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Review

A Review Concerning the Offshore Wind and Wave Energy Potential in the Black Sea

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Abstract

This paper aims to analyze the Black Sea region's potential for renewable energy, focusing on offshore wind and waves. The study highlights the Black Sea as a new region for marine renewables exploitation in the context of climate objectives and the European shift to renewable energy. It also incorporates results from different previous studies, when data from in situ measurements, satellite observations, and numerical simulations and climate reanalysis have been considered and analyzed. The reviewed studies cover a wide time span from historical data in the late 20th century to projections extending until 2100, considering the climate change impact. They focus on both localized coastal regions (predominantly Romanian waters) and the larger Black Sea Basin. The comparative analysis identifies the northwestern part of the sea as the most favorable region for the development of offshore wind farms. The present work also discusses the environmental implications and technological development of different types of wave energy converters (WECs) and their use in hybrid systems integrating multiple marine energy resources. The review concludes by highlighting the region's outstanding potential for renewable energy and stressing the need for technological development, regional policy integration, and investment in infrastructure to enable sustainable marine energy harnessing.

Keywords: offshore wind; WEC; Black Sea; renewable energy

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1. Introduction

The negative effects of global warming have not delayed their appearance and have made their presence felt in recent decades. The excessive use of fossil fuels to generate energy represents a significant threat to the environment. Population growth, rapid economic growth, extensive industrialization, increased mobility, and infrastructure development are factors that have contributed to the increase in energy consumption in recent decades [1].

The economic development of a country largely depends on the creation and optimization of access to energy sources. Energy consumption is directly proportional to the population size, and with the demographic explosion, a greater number of resources are needed to cover the minimum necessary for consumers [2].

Economic growth stands as the main indicator of global prosperity, which drives urbanization and increased energy consumption. A major downside of this process is the increase in carbon dioxide emissions, which accelerates global warming [3].

The year 2023 signaled an outstanding progress achieved in the global energy transition, according to the significant steps covered by renewable energy sources, as mentioned in the framework of the 28th session of the Conference of the Parties, COP28 conference. Moreover, bold objectives were set, with the central aim of the conference being that, by 2030, the world's total energy production from renewable sources, along with improvements in energy efficiency, should substantially increase [4].

In 2024, record-breaking temperatures were registered globally, after the record-breaking heat of 2023. It also became the first year to register an average temperature significantly higher than 1.5 °C above the pre-industrial baseline, a threshold set by the Paris Agreement as the point at which the dangerous impact of climate change must be sharply cut out. Various records have been shattered regarding the greenhouse gas (GHG) concentration, sea-surface temperature (SST), and air temperature, and all these are among the factors contributing to abnormal events like heatwaves, flooding, and fires. All these new records shed light on the human climate-changing effects [5].

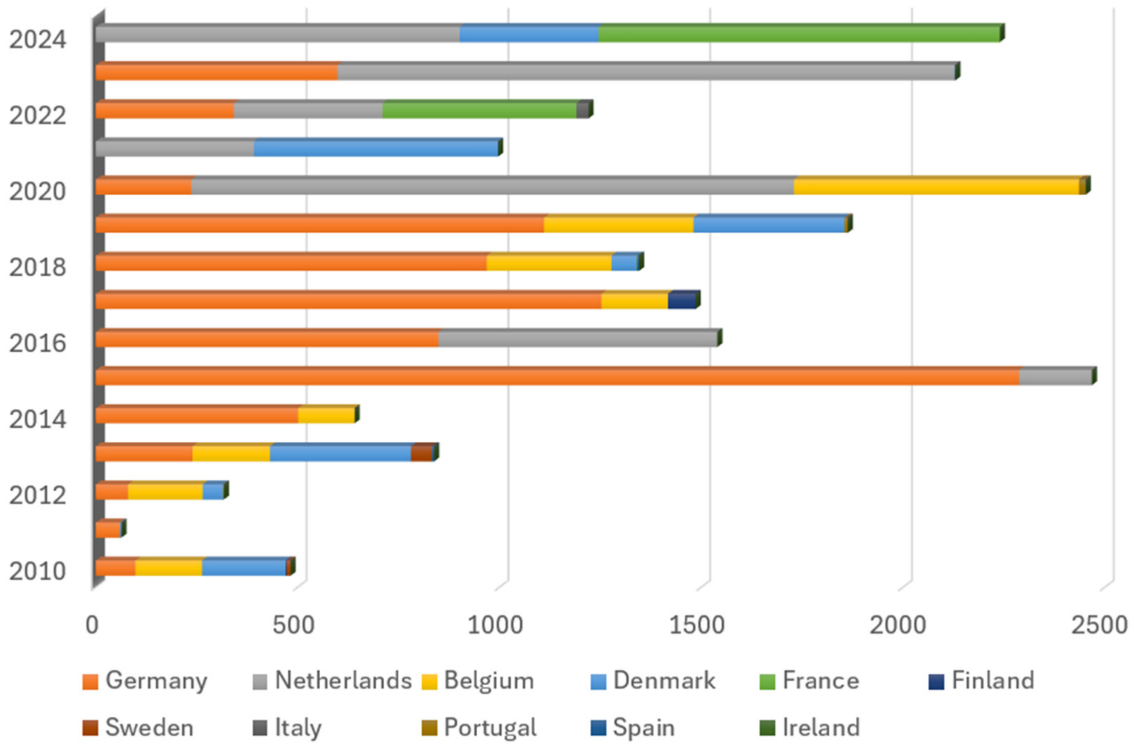
The greenhouse effect caused by human activities is the main driver of current climate change. The atmosphere of the Earth traps and holds Earth's surface heat, which results in global warming. The high energy demands, which are increasing, require the application of alternatives to fossil fuel combustion in the form of clean energy sources in a general effort to prevent pollution as well as global warming [6]. Under these circumstances, it is clear that addressing climate change and global warming demands immediate action to manage GHG emissions, with solutions focused on enhancing energy efficiency and shifting toward renewable energy sources [7].

The concept of "renewable energy" sparks debate among researchers. Some voices critically analyze the term, arguing that it should be abandoned in favor of more precise classifications. The authors of this study [8] claim that, for effective climate change mitigation policies, it would be more useful to move away from the broad term "renewable energy" and instead adopt a more detailed model that classifies energy sources based on their carbon emissions and combustible nature.

