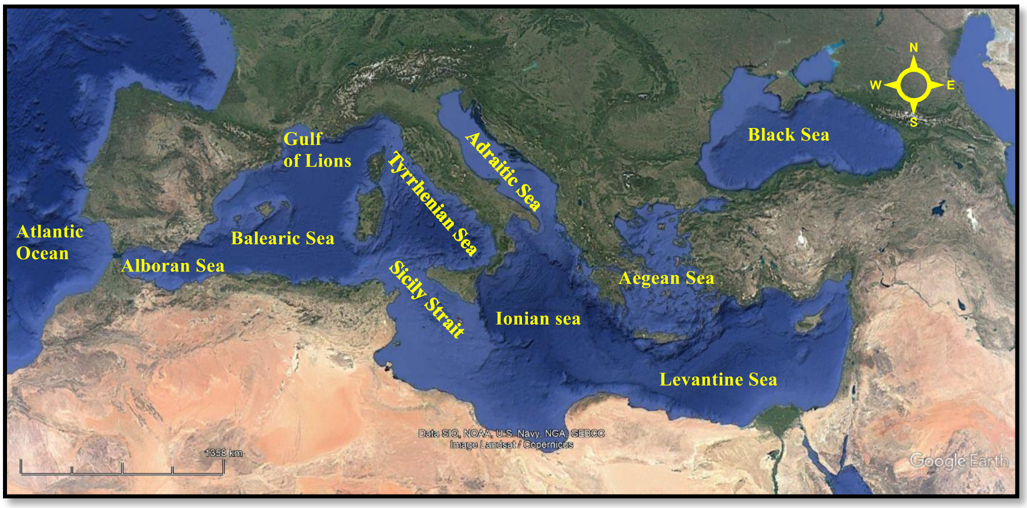
Although established renewable energy sources like solar, wind, biomass, geothermal, and hydropower, are widely utilized, there is an urgent need to diversify the energy mix to effectively mitigate climate change. Wave energy, an abundant yet underutilized resource, has emerged as a promising candidate to complement existing renewable energy sources and reduce dependence on fossil fuels.

According to Mørk et al. (2010), the global gross wave energy resource is estimated to be 3.7 terawatts (TW), with regions such as the North Atlantic and the Mediterranean Sea exhibiting considerable wave energy potential. These areas are home to some of the highest wave power densities, ranging from 10 to 40 kW/m. High-energy regions, such as the Atlantic coastlines of Europe, specifically the United Kingdom, Portugal, and Ireland, exhibit more significant wave energy fluxes, reaching up to 70 kW/m in certain locations (Kalogeri et al. 2017). However, these areas pose operational challenges due to harsh weather conditions, which can hinder the survivability of WECs. Semi-enclosed seas, such as the Mediterranean Sea, offer a viable alternative due to their moderate wave energy levels and reduced risk of extreme events.

The Mediterranean Sea (Figure 2) characterized by an average wave energy power lower than that of the Atlantic, has nonetheless garnered attention for its potential to support sustainable energy projects. Studies have highlighted several promising locations, including the northwestern Mediterranean, southern Italy, and parts of Greece, where wave power levels range from 7 to 15 kW/m (Dialyna and Tsoutsos 2021). Their findings suggest that although the Mediterranean may not rival the Atlantic in raw energy potential, its relatively stable conditions could facilitate cost-effective and reliable wave energy exploitation.

This paper provides a comprehensive qualitative overview of the wave energy landscape of the Mediterranean Sea. The primary objectives of this study are to assess the existing wave energy capacity, analyze the performance and deployment experiences of various WECs across different Mediterranean locations, and identify the key challenges that hinder their widespread adoption. The paper also explores the integration of wave energy with other renewable sources, such as solar and winds, to enhance energy resilience and grid stability in the region. The novelty of this work lies in its interdisciplinary framework, linking wave energy development to broader climate action strategies, socioeconomic benefits, and sustainable coastal infrastructure. By addressing current knowledge gaps and identifying regional opportunities and challenges, this study contributes to advancing wave energy as a viable component of the Mediterranean's sustainable energy future.

