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

The Mediterranean Sea offers a unique opportunity for harnessing wave energy as a renewable resource, despite its moderate energy flux compared to open oceanic regions. This paper is a qualitative research that provides as an overview of wave energy capacity within the Mediterranean basin, highlighting the performance and deployment of wave energy converters in different locations within the basin. This paper highlights key challenges and discusses future prospects. Key topics include resource assessment and integration with other renewable energy resources. Findings revealed significant opportunities throughout the Mediterranean for energy production and sustainable development. Moreover, the findings emphasize the need for region-specific approaches, innovative technologies, and transboundary collaboration to develop the Mediterranean wave energy sources.

Keywords: *Mediterranean Sea; Wave energy resource; SDGs; WECs; Assessment*

Introduction

These days it is a fact that the world's energy demand is increasing in order to satisfy the world's ambitious development goals. Between 2003 and 2030, energy consumption is anticipated to rise 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. 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 complete 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 the monitoring of implementation and accomplishments towards Agenda 2030. 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, the tides, wave energy from the ocean, 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 total worldwide power capacity built in 2019 (IRENA, 2020).

Figure 1. *The 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/#)

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 has the advantage of being more predictable and stable due to its relationship with ocean currents and wind patterns. As the world moves toward decarbonization, 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). The contribution of ocean waves, as a renewable energy resource, to fulfilling SDGs can be highlighted, according to priorities, in the following points:

- SDG 7: Affordable and Clean Energy

Wave energy has the potential to provide 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).

- 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 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, which can create new industries, provide employment opportunities, and foster economic growth in regions with significant wave energy potential (IEA-OES, 2021).

- Additionally, wave energy 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 wave energy converters (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 mitigate climate change effectively. Wave energy, an abundant yet underutilized resource, has emerged as a promising candidate to complement existing renewable energy sources and reduce dependency on fossil fuels.

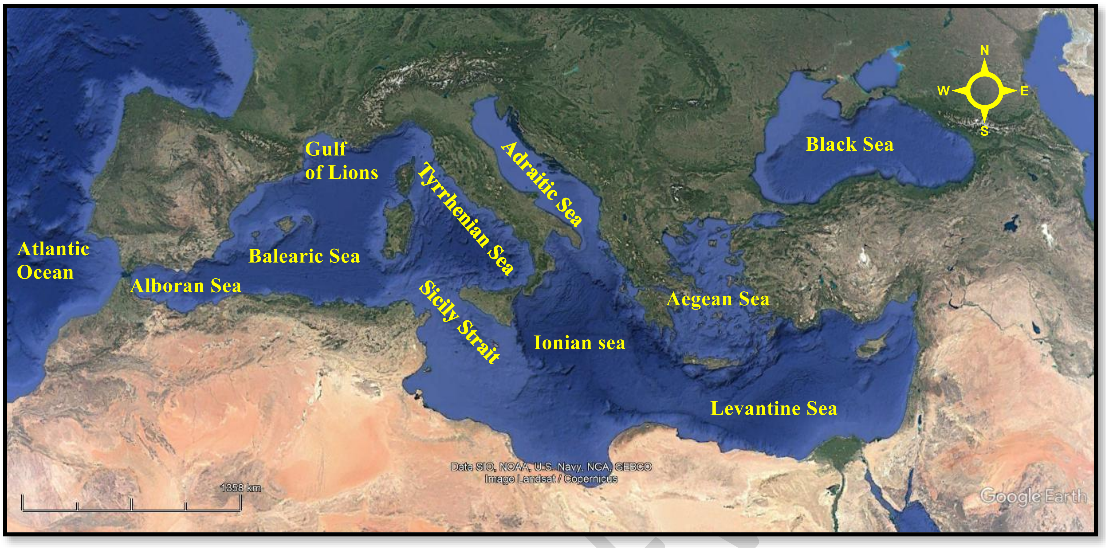
According to Mørk et al. (2010), the global gross wave energy resource is estimated to be 3.7 terawatts (TW), with regions such as the North Atlantic and the Mediterranean Sea exhibiting considerable wave energy potential. These areas are home to some of the highest wave power densities, ranging from 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 risks of extreme events.

The Mediterranean Sea (Fig. 2), characterized by an average wave energy power lower than 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 is a qualitative research that explores the relation of wave energy resources to the SDGs and their role in fostering a sustainable future. It evaluates the current state of wave energy research and deployment in the Mediterranean. Furthermore, this study discusses the spatial and temporal variability of wave energy resources and the integration of WECs with other renewable energy technologies.

By addressing these factors, this work provides a comprehensive understanding of wave energy's role in the Mediterranean's sustainable energy future.

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



Source: Authors by using Surfer16® Software

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. Wave energy potential in the Mediterranean region is highly variable, and is influenced by factors such as 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 compared to 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 average wave power reaching up to 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 average wave energy potential 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 at 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 wave energy exploitation, 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 Argenteria 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. Its relatively stable wave conditions, combined with a 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	(Besio et al., 2016; Liberti et al., 2013)
Libyan Sea	*In-Situ* Measurements	(Lavidas and Venugopal, 2017)
Aegean and Levantine Seas	Numerical Wave Models, *In-Situ* Measurements, Satellite Data	(Ayat, 2013; Zodiatis et al., 2014; El-Sharkawy et al., 2017)
Greek Coasts	Numerical Wave Models, *In-Situ* Measurements	(Soukissian et al., 2011)
Sardinian Coasts	Numerical Wave Models, *In-Situ* Measurements	(Vicinanza et al., 2013)

Technological Advancements in Wave Energy

Advances in wave energy conversion technologies have been significant in recent years. 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, has proven to be 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 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. Fragmented regulatory framework and a lack of region-specific policies hinder the deployment of wave energy projects. The Mediterranean countries' varied economic and political landscapes further complicate collaborative initiatives.

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 suggest 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 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 overgeneration 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 about 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 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. Fragmented regulatory framework and lack of region-specific policies hinder the deployment of wave energy projects. The Mediterranean countries’ varied economic and political landscapes 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.

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.

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.

Conclusion

The Mediterranean Sea, despite its moderate wave energy potential compared with open oceanic regions, presents significant opportunities for sustainable energy development. The relatively stable conditions of the Mediterranean region make it an attractive environment for deploying wave energy converters (WECs), reducing the challenges associated with extreme weather events in high-energy regions. Integration with other renewable energy sources, such as wind and solar energy, further enhances the feasibility and efficiency of wave energy systems in the region. In addition, applications such as coastal protection and water desalination provide pathways to maximize the socioeconomic and environmental benefits of wave energy technologies.

However, challenges remain. Advancements in WEC design, improved cost-effectiveness, and robust policy support are essential for unlocking the full potential of wave energy in the Mediterranean. Future research should focus on addressing these barriers while adapting to the impacts of climate change on wave resources.

Wave energy holds immense promise for the Mediterranean region's energy transition, offering a pathway to diversify the renewable energy mix, enhance energy security, and contribute to global climate goals. With coordinated efforts from stakeholders, the Mediterranean can emerge as a leader in sustainable wave energy development.

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