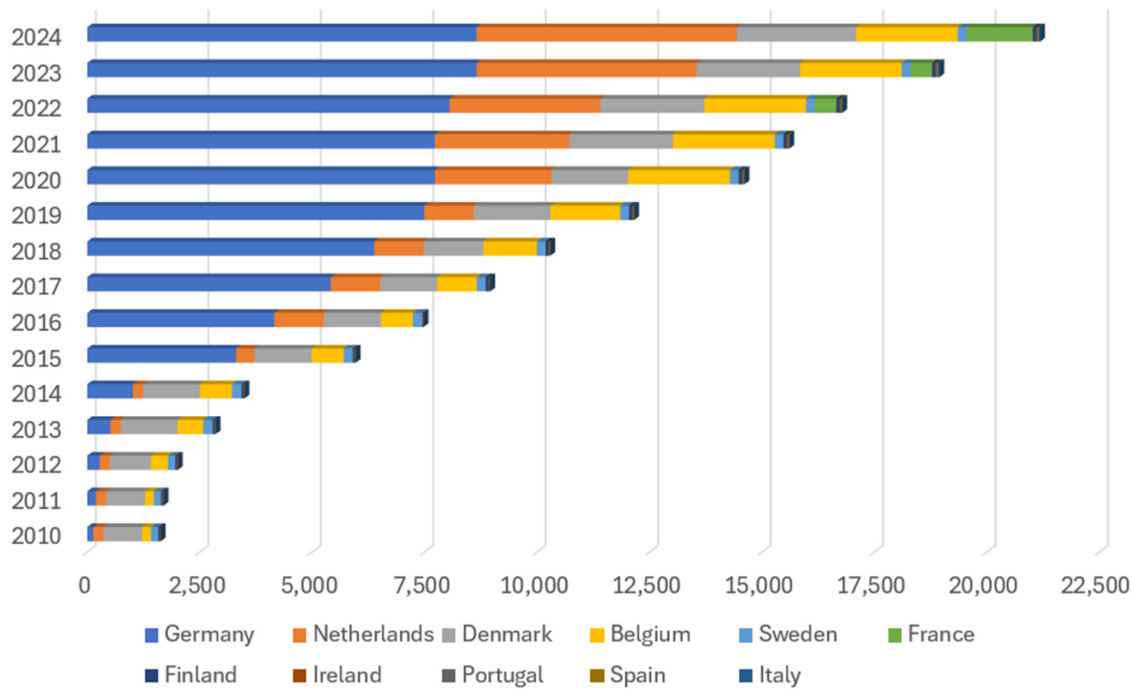
Energy systems depend on offshore renewable energy to transition from finite conventional resources to sustainable and unlimited natural energy sources. Although several countries border the Black Sea, which contains marine renewable resources, they must use them through efficient exploitation strategies, and the development of advanced technologies plays a key role [9]. The importance of the offshore renewable resources is also confirmed and highlighted by the "European Green Deal" strategy [10].

Before new technologies and infrastructure can be developed, government policies and finances need to speed up the shift to renewable energy, which will happen anyway. The integration of clean energy alternatives into the power production system is progressing, driven by various factors, such as new studies on energy system stability, advancements in renewable energy technology, the construction of new infrastructure, government policy enhancements, and more. The mitigation of the impact on the environment in the long run, energy loss reduction, and many more vital outcomes are achievable when attempting to optimize this integration [11]. All around the world, the current situation is far from ideal, and reducing the carbon footprint in the atmosphere is essential [12].

Transition to renewable sources is not only imminent but also necessary to combat climate change and provide long-term energy security. However, the effort to make this transition must be considerably ramped up. Governments need to introduce firm policies and make considerable funds available, specifically to drive nascent technologies and refurbish aging networks of power transmission and distribution. Without this assistance, the rate of transformation could lag what is required to advance global climate action, as global energy consumption continues to rise. The shift toward a cleaner energy mix remains slow [13]. Europe continues to expand its energy production from renewable sources, driven largely by rapid growth in offshore wind power, as indicated by the trends presented in Figure 1a,b. Even if it does not reach the potential of offshore wind energy, wave power in Europe shows promising potential, with significant installed capacity for validating technologies and consolidating a growth trajectory, as shown in Figure 1c.



(**a**)



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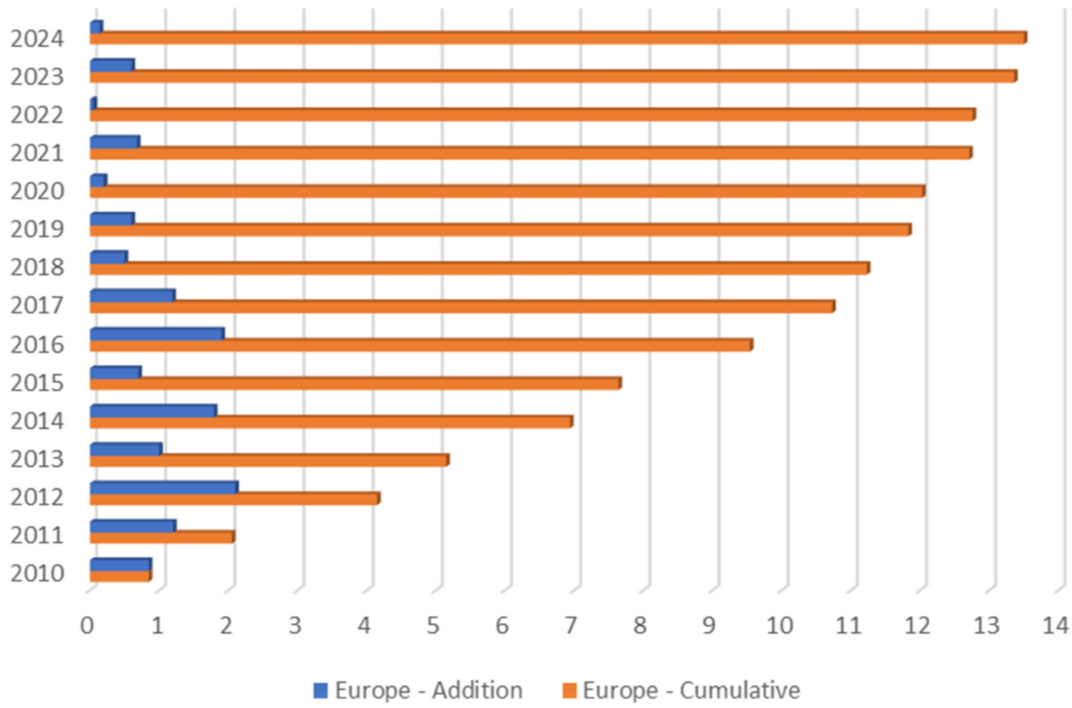

(**c**)

Figure 1. Offshore wind energy capacity additions (MW): (**a**) offshore wind energy installed capacity (MW), (**b**) wave power addition and cumulative (MW), (**c**) in the period 2010–2024. Adapted from [14].

Exploring the role of renewable energy, developing particular technologies, and integrating them into low-carbon power systems [15], such as solar power, wind power, and wave power, are emphasized as major solutions to reduce fossil fuel dependence and minimize carbon emissions [16]. An increasing interest in studying warming in coastal regions can be noticed in the context of global warming under climate change. In line with the global fast-paced and heterogeneous nature of this phenomenon, and compared with the 1995–2014 reference period, the coastal regions are certainly warming more rapidly, and the SSTs are set to rise by about 1 °C by the middle of the 21st century [17].