Figure 2. *Mediterranean Sea and its Sub-seas*



Source: Authors by using Surfer16® Software

Global Climate Action and the Role of Renewable Energy

While climate change remains a pressing global challenge, notable advancements have been made in mitigation and adaptation strategies, particularly through the adoption of renewable energy systems. These successful advancements often stem from a combination of technological innovation, supportive policy frameworks, and increased public and private investment.

One significant area of success lies in the rapid advancement and deployment of renewable energy technologies, particularly solar and wind power. The global renewable power capacity built in 2019 accounted for one-third of the total worldwide power capacity (IRENA 2020). The drastic decrease in the cost of solar photovoltaic and wind energy over the past decade has made them economically competitive with, and often cheaper than, fossil fuels in many regions (Osman 2023). This cost reduction, driven by research and development, economies of scale, and supportive government incentives (such as feed-in tariffs and tax credits), has led to a significant increase in their adoption (Rydehell et al. 2024). This demonstrates the power of sustained investment and policy support in transforming energy landscapes.

Furthermore, international agreements and frameworks, though sometimes criticized for their pace, have played a crucial role in galvanizing action. For instance, the Paris Agreement established a global framework for climate action, with countries committing to nationally determined contributions (NDCs) to reduce greenhouse gas emissions (Siriwardana and Nong 2019). The focus on achieving the SDGs, particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), has also provided a common agenda for governments, industries, and researchers to pursue cleaner energy solutions.

Another area of success is the growing recognition and implementation of circular economy principles (Velenturf and Purnell 2021). Although not a direct energy source, the circular economy indirectly contributes to climate change mitigation by reducing overall energy consumption and associated emissions (Knäble et al. 2022). This involves reducing waste, reusing materials, and recycling, thereby decreasing the demand for virgin resources and the energy required for their extraction and processing (Velenturf and Purnell 2021, Knäble et al. 2022).

However, a critical analysis of these successes also reveals important caveats. The pace of renewable energy adoption, while impressive, is still not sufficient to meet the ambitious targets required to limit global warming to 1.5°C above pre-industrial levels. Significant challenges remain in grid integration, energy storage, and ensuring grid stability with a high penetration of intermittent renewables (Ergun et al. 2025). The successes achieved often represent the initial steps, and the true test lies in scaling these solutions globally and equitably.

In the context of the Mediterranean region, several successful initiatives demonstrate progress toward decarbonisation and resilience. Several Mediterranean countries have integrated climate goals into their national energy policies. For example, Greece and Italy have implemented strategies to increase the share of renewables, aligning with SDG 7 and SDG 13. These policies have led to the expansion of solar, wind, and, more recently, wave energy pilot projects. EU-funded programs such as Horizon 2020 and regional initiatives under the Union for the Mediterranean have supported joint ventures in marine renewable energy. These programs facilitate technology transfer, data sharing, and capacity building, all of which are crucial for climate adaptation and low-carbon innovation. From a coastal protection point of view, projects in Spain and Italy have demonstrated how WECs can reduce shoreline erosion, offering dual benefits in the face of sea-level rise and intensifying storms, both consequences of climate change (Bergillos et al. 2019, Rodriguez-Delgado et al. 2019).

Despite these successes, progress remains uneven. Many Mediterranean nations still lack cohesive regulatory frameworks for marine renewables, and large-scale WEC deployment remains rare. Additionally, monitoring and evaluating the long-term climate benefits of wave energy projects are still in the early stages.

Wave Energy in the Mediterranean Sea

Resource Assessment

Extensive research has been conducted to evaluate wave energy potential across the Mediterranean basin, with particular emphasis on identifying high-energy hotspots and understanding seasonal variations. The wave energy potential in the Mediterranean region is highly variable, and influenced wind regimes, fetch length, and bathymetry. Studies using wave models and satellite data indicate that the western Mediterranean and specific hotspots like the Ligurian Sea and the Alboran Sea exhibit higher wave energy densities than the eastern Mediterranean (Acar et al. 2023). Seasonal variability is also significant, with peak energy observed during the winter months.

Arena et al. (2015) identified the northwestern Mediterranean, including the Alghero region (west of Italy), as the most energetic area, with an average wave power of 15.1 kW/m. Besio et al. (2016), utilizing 35 years of wave data, pinpointed regions between Sardinia, Corsica, northern Algeria, and the Balearic Islands as particularly promising, with an average wave energy potential of around 10 kW/m. The eastern Mediterranean has been the focal point of numerous studies due to its unique characteristics and moderate wave energy potential. Key locations, such as northern Tunisia, western Crete, southern Sicily, and the southern Ionian Sea, exhibit wave power levels ranging from 7.3 to 11.1 kW/m (Ayat 2013). Vicinanza et al. (2013) highlighted the western Sardinian coastline as a prime site, specifically the Porto Alabe and Torre del Porticciolo areas. Zodiatis et al. (2014) estimated the mean wave energy in the eastern Mediterranean as 10 kW/m. Similarly, studies in Sicily have identified the western coastline and the Strait of Sicily as regions with strong wave energy potential, with average wave power fluxes of 8 kW/m and 4-6 kW/m, respectively (Iuppa et al. 2015, Dialyna and Tsoutsos 2021).

Within this region, the Aegean Sea, Levantine Basin, and Libyan Sea have shown considerable promise for exploitation of wave energy, albeit with varying levels of seasonal and spatial variability.

The Aegean Sea, a semi-enclosed area with a complex coastline and numerous islands, offers a mix of opportunities and challenges for wave energy development. Studies by Ayat (2013) and others have identified regions such as southern Crete, Karpathos, and eastern Crete as having consistently high wave energy flux, with an average of around 8 kW/m during the winter months. Additionally, central areas of the Aegean, including the straits between islands such as Mykonos and Ikaria or between Crete and Kasos, exhibit localized energy peaks driven by strong winds and favorable topography (Porichis 2023). These regions are particularly appealing due to their relatively low variability compared to the central Aegean region, which experiences greater fluctuations. The Adriatic and Aegean Seas have promising but underutilized potential, averaging 3-7 kW/m (Lavidas and Venugopal 2017). Other promising locations include the Aegadian Islands, the northern Latium coasts, and specific nearshore areas, such as Argentario in Tuscany (Lo Re et al. 2019, Dialyna and Tsoutsos 2021). The regions near Crete and Karpathos demonstrate consistent energy levels of around 8 kW/m (Lavidas and Venugopal 2017). Seasonal studies in these areas emphasize lower variability compared to the central Aegean, suggesting their suitability for wave energy exploitation.

The Levantine Basin, encompassing the coasts of Cyprus, Israel, Lebanon, and Egypt, is another significant area of interest. Zodiatis et al. (2014) highlighted the western coastline of Cyprus and parts of the Israeli shoreline as high-potential zones for wave energy, with average wave power levels of around 6–7 kW/m. El-Sharkawy et al. (2017) evaluated the wave energy resource off Port Said along the eastern Egyptian Mediterranean coastline to be 4.5-6.2 kW/m. These sites are characterized by stable wave conditions and proximity to densely populated coastal regions, making them suitable for localized energy generation projects. Furthermore, the basin's relatively calm conditions reduce the risk of extreme weather events, enhancing the operational reliability of WECs.

The Libyan Sea, located to the south of Crete, also stands out as a key area for wave energy research. Lavidas and Venugopal (2017) assessed the wave energy flux in this region, reporting seasonal averages between 8 and 10 kW/m during winter months, with reduced variability compared to other parts of the Mediterranean. This stability, coupled with its proximity to key maritime routes and emerging markets in North Africa, positions the Libyan Sea as a strategic location for future wave energy investments.

Overall, these studies demonstrate that although the eastern Mediterranean has lower wave energy levels than the Atlantic, it offers significant opportunities for sustainable energy development. The relatively stable wave conditions and strategic geographical location make this region attractive for localized energy production and integration into renewable energy systems.

Table 1 outlines some previous studies on wave energy potential across the Mediterranean Sea, showing the region of interest and type of data used.