Given that the Black Sea region faces significant environmental challenges, such as eutrophication, industrial contamination, and biodiversity loss, it is important to emphasize the importance of sustainable growth. Six states managing this region make the carbon emissions-reducing policies of the EU important, exactly due to the heterogeneity of economies and regimes there [18].

Every ton of carbon dioxide (CO_2) that we successfully reduce not only helps mitigate the effects of global warming but also plays a crucial role in addressing the broader issue of climate change. The International Renewable Energy Agency (IRENA) emphasizes the need for a closer alignment of the energy policies with climate objectives and a series of urgent actions to facilitate the transition to a decarbonized energy system [19].

The transition to green technologies is essential for combating climate change, but the possible opportunities and risks associated with these activities should not be overlooked [20]. Geopolitical [21–23] and security [24,25] challenges, as well as some technical and financial challenges [26,27], can impact the progress of projects during their implementation process. To have a significant impact on the financial feasibility of energy generated from renewable sources, it is necessary to take into account artificial intelligence as well, since it is a current topic these days and which, according to some studies [28–30], can contribute to a more resilient and sustainable energy system by improving current practices and fostering new technologies in the sector. This paper provides a detailed analysis of the potential energy generation from offshore wind and wave power in the Black Sea.

The main objective is to synthesize existing knowledge regarding the climatic conditions, geographical features, applicable technologies, and feasibility studies related to these two marine energy sources.

This work is structured into seven sections and begins with an overview of the global and European context concerning the energy transition. It continues with a detailed characterization of the Black Sea and its climate particularities relevant to the development of the offshore wind and wave energy. Subsequently, the offshore wind potential in the Black Sea is analyzed in depth, along with the turbine technologies suitable for this maritime basin. A dedicated section on wave energy follows, covering different types of wave energy converters (WECs) and evaluating their performance in the specific environmental context of the Black Sea, including the key parameters influencing their efficiency. The analysis then proceeds to the combined use of the two energy resources, evaluating the integration of wind and wave energy technologies into hybrid systems, with a focus on the benefits of resource complementarity, system stability, and improved energy efficiency. Before the final section, the paper addresses the risks and environmental impacts associated with the development of marine renewable energy infrastructure in the Black Sea. The final section presents the main conclusions, focusing on the technical, economic, and strategic viability of harnessing the two resources in the Black Sea region.

By reviewing and integrating multidisciplinary studies, the aim of this work is to support future initiatives in research, investment, and public policy focused on the sustainable exploitation of the marine energy potential of the Black Sea.

2. The Black Sea

The Black Sea has an elliptical shape, stretching from east to west [31] and provides Romania with free access to the Atlantic Ocean through a series of straits and seas. The route Bosphorus Strait–Sea of Marmara–Dardanelles Strait–Aegean Sea–Mediterranean Sea–Strait of Gibraltar connects with the Atlantic Ocean, and through the Kerch Strait, the Black Sea is connected with the Sea of Azov, as we can see in Figure 2.

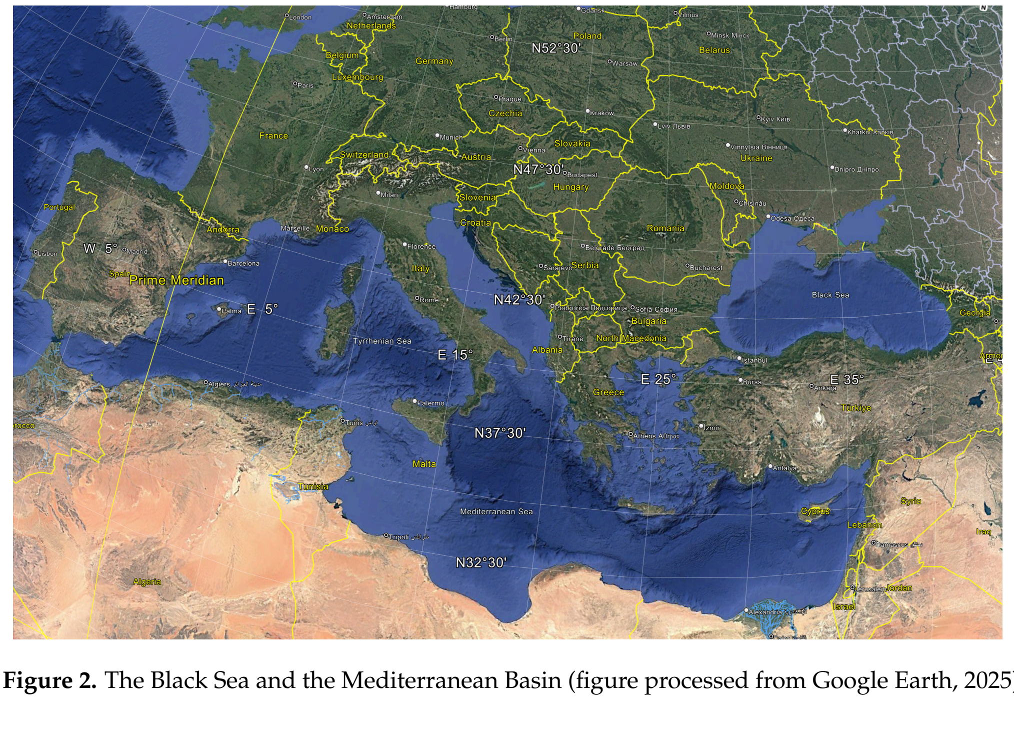

Figure 2. The Black Sea and the Mediterranean Basin (figure processed from Google Earth, 2025).

The Black Sea is an area of significant importance and holds significant value from multiple perspectives: economic, political, social, environmental, and strategic. Situated at the crossroads of Europe and Asia, it is bordered by Romania, Bulgaria, Turkey, Ukraine, Russia, and Georgia, and it could become a key corridor for energy transportation and production [32].

The Black Sea winds directly influence the wave characteristics, both wave height and period, and there is a clear connection between them. Extremely powerful winter winds, blowing especially from the north and northeast, generate the largest waves in the Black Sea, e.g., extreme waves up to 7 m in significant wave height, which are associated with powerful wind events, such as Bora [33]. In summer, when the winds are weaker and more stable from the west and southwest, the waves become shorter and the sea becomes rougher. Figure 3 illustrates the wind and wave climate calculated over 30 years, indicating that the western side of the Black Sea Basin is characterized by higher wind speeds and notable wave heights compared to the eastern side climate.

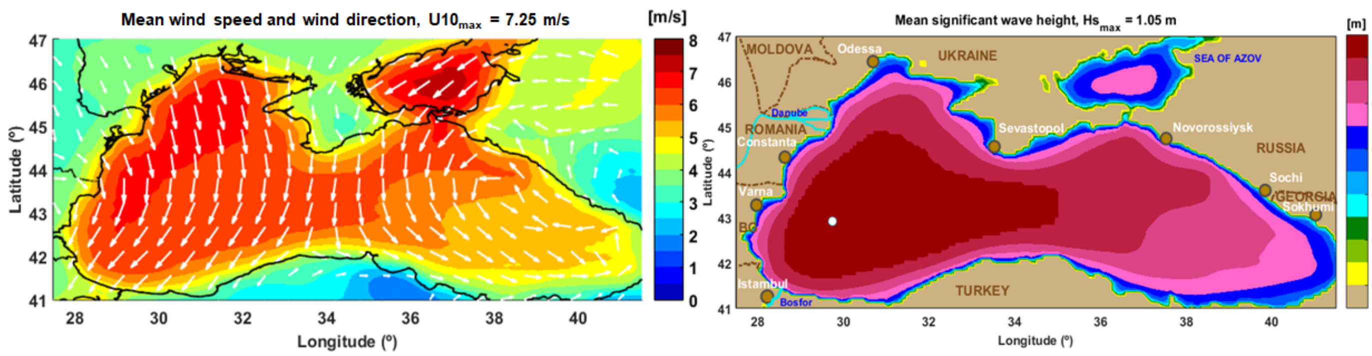

Figure 3. Mean wind speed fields and wind directions (**left panel**) and mean significant wave height (**right panel**) over 30 years (1987–2016). Adapted from [34].

The Black Sea climate is influenced by various factors, such as the geographical position of the basin, continental surroundings, and atmospheric circulation as a whole. The climate of the Black Sea Romanian coastal area is temperate-continental, moderate with maritime influences, particularly enhanced in the case of the region of Dobrogea. Continental, polar, and tropical air masses mix and generate storms that may obstruct offshore operations [35].

Besides these, high winter waves and strong winds also create difficult navigation conditions [36]. Coastal waves also induce erosion along the coast, particularly on low-lying coastal margins such as the western Black Sea on the Danube Delta [37]. Summer is, however, very calm both in waves and wind activity, hence making navigation safer and simpler in the Black Sea.

Climate change is a critical issue, which is why many researchers have turned their attention to this topic [38]. Due to specific basin influences, climate change, and other contributing factors, the coastal shape of the Black Sea is evolving, prompting many researchers to study this phenomenon. Thus, changes in the Black Sea's shoreline have been explored by analyzing both historical/present trends (e.g., from 1972 to 2018) [39] and future projections, considering short-term horizons (2021–2060), as well as medium-term ones (2061–2100) [40].

The Black Sea is considered a favorable environment for the development of marine projects, such as offshore wind farms, offering suitable maritime weather conditions, particularly during spring and summer. However, autumn and winter present significant challenges in the western part of the Black Sea [41], and climate change may negatively impact the development of the major renewable energy projects [42].

Based on these studies, which contribute to a better understanding of the climate risks for coastal regions and support future protection measures, it is clear that climate change is already present in the region and may have significant implications for its sustainable development.

As a consequence of global warming, temperature fluctuations have also emerged. Registrations made by several meteorological stations deployed along the Romanian coast indicate a moderate rise in the average annual air temperature. Thus, during the period 1965–2014, the average annual air temperature was around 11.7 °C, showing an increase of about 0.3 °C compared with the previous period 1885–1964 [43]. Although coastal tourism would appear to be short-term stimulated by global warming, via the extension of the tourist season, the negative impacts are tremendous and extensive [44].

3. Offshore Wind Energy

Offshore wind energy represents, at this moment, the best-developed alternative energy technology, and Europe dominates the business, as depicted in [45]. Offshore winds are stronger and more stable than on land, providing significant advantages that make offshore wind energy one of the most efficient and competitive forms of renewable energy [46]. The energy potential of Romania's exclusive economic zone in the Black Sea for the development of offshore wind projects is notable and widely studied. The Black Sea is described as having high potential due to its stable winds and wide continental shelf [47]. Offshore wind power is increasing in popularity at a very fast pace because it has been considered a stable and affordable technology. In 2020, offshore wind capacity was expected to grow from 17 MW to 6.5 GW by 2030 [48]. But only a year later, the forecast was revised, and the new estimate is much greater, with expected growth up to 16.5 GW by 2030 [49].

According to the Global Wind Energy Council (GWEC) report [50], in 2023, 11 GW of offshore wind power were connected to the grid, 24% more than the previous year. Such outcomes place 2023 as the second-best year on record for offshore wind energy after 2021, as mentioned in the 2022 report [51], also published by GWEC.

Figure 4 below illustrates the correlation between the development of the substructure costs, water depth, and the various foundation types applied to offshore wind turbines. As the water depth rises, the installation cost also increases, thereby affecting the selection of the technical solutions. For shallow waters (left), up to 30 m, fixed foundations such as monopiles, gravity bases, or suction buckets are typically used as they have lower costs and relatively simple technologies. For intermediate depths ("transitional", middle), 30–60 m, more complex and expensive structures must be used, e.g., tripods, guyed tubes, or jacket frames. In deep water (right side), beyond 60–100 m, floating platforms are the sole viable option, which has a higher cost but can be installed in more hostile marine environments. Foundation type is, therefore, strongly related to water depth, and the choice of the most appropriate technology relies on a trade-off between technical feasibility and total costs of implementation.

As the substructure costs increase with water depth, it becomes clear that the choice of the foundation type is not merely an economic decision but also an engineering one, with direct implications for the design of offshore wind turbines. In this context, the design process must consider not only the structural performance of the system but also its adaptability to the specific conditions of the marine site.