Table 1. *Wave Energy Resource Assessment Studies in the Mediterranean Sea*

Geographical Region	Data Types	References
Mediterranean Sea (Entire)	Numerical Wave Models, Satellite Data; ERA5	(Liberti et al. 2013, Besio et al. 2016, Acar et al. 2023)
Libyan Sea	*In-Situ* Measurements; ERA5	(Lavidas and Venugopal 2017, Foti et al. 2022)
Aegean and Levantine Seas	Numerical Wave Models, *In-Situ* Measurements, Satellite Data	(Ayat 2013, Zodiatis et al. 2014, El-Sharkawy et al. 2017, Porichis 2023)
Greek Coasts	Numerical Wave Models, *In-Situ* Measurements	(Soukissian et al. 2011, Emmanouil et al. 2016, Porichis, 2023)
Sardinian Coasts	Numerical Wave Models, *In-Situ* Measurements	(Vicinanza et al. 2013)

Technological Advances in Wave Energy

Recent advances in wave energy conversion technologies have been significant. The development of various WECs, such as point absorbers, oscillating water columns (OWC), and overtopping devices, has led to successful pilot projects and deployments worldwide. The integration of these devices into coastal infrastructure, such as breakwaters and ports is a cost-effective and environmentally friendly solution (Vicinanza et al. 2013).

In terms of technological readiness, the most advanced WECs are those tested in real-world environments. For example, the Resonant Wave Energy Converter 3 (REWEC3) device, deployed in Civitavecchia, Italy, has demonstrated a substantial ability to generate electricity, with installed capacities ranging from 50 kW to 2500 kW, depending on the technology and location (Arena et al. 2015). Additionally, hybrid systems that combine wave energy with other renewable energy sources, such as wind and solar, have been identified as promising solutions to increase overall energy generation and provide more consistent energy outputs (Ferrari et al. 2020).

However, challenges arise when using the different technologies to harness wave energy. Wave energy technologies face hurdles such as high capital costs, durability in marine environments, and low efficiency under moderate wave climates. Point absorbers, oscillating water columns, and overtopping devices are among the technologies explored for the Mediterranean. In addition, potential impacts on marine ecosystems, such as noise pollution and habitat disruption, necessitate comprehensive environmental impact assessments. The Mediterranean's biodiversity and designation as a semi-enclosed sea intensify these concerns. Lastly, policy and regulatory barriers remain important challenges to harnessing energy from the Mediterranean wave regime.

Integration with Other Renewable Energy Sources

Recent research has explored the feasibility of combining wave energy with other renewables such as wind and solar. Such hybrid systems aim to enhance energy generation reliability and efficiency by leveraging the complementary nature of these resources. Hybrid systems have shown promise in maximizing energy output and stabilizing supply (Hassan et al. 2023). Several studies have evaluated the feasibility of integrated wave and wind energy systems across the Mediterranean. Ferrari et al. (2020) identified the Algerian coastline as an advantageous area for harvesting both wave and wind energy. Studies indicate that regions like the Strait of Sicily, the Gulf of Lions, and offshore areas near Sardinia and the Balearic Islands are particularly well-suited for integrated wave and wind energy harvesting (Kalogeri et al. 2017, Azzellino et al. 2019, Dialyna and Tsoutsos 2021). These locations exhibit consistent wave activity and favorable wind conditions, enabling stable and high-yield energy production.

In the eastern Mediterranean, Greece has emerged as a promising region for wave-wind hybrid systems. The Greek wave and wind potential, which underlies the largest wave power potential in the southern Ionian Sea and the western Cretan Sea -nearly 7 kW/m- was assessed by Emmanouil et al. (2016). In addition, locations such as southeastern Mykonos and northwestern Crete have been identified as optimal for combined exploitation (Ganea et al. 2017). Assessments of the Italian coastlines revealed viable sites for co-deployment, considering factors like depth, environmental impact, and accessibility (Azzellino et al. 2019). Their findings suggest that locations near Elba Island, the Aeolian Islands, and the southern Adriatic and Ionian Seas offer significant potential for such hybrid installations. These areas are strategically advantageous, considering environmental factors, sea depth, and accessibility.

Table 2 summarizes studies on hybrid wave-wind energy systems, highlighting key regions and the potential for combined energy harvesting.

Table 2. *Examples of Wave and Wind Energy Resource Assessments in the Mediterranean Sea*

Geographical Area	Wind and Wave Energy Hybrid System	Reference
Strait of Sicily	High potential for combined energy systems	(Kalogeri et al. 2017)
Greek Coasts	Optimized hybrid systems for energy generation	(Vasileiou et al. 2017)
Balearic Islands	Potential for co-deployment of wind and wave energy	(Azzellino et al. 2019)

These findings highlight the potential of hybrid renewable energy systems to enhance energy security and sustainability in the Mediterranean region. By integrating wave energy with other renewable sources, the Mediterranean region can optimize energy production, improve grid stability, and reduce reliance on fossil fuels. These synergies could also lead to innovative applications, such as powering desalination plants and providing clean energy to coastal communities.