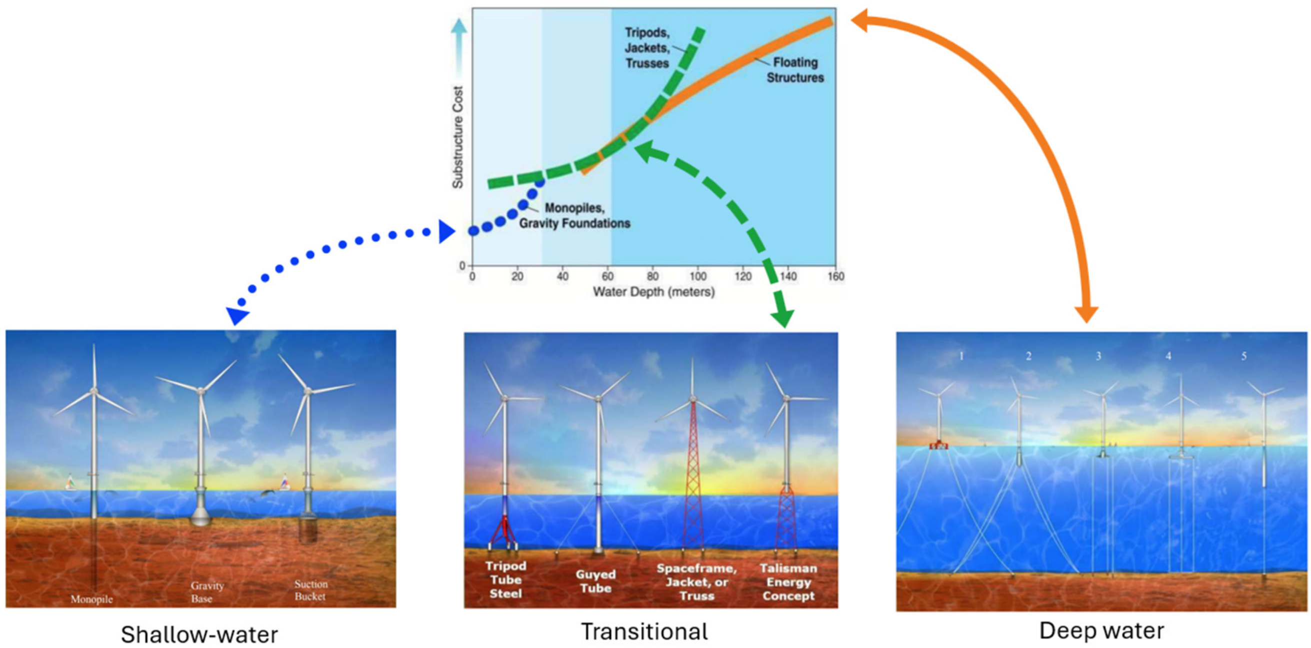

Figure 4. Cost evolution depending on the type of foundation. Adapted from [52].

Nowadays, the relationship between water depth and foundation type remains robust as a general paradigm, but it is also undergoing a significant evolution. Floating foundations are not just a theoretical solution for deep water, but they have become a commercial case, reducing costs through shared anchorages and structural optimization [53]. The National Renewable Energy Laboratory (NREL) cost models (2024) [54] and the literature published in 2025 [55] confirm that LCOE for floating farms is rapidly approaching fixed levels, making the schematic scheme still valid, but smoothed by technical advances and economies of scale.

There are numerous parameters influencing the contemporary vision of the floating wind turbine platforms that can be described in terms of system dynamics and platform stability [56]. It is reasonable to assert that these systems must be designed in a way that reduces external loads caused simultaneously by two equally significant forces: wind and waves [57].

Due to the large variety of anchor types [58], mooring systems [59], floater geometry [60], and ballast options available [61], there is a wide variety of possible configurations for floating platforms for offshore wind applications. To further streamline the design process, NREL created a generalized framework (see Figure 5), referred to as the "stability triangle", which categorizes floating wind turbine platforms based on the dominating mechanism by which static stability is achieved. The framework provides a graphical depiction of the design space that can be used for most floating platform concepts, thereby informing early design decisions.

In real-world applications, platforms are always hybrid designs that combine elements of all three stability methods, typically with a higher emphasis on one. Real-world designs are typically located within the triangular area between the three extremes. Design engineers aim to establish an optimal arrangement that guarantees stability and minimization of total system expense. Given that a single solution is not optimal for all circumstances, every platform is a strategic compromise formulated to deal with the distinct technical issues at hand effectively.

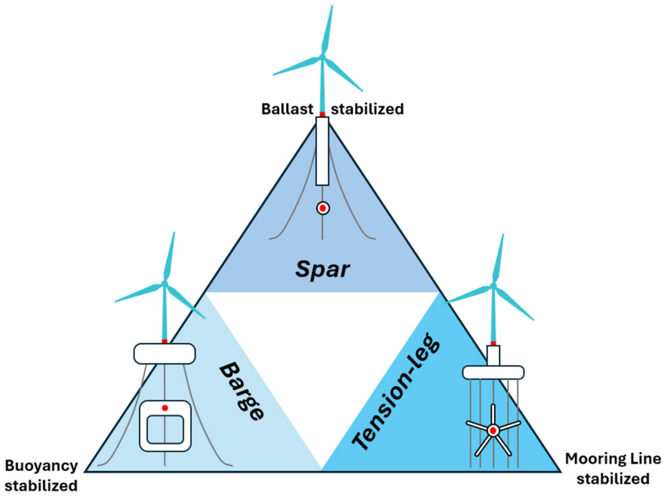

Figure 5. Stability triangle, adapted from [62].

3.1. Current Wind Energy Potential in the Black Sea

The Black Sea Basin features a moderate to high wind energy potential, with notable spatial and seasonal variations. As can be seen in Figure 3 (left side), the northwestern sector off the coasts of Romania is particularly energetic, which makes it attractive for wind power development [63]. The World Bank Group [64] has also estimated the offshore wind technical potential in the Black Sea, highlighting opportunities along the western coast. However, the 1000 m water depth isoline considered for floating foundations does not reflect current technological advances in offshore wind (can be viewed as a perspective on where technologies will go in the future); the threshold of 300 m water depth would be a more realistic approach.

The research studies listed in Table 1 conduct a comprehensive analysis of the wind resource assessment in the Black Sea region, with special emphasis on describing the prevailing wind climate, estimating energy potential, and considering the impact of climate change. The main goal of such research is to create a full and fact-based understanding of wind conditions in the region, enabling the sustainable development of wind power exploitation, particularly in coastal and offshore areas. The particular objectives involve the spatial and temporal description of the distribution of wind speed, choosing the best possible sites for the installation of wind farms, testing and comparing the various climate databases (reanalyses, satellite, in situ), and estimating the impact of climate change on wind resources on both near- and long-time scales.

Table 1. Research papers on offshore wind energy in the Black Sea.

Study	Type of Data Used	Analyzed Period	Analysis's Performed Height (m)	Analyzed Area	Study's Purpose
[65]	ERA-Interim (ECMWF), NCEP satellite (AVISO) in situ	14 years: 1999–2012	10 m	Black Sea	The main objective of the work is to provide a more comprehensive picture of the wind patterns in the Black Sea Basin.
[66]	ERA-Interim (ECMWF) In situ	7 years: 2003–2009 11 years: 1999–2009	80 m	North-western Black Sea	The objective of the work is to evaluate the opportunity of wind farm implementation in the northwestern side of the Black Sea.

Table 1. *Cont.*

Study	Type of Data Used	Analyzed Period	Analysis's Performed Height (m)	Analyzed Area	Study's Purpose
[67]	NCEP-CFSR In situ satellite (AVISO)	10 years: 1999–2008 5 years: 2010–2014	10 m	Black Sea	The work presents a comprehensive picture of the wind energy potential in the coastal environment of the Black and the Caspian Seas.
[68]	Reanalysis (CORDEX/RCA4, CMIP5)	Historical: 1979–2004 Future 1: 2021–2050 Future 2: 2061–2090	120 m	Europe focus on the Black Sea	Assessment of climate change impact on wind energy resources in Europe, with a special focus on offshore potential in the Black Sea region.
[69]	ERA-Interim (ECMWF) satellite (AVISO) in situ	20 years: 1998–2017 8 years: September 2009–September 2017	80 m	Western Black Sea coastal area (Romania, Bulgaria)	The main objective of this work was to evaluate the nearshore wind resources in the Black Sea area.
[70]	ERA-Interim (ECMWF), CORDEX (RCM), RCA4 (RCP4.5 and RCP8.5)	30 years: 1981–2010 Future: 2021–2050	100 m	Black Sea basin	To quantify the recent past and explore the near future wind power potential in the Black Sea Basin, evaluating possible changes.
[71]	ERA-Interim (ECMWF)	20 years: 1998–2017	80 m	Romanian coastal zone	To identify the most suitable sites where a wind project can be developed in the Romanian coastal areas.
[72]	EURO-CORDEX (RCA4: RCP4.5, and RCP8.5) EC-EARTH, CMIP5	Historical: 1976–2005 Future: 2021–2050	80 m	Black Sea coastal zone	To evaluate the wind energy resources in the coastal environment of the Black Sea.
[73]	ERA5 (ECMWF) In situ	42 years: 1979–2020 3 years: 2006–2009	100 m	Romanian coastal zone (16 sites)	To provide a comprehensive picture of the wind energy potential along the Romanian coastal environment.

Table 1. *Cont.*

Study	Type of Data Used	Analyzed Period	Analysis's Performed Height (m)	Analyzed Area	Study's Purpose
[74]	EURO-CORDEX, RCP4.5 (SMHI-RCA4)	Near future: 2021–2050 Distant future: 2071–2100	90 m	Western Black Sea coast (six reference sites)	To evaluate the energy potential of six sites near the Romanian Black Sea shore.
[75]	GeoEcoMar (autonomous marine stations) in situ	6 years: May 2015–Dec 2020	2.5 m	North-western Black Sea coast	To analyze the dynamics of wind parameters along the western coast of the Black Sea.
[76]	ANM weather stations in situ	13 years: 2009–2021	10 m	Romanian coastline (seven weather stations)	To outline a general overview of the wind energy potential along the Romanian coast of the Black Sea.
[77]	ERA5 (ECMWF), RCA4 (RCM) climate modeling	Recent past: 1980–2019 Near future: 2021–2060 Distant future: 2061–2100	10 m	The entire Black Sea basin and the Sea of Azov	To analyze the most credible scenarios concerning the expected dynamics of the wind climate in the 21st century in the Black Sea Basin.

The Black Sea Basin features a moderate to high wind energy potential, with notable spatial and seasonal variations. The northwestern sector (off the coasts of Romania and Ukraine) is particularly energetic, which makes it attractive for wind power development [78].

The studies approach the evaluation of the wind energy potential in the Black Sea in various ways. Some rely on long-term in situ measurements at coastal meteorological stations [76] or marine platforms and offshore buoys in the northwestern Black Sea [75]. Other studies use long-term climate reanalysis data: ref. [73] combined local measurements with ERA5 data over 42 years, highlighting the accuracy of the reanalysis compared to land-based stations, while [65,67] mainly relied on NCEP reanalysis—14 years for the northwestern Black Sea [65] and 10 years for the entire Black Sea Basin, also including a comparison with the Caspian Sea [67]. Several studies employed the ERA-Interim reanalysis [71], in combination with satellite observations [65,69] and stationary data [66,73], to provide a comprehensive picture of the Black Sea Basin. Other works adopted regional climate models for future projections: ref. [70] quantified the current and future wind potential using ERA-Interim and a regional climate model from EURO-CORDEX under RCP4.5/8.5 scenarios. Similarly, ref. [72] used the RCA4 model to project wind resources toward a more distant horizon, 2050, while ref. [68] used a single-model ensemble with RCA4 forced by five global CMIP5 models, focusing on wind-related climate changes in the Black Sea region.

In conclusion, the methodologies range from local observations to satellite data, global reanalyses, and climate simulations [74,77], with many studies using hybrid approaches (e.g., validating reanalyses with measurements, and evaluating models through historical data) to enhance accuracy.

Regarding the periods analyzed, see Figure 6, the above studies can be grouped into three categories:

- **Older studies** [65–69] published between 2012 and 2018, mainly focus on historical periods. Some of them analyze short and recent intervals (e.g., [65,66]).

- **Intermediate studies** [70–73] published between 2018 and 2021, begin to include future projections, studying both past periods and periods extending as far as 2050.
- **Recent studies** [74–77] published between 2021 and 2023, have a highly diverse focus: some concentrate on short and recent periods [75], while others cover a very wide temporal range [74,77].

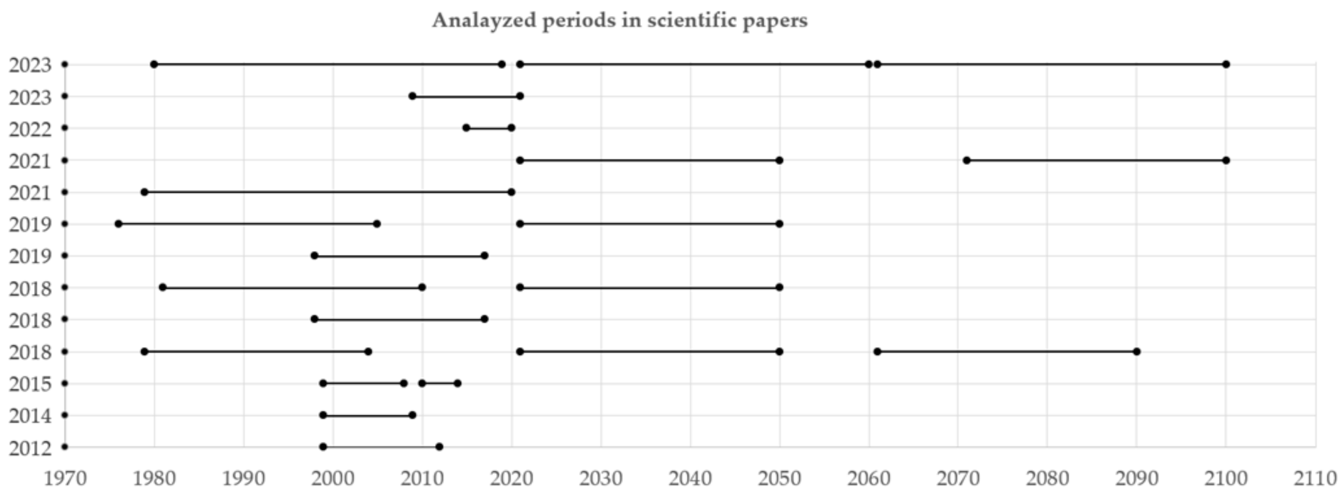

Figure 6. Analyzed periods in scientific papers. Values on the vertical axis correspond to the publication years of the analyzed references [65–77].

Ref. [77] is the only study that appears to analyze the past, present, and distant future simultaneously (1980–2100).

The time intervals covered vary substantially. Studies based on recent observations focus on the last decade: for example [76] evaluated the 2009–2021 period along the Romanian coast, while ref. [75] covered the 2015–2020 interval in the northwestern part of the sea. Other works span multi-decadal climate intervals: ref. [73] analyzed 42 years (1979–2020), and [65] approximately 14 years (1999–2012) of data for the entire basin. The study in [66] considered nearly 11 years (approx. 1999–2009) for the northwestern Black Sea, combined with ERA-Interim data, while [67] used a 10-year series (1999–2008) from NCEP reanalysis for comparison. The study in [71] focused on 20 years (1998–2017) in the Romanian coastal zone, highlighting coast-to-offshore spatial trends.