Ongoing Trends of Wave-Climate

Climate change has a profound impact on wave energy resources, influencing key parameters such as wave height, period, and propagation direction. Factually, ocean waves respond complexly to climate change, which may have a direct impact on the variables involved in their genesis, transformation, and dissipation (Simonetti and Cappietti 2023, de Leo et al. 2024). Recent studies have examined how these trends might alter the viability of wave energy projects in the Mediterranean (e.g., Morim et al. 2019, Acar et al. 2023, De Leo et al. 2024). Sierra et al. (2017) explored future wave climate scenarios for Menorca, Spain, revealing a potential decline in wave energy during the autumn and winter, coupled with spatial variability in the summer. In contrast, studies on the Moroccan Mediterranean coast have predicted relatively stable wave energy resources under future climate scenarios, indicating minimal disruption to energy harvesting potential. A projected increase in wave power due to longer wave periods along the Calabria coasts was concluded through analysis of wave-climatology data in the Italian seas (Foti et al. 2022). Their research also indicated positive trends in wave energy potential for most Italian coastal regions, excluding the Adriatic and Ligurian Seas. Similar trends were identified by Casas-Prat et al. (2022), who estimated changes in the wave parameters in the northwestern Mediterranean. Their findings suggest seasonal variations, with winter waves becoming more energetic while summer conditions remain stable. De Leo et al. (2024) reviewed studies that used multi-decadal datasets from numerical models, satellite observations, and *in-situ* measurements to draw up trends in ocean wave climates within the Mediterranean Sea, focusing mainly on significant wave height (Hs). Negative trends were more commonly observed, although often not statistically significant. Positive and significant trends are notable in the western Mediterranean, particularly in the Gulf of Lion and the Tyrrhenian Sea. The authors recommended the need for rigorous, high-resolution studies to address the gaps in understanding and provide actionable insights for climate change adaptation in the Mediterranean region. Acar et al. (2023)

investigated long-term trends in wave power in the Mediterranean Sea using data from the ERA5 reanalysis spanning 60 years (1962–2021) by employing classical statistical approaches such as the Mann–Kendall test and innovative methods, including the Innovative Trend Analysis (ITA) and Innovative Polygon Trend Analysis (IPTA), to evaluate annual and seasonal changes in wave power. Notable increasing trends in areas like the Libyan Sea suggest promising zones for renewable energy exploitation through WECs. However, this variability emphasizes the need for careful planning to address potential risks and optimize the sustainability of wave energy installations. The use of advanced methods such as ITA and IPTA is encouraged for nuanced analyses of wave energy trends in future studies.

Overall, the findings of wave-climate studies emphasize the need for adaptive strategies in wave energy system design to account for evolving wave climate conditions. By anticipating these changes, developers can ensure the long-term viability and resilience of wave energy projects in the Mediterranean.

Wave Energy and Other Considerations

The exploitation of wave energy in the Mediterranean involves multidimensional considerations, including coastal protection, socioeconomic benefits, environmental impacts, and integration with desalination technologies.

Wave energy converters have the potential to serve dual purposes by generating clean energy while protecting coastal areas from erosion. Bergillos et al. (2018) investigated the role of WECs in safeguarding the Guadalfeo deltaic coast in southern Spain and demonstrated their effectiveness in reducing erosion in vulnerable regions. Similarly, different configurations of WEC installations in low-energy seas were evaluated by Foteinis (2022), emphasizing the ability of deployed WECs to enhance coastal sustainability while mitigating the high capital costs typically associated with wave energy projects. The socioeconomic implications of wave energy development are particularly significant for Mediterranean countries. Lavidas (2019) explored the opportunities for WECs in Greece, where the relatively moderate wave energy potential could be advantageous due to reduced risks of extreme weather events. His study highlighted the potential for job creation, economic growth, and energy security, and advocated for policy support to foster wave energy adoption in regions like Greece.