Studies that include future projections usually analyze a base period for validation: ref. [70] assessed both the "present" (1981–2010) and the future (2021–2050); similarly, ref. [72] validated the model over 1976–2005 and projected for 2021–2050, meanwhile, ref. [68] investigated two climate horizons (mid and end of the 21st century) under RCP4.5/8.5 scenarios, identifying a persistent change pattern from 2050 to 2090.

Overall, there are notable overlaps: many studies covered the period from 1998 to 2009 [66,67], partially ERA-Interim in [65], and the 1998–2017 interval appears in both [69,71]. A 30-year period (1981–2010) is included in several analyses [70,73], allowing for cross-study comparisons on common intervals. In general, the reference period for the wind climate of the Black Sea centers on the last few decades (1979 to the present), and projections mostly target the 2050 horizon [72], with some studies extending their evaluation up to 2100 [74,77].

There is a clear trend: the more recent the studies are, the more they tend to analyze the future. Some studies cover multiple periods, represented by several lines on the same row. Both historical and projection scenarios are analyzed, suggesting an increasingly complex and forward-looking approach in recent research.

Many studies analyze the wind speed at 10 m, 50 m, or 80 m above sea level, corresponding to standard meteorological and wind turbine hub heights. The choice of the height directly affects the wind speed values and, hence, the estimated energy potential, due to wind shear. Studies with 10 m data [65,67,76] provide long-term trend validation but need vertical extrapolation (e.g., via power law or logarithmic profiles) to assess turbine-level conditions. For those studies that are using data at 80 m height, [66,69,71,72] are particularly relevant for onshore or nearshore projects, aligned with classic turbine hub levels. Studies like [68,70,73,74] offer the most practical insight for future offshore wind development, with analysis at or near hub heights (90–120 m). The very low 2.5 m height is considered by [75], primarily to study boundary layer or sea surface behavior, not for wind energy extraction. Variability in the chosen analysis height must be carefully considered when comparing datasets, projecting energy outputs, or assessing the technology compatibility.

Studies addressing the potential of offshore wind energy in the Black Sea region cover a variety of geographical scales, ranging from the entire Black Sea Basin to specific coastal areas [72]. Most studies analyze the entire Black Sea Basin [65,67,70] sometimes also including the Sea of Azov [77], to provide a comprehensive regional perspective. A significant number of works focus on the western sector of the Black Sea [74], particularly the coastal areas of Romania and Bulgaria [69], identified as the most promising in terms of energy potential. Additionally, several studies examine in detail the northwestern area of the Black Sea [66,75] and the Romanian coastal segments [71,73,76] using between 6 and 16 reference points or meteorological stations. Some research also extends the analysis to a European level, but with a focus on the Black Sea region [68].

In conclusion, the geographical coverage reflects a shared interest in the western and northwestern areas of the Black Sea, considered the most favorable for the development of offshore wind projects, both in terms of wind resources and coastal accessibility.

3.2. Offshore Wind Turbine

Wind turbines embody a key element in the global transition to renewable energy sources [79]. Due to the increasing need for renewable energy and the constraints on land-based resources, offshore wind turbines are a good substitute because they can harness more powerful and consistent winds found in maritime areas [80].The evolution of offshore wind turbines over time has been and is remarkable, their capacity increasing significantly in the last two decades. This development comes as an industry response to the increasing demand for energy today [81].

The renewable energy landscape has been impacted by the transformation of the offshore wind turbines from smaller capacities to increasingly complex, high-capacity models, as shown in Figure 7. At the beginning of the development of offshore wind energy, turbines had relatively modest capacities, such as the example of the first offshore wind farm in the world, built in Denmark in 1991, where the turbines had a capacity of approximately 0.45 MW [82]. Over time, the average capacity of offshore wind turbines has increased significantly as a result of technological advances, but also due to the need to capitalize on increasingly strong winds from deeper and deeper waters [83].

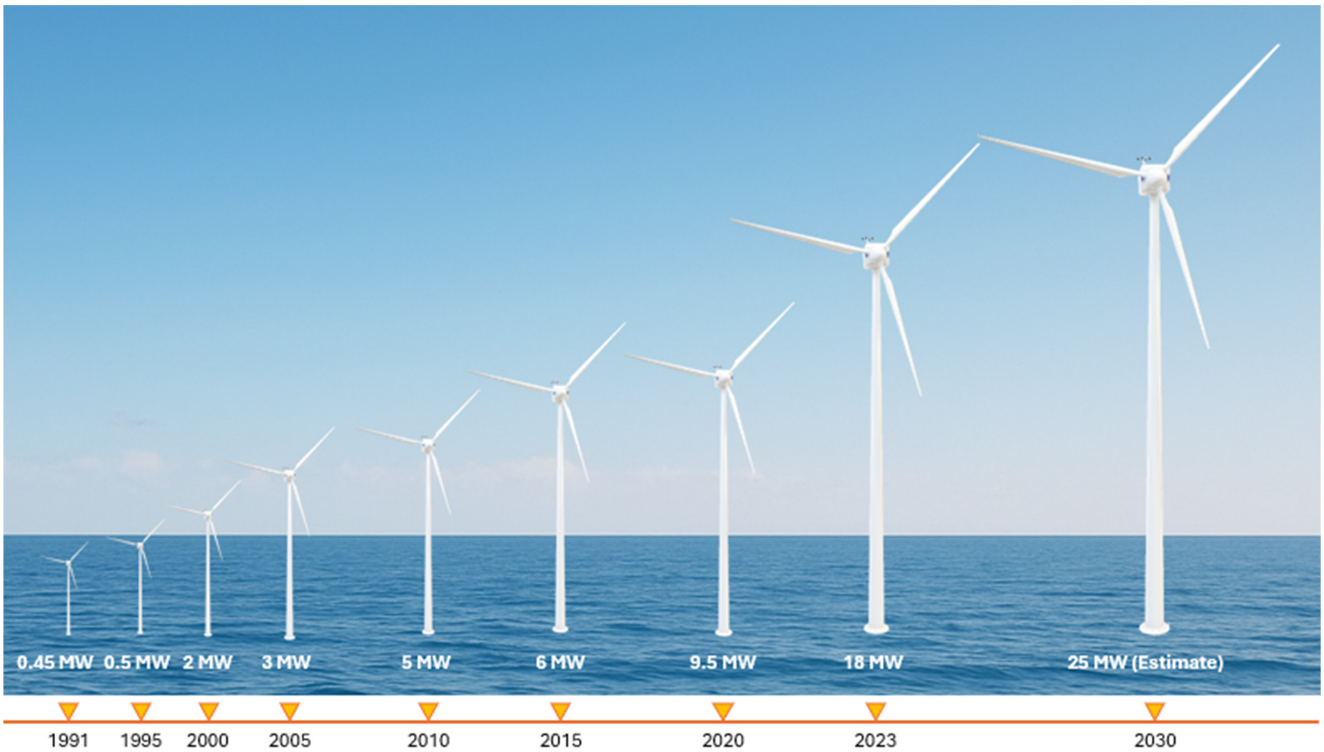

Figure 7. Offshore wind turbine capacity evolution. Adapted from [84].