Environmental assessments of WEC installations have focused on minimizing their ecological footprint. For instance, Corsini et al. (2015) examined the deployment of nearshore WECs on Ponza Island, Italy, and identified their low environmental impact while producing sustainable energy. Additionally, Buscaino et al. (2019) studied the acoustic emissions of WECs in Mediterranean shallow waters, and found that their impact on marine life was minimal and could be managed effectively with proper planning and monitoring.

Desalination is a critical application of wave energy in water-scarce Mediterranean regions, but its high energy demands pose economic and environmental challenges. Viola et al. (2016) demonstrated the feasibility of WEC-powered desalination systems in Sicily, Italy, highlighting their potential to provide a sustainable water supply. Similarly, Hwang and Kiung (2017) assessed the use of point absorbers for wave energy extraction around Sicily, and integrated this technology into existing desalination plants. These studies suggested that coupling wave energy with desalination offers a practical solution to address both energy and water needs in the Mediterranean.

While wave energy shows promise, several challenges remain, including high capital costs, technological maturity, and environmental concerns. The scalability of wave energy projects requires further investigation, particularly in terms of long-term durability and the economic feasibility of large-scale deployments. Additionally, the integration of WECs into national grids must be carefully managed to ensure grid stability and to prevent over generation during peak production periods. Future research should focus on reducing the costs of WECs, improving their efficiency, and developing hybrid systems that combine wave energy with other renewable sources, such as solar and wind. Increased investments in research and development, along with supportive government policies, will be critical in advancing wave energy technology and making it a commercially viable energy source.

Installed Capacities and Performances of Wave Energy Converters (WECs)

Overview of Installations across the Mediterranean Basin

The Mediterranean basin hosts several pilot and operational WEC installations, reflecting diverse wave energy harnessing approaches. Despite its moderate wave climate, technological advancements have facilitated deployment in key regions:

- **Egypt** (Salah et al. 2022): While still in nascent stages, Egypt has initiated studies of its wave energy potential along its Mediterranean coastline, particularly near Alexandria. Preliminary pilot projects aim to test oscillating water column (OWC) technologies, targeting energy outputs of 50-75 kW. These efforts align with the country's broader renewable energy strategy.
- **Israel** (Dialyna and Tsoutsos 2021): Coastal installations, such as Eco Wave Power's project in Jaffa Port, use innovative float-based WECs. These systems have achieved capacities up to 100 kW, with scalability plans are underway.
- **Italy** (Alfano 2023): Projects such as the ENEA Wave Energy Pilot near Pantelleria have demonstrated the potential of point absorber technologies. Recent evaluations indicate energy outputs averaging 80-100 MWh annually for moderate wave climates.
- **Greece** (Pompodakis et al. 2024): The Aegean Sea features small-scale installations, including the Poseidon Platform, which integrates wave and solar energy. These systems have high capacity factors during winter months, reaching 35% efficiency.
- **Spain** (Carreno-Madinabeitia et al. 2024): along the Bay of Biscay, the Mutriku Breakwater wave plant was integrated into a breakwater structure and utilizes oscillating water column (OWC) technology. Inaugurated in July 2011, it has a capacity of 296 kW from 16 turbine units. By October 2022,

the plant had delivered 2.7 GWh of energy to the grid, demonstrating the viability of wave energy in the region.

These installations represent significant steps towards the commercialization of wave energy in the Mediterranean Basin. They provide valuable data on device performance, grid integration, and environmental impact, paving the way for future large-scale deployments.

Performance Analysis

Vannucchi and Cappietti (2016) highlighted the following performance metrics for WEC installations in the Mediterranean basin:

1. **Capacity Utilization**: Efficiency ranges from 20% to 40%, depending on the location and wave climate.
2. **Durability**: Long-term operations emphasize the importance of corrosion-resistant materials and adaptive maintenance strategies.
3. **Economic Viability**: Subsidies and incentives have played a significant role in supporting initial deployments, particularly in regions with higher energy costs.

Challenges in Harnessing Wave Energy

Technological Challenges

Developing efficient and durable WECs is a primary technical hurdle. Wave energy technologies face hurdles such as high capital costs, poor durability in marine environments, and efficiency under moderate wave climates. Point absorbers, oscillating water columns, and overtopping devices are among the technologies explored for the Mediterranean. A review by McLeod and Ringwood (2022) highlighted that the irregular, low-frequency nature of ocean waves poses challenges to conventional energy conversion systems, necessitating specialized designs for effective energy capture. Optimization of WEC layouts and power take-off (PTO) systems is crucial for maximizing energy extraction. Recent research has focused on enhancing PTO parameters and site selection procedures to improve efficiency. For instance, Mehdipoura et al. (2023) introduced a novel hybrid algorithm that achieved a 3.31% increase in power output, demonstrating the potential of advanced optimization techniques. While the Mediterranean's semi-enclosed nature offers a less extreme environment than open oceans, ensuring the durability of WECs against storms and long-term wear remains a concern (Dialyna and Tsoutsos 2021).

Environmental Concerns

Potential impacts on marine ecosystems, such as noise pollution and habitat disruption, necessitate comprehensive environmental impact assessments. The

Mediterranean's biodiversity and designation as a semi-enclosed sea intensify these concerns (Buscaino et al. 2019). Allocating maritime space for WECs must consider existing uses such as fishing, tourism, and shipping lanes to minimize conflicts and ensure sustainable development.

Economic Viability

The economic feasibility of wave energy in the Mediterranean (Pompodakis et al. 2024) is influenced by the following:

High Initial Costs: The development and deployment of WECs involve substantial upfront investments, which can be a barrier to entry.

Market Competition: Wave energy must compete with more established renewable sources like wind and solar, which currently benefit from lower costs and more mature technologies.

Table 3 summarizes studies that discuss the economic impact, job creation, and energy security benefits of deploying wave energy converters in Mediterranean countries.

Table 3. *Socioeconomic Benefits of Wave Energy in the Mediterranean Region*

Country/Region	Socioeconomic Benefits	Reference
Greece	Job creation, economic growth, energy security	(Lavidas 2019)
Italy	Coastal protection, energy independence	Bergillos et al. (2018)
Cyprus	Sustainable water supply (desalination)	(Viola et al. 2016)

Policy and Regulatory Barriers

Efforts are underway to develop supportive regulatory frameworks and incentives to attract investment and facilitate the integration of wave energy into national energy strategies. A fragmented regulatory framework and a lack of region-specific policies hinder the deployment of wave energy projects. The varied economic and political landscapes of the Mediterranean countries further complicate collaborative initiatives.

Future Prospects

Technological Innovations

Advances in WECs, materials, and hybrid systems can enhance efficiency and reduce costs. Floating WECs and multi-purpose platforms for integrating wave, wind, and solar energy are promising. Materials science advancements, energy collection techniques, and power take-off systems are projected to increase efficiency and lower operational costs. Furthermore, digitalisation and artificial intelligence can improve the performance prediction, remote monitoring, and adaptive maintenance of WECs in complicated marine environments.

Regional Cooperation

Transboundary collaboration is essential for large-scale deployment. Initiatives like the Union for the Mediterranean's renewable energy agenda can play a pivotal role in fostering joint ventures and knowledge sharing. Future progress depends on improved regional cooperation, such as standardised permission frameworks, grid integration standards, and maritime spatial planning. Cross-border research and demonstration activities will also aid in the development of WECs, with funding from the EU and foreign sources. Policy instruments such as feed-in tariffs, green procurement rules, and innovation incentives are critical for lowering investment risk and attracting private sector participation.

Climate Change Considerations

Climate change may alter the wave energy patterns in the Mediterranean. While some studies have predicted an overall decrease in wave energy due to weaker winds, localized increases in extreme wave events could offer new opportunities. Future wave energy projects must undergo comprehensive environmental impact studies to ensure minimum harm to marine biodiversity and fisheries. These projects should be integrated into multi-use coastal zones so that they can give additional advantages like coastal preservation and habitat enhancement. In addition, coupling wave energy with sustainable desalination technologies can address both energy and water security concerns in arid Mediterranean regions.

Discussion

This detailed analysis highlights the considerable, yet frequently under-valued, potential of wave energy in the Mediterranean Sea. While generally regarded as an area with low energy flux when compared to open oceans, our research, confirmed by current literature, identifies particular hotspots with high wave power density. The detailed assessment of wave energy potential across diverse Mediterranean regions, which incorporates current data, lays a solid platform for future site-specific developments and resource allocation. The study's findings are consistent with recent research highlighting the western Sardinian coast, Aegean Sea, and parts of the Libyan and Levantine Seas as viable hotspots for wave energy exploitation.

This work stands out for its integrated perspective, which links spatial resource variability to SDG alignment, environmental issues, and socioeconomic results. For example, while technical promise alone may not justify large-scale investment in some places, combining wave energy with desalination or coastal protection infrastructure might increase economic feasibility and social acceptance.

The progress in Wave Energy Converter (WEC) technology within the Mediterranean is particularly noteworthy. The evolution of WEC designs—particularly hybrid and nearshore-integrated systems—demonstrates increasing adaptability to the Mediterranean's specific wave climate. Pilot projects in Spain, Greece, and Italy have demonstrated that innovations like overtopping devices and oscillating water columns can be beneficial even in low-energy situations. However, widespread deployment is hampered by high capital costs and the requirement for long-term endurance in corrosive marine environments. This technological advancement is a result of ongoing research and development efforts, reflecting important triumphs witnessed in other renewable industries such as solar and wind power, where persistent innovation and scale have brought down costs and improved adoption rates.

Beyond the technical feasibility, the socioeconomic benefits associated with wave energy deployment in the Mediterranean are substantial and multifaceted. The capacity for significant job creation across the entire value chain—from research and development to manufacturing, installation, operation, and maintenance—presents a compelling case for national and regional investment. This potential for green job creation aligns perfectly with broader sustainable development goals and can help foster economic growth in coastal communities. Furthermore, by providing a stable and predictable source of renewable electricity, wave energy can markedly enhance energy security, reducing the region's reliance on volatile fossil fuel markets and contributing to macroeconomic stability. The environmental advantages, highlighted by Life Cycle Assessment data, solidify wave energy's role as a clean alternative, offering a pathway to significantly reduce carbon emissions in the energy sector.

However, realizing the full potential of wave energy in the Mediterranean necessitates addressing several critical challenges. While evolving, policy and regulatory frameworks often lack the long-term consistency and clarity required to attract the substantial private investment needed for large-scale projects. The upfront capital costs of WEC technologies, though decreasing, still represent a barrier, necessitating innovative financing mechanisms and targeted incentives. Grid integration, particularly for island nations or remote coastal areas, poses technical and infrastructural challenges that require strategic planning and investment. Moreover, ensuring public and local community acceptance through transparent engagement and benefit-sharing mechanisms is paramount for successful deployment.

Despite its contributions, this study acknowledges certain limitations. Data variability among regional models, limited validation of long-term trends, and the still-emerging body of Mediterranean-specific WEC performance data necessitate cautious generalizations. Further empirical research and in-situ experimentation are required to refine site selection and improve the techno-economic assessment of projects under real-world conditions.

Conclusion

In conclusion, the Mediterranean Sea, despite its moderate wave energy potential in comparison to high-energy oceanic regions, stands as a vital region for diversifying the global energy mix and advancing towards a sustainable future. This study provided a comprehensive assessment of wave energy resources across the basin, emphasizing the interplay between technological advancements, spatial variability, climate resilience, and regional policy dynamics. Harnessing wave energy potential within the Mediterranean basin requires a multi-faceted approach encompassing continued technological innovation, supportive regulatory environments, and collaborative efforts among Mediterranean countries. Exploration of the Mediterranean wave energy resources aligns strongly with the SDGs of the UN, particularly SDG 7 (Affordable and Clean Energy), SDG 13 (Climate Action), and SDG 9 (Industry, Innovation, and Infrastructure). The findings underscore that while wave energy fluxes in the Mediterranean generally range from 5 to 15 kW/m, specific hotspots such as the western Sardinian coast, the Aegean Sea, the Libyan Sea, and parts of the Levantine Basin show stable and viable energy levels for localized deployments. These regions are particularly favorable due to their milder sea states, reduced risks of extreme wave conditions, and proximity to densely populated coastlines. Future research should focus on detailed techno-economic analyses of integrated hybrid renewable energy systems (wave-wind-solar), exploring optimal WEC configurations for specific regional characteristics, and conducting comprehensive social acceptance studies. By strategically investing in and collaboratively developing its inherent wave energy resources, the Mediterranean can significantly contribute to global decarbonisation efforts, enhance regional energy independence, and foster sustainable economic development in line with the UN-SDGs.

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