Since 2000, turbines such as the Siemens SWT-2.3-93 and GE Energy 2.5 XL [85] have set the stage for increased power generation capacities, typically targeting around 2.3 to 2.5 MW of power per turbine [86]. By 2010, wind turbine technology had advanced to models such as the Vestas V90-3.0 MW [69], illustrating a paradigm shift toward larger capacities with more efficient designs capable of harnessing offshore wind resources more efficiently. This progression has led to recent trends where the average capacity of newly announced offshore wind projects is expected to increase from 10 MW to 16.7 MW by 2029, demonstrating a pronounced trend toward larger turbines [85].

The introduction of floating offshore wind turbines (FOWT) has further boosted capacity growth, as these devices allow installation in deeper waters where fixed-bottom turbines could not operate economically [87]. Furthermore, recent developments have led to designs such as the Vestas V164 [69,88] (with capacities reaching up to 9.5 MW [74]), the Siemens Gamesa SG 167-8.0 MW [74] and larger floating concepts such as the 10 MW SeaTitan [73], designed to maximize efficiency and reduce the cost of energy (CoE) associated with offshore wind power generation [89]. The deployment of these highly sophisticated and high-capacity turbines has not only improved the efficiency of offshore wind farms but has also contributed to reducing the levelised cost of electricity (LCOE) over time, enabling offshore wind energy to become a more competitive energy source in the wider energy market [90]. This is crucial given that recent studies indicate significant LCOE reductions for offshore wind projects that aim to be cost-competitive with both fossil fuels and onshore wind electricity generation [91].

OWT in the Black Sea

Regarding the wind energy potential of the Black Sea, Table 2 brings together a series of representative turbines, either used or proposed in scenarios evaluating offshore wind resources in the region. The turbines also exhibit variability in rated power, from 2.3 MW to 10 MW, and in estimated capacity factor and annual energy production. Turbines with capacities of less than 5 MW, for example, the Vestas V90-3.0 MW [69] and GE 2.5 [71], are under the “medium-capacity turbine” category. Turbines like the SeaTitan 10 MW and Samsung 7.0-171 [73] are under the “high-capacity turbines” category, used for the effective utilization of offshore areas with abundant wind resources.

Table 2. Wind turbines evaluated for the Black Sea region.

Turbine	Rated Power (MW)	Estimated Capacity Factor (%)	Estimated Annual Production (MWh)	Study
Vestas V90-3.0 MW	3.0	~25%	~6500	[69]
Areva M5000-116 (5 MW)	5.0	~35%	~20,000	
Senvion 6.2 M126	6.15	~34%	~22,000	
Vestas V164-8.8 MW	8.8	~33%	~25,000	
Vestas V164-9.5 MW	9.5	~34%	~25,000	
GE Energy 2.5 xl	2.5	~25%	~2000	[71]
Siemens SWT-2.3-93	2.3	~29%	~14,000	
Samsung 7.0-171	7.0	~50%	~30,000	[73]
SeaTitan 10 MW	10.0	~47%	~41,000	
MHI Vestas 164	9.5	~33%	~28,000	[74]
Siemens Gamesa-167-8.0 MW	8.0	~43%	~30,000	
GE Haliade 150	6.0	~38%	~25,000	
Mingyang MySE-155	7.0	~35%	~22,000	
GE 2.5	2.5	~30%	~6500	[88]
Siemens SWT 3.6	3.6	~32%	~10,000	
Vestas V164	8.0	~43%	~30,000	
Siemens SWT 6.0	6.0	~34%	~19,000	[92]

Unlike onshore wind turbines, offshore wind turbines can be placed in bodies of water with varying depths through stable foundations for shallower water [93] or buoyant floating platforms for deeper waters [94]. With this versatility, energy generation can be augmented where there is no land available or even where the offshore environment is more favorable [95].

4. Wave Power

Wave energy is one of the densest, most predictable, and persistent renewable energy sources [96], yet it remains underexploited, despite many countries having access to it. Although wind energy is the most developed, wave and tidal energy also have great potential, especially in coastal areas with favorable conditions. However, these technologies are still in early stages of development [97].

4.1. Current Wave Power Potential in the Black Sea

The wave power potential in the Black Sea has been evaluated in recent decades, even though it is lower than in open oceans. Numerous studies have assessed the wave power in coastal areas using calibrated numerical models and metocean data, both for recent past (hindcast or historical) and future projections under various climate change scenarios. Table 3 shows the results of an analysis of several works that quantify the wave power potential in the Black Sea, highlighting the methodology, data sources, periods covered by data, climate scenarios, targeted areas, obtained results, and conclusions regarding the use of wave power for electricity generation, coastal protection, and climate trends.

Table 3. Research papers on wave energy in the Black Sea.

Study	Wave	Wind	Analyzed Period	Climate Scenarios	Area
[98]	SWAN	NCEP-CFSR	1999–2013	-	Black Sea and Sea of Azov
[99]	SWAN	RCA4 (SMHI) ALADIN6 (CNRM -RCSM6)	1976–2005 1979–2008 2041–2070	RCP 4.5, RCP 8.5 SSP 5–8.5	Black Sea
[100]	MIKE 21 SW	ECMWF	1996–2009	-	Black Sea
[101]	SWAN	RCA4 (EURO-CORDEX)	1976–2005 2021–2050	RCP 4.5, RCP 8.5	Black Sea
[102]	SWAN	RCA4 (EURO-CORDEX)	1976–2005 2021–2050 2071–2100	RCP 4.5, RCP 8.5	Black Sea
[103]	SWAN	ERA5, NCEP-CFSR, RCA4	Long term	RCP 4.5, RCP 8.5	Romanian Black Sea coast
[104]	Visual observations	-	1960–2011	-	Black Sea
[105]	WAM Cycle 4	REMO	1948–2006	-	Western and southwestern Black Sea
[106]	SWAN	ERA-Interim	1995–2009	-	Black Sea
[107]	SWAN	CFSR	1979–2009	-	Black Sea and Sea of Azov
[108]	SWAN	CFSR	1999–2013	-	Western Black Sea
[109]	Visual observations	-	2013–2018	-	Romanian Black Sea coast
[110]	SWAN v40.72	ECMWF–ERA Interim	1995–2009	-	Southeast coast of the Black Sea

Globally, the Black Sea provides a medium-to-low wave power resource [111]. According to the recent data, the average annual values along the southwest coast of Turkey and Bulgaria are roughly 4–5 kW/m [98], with notable seasonal variations (up to ~10 kW/m in winter and ~1 kW/m in summer at the same locations). Mean values in the eastern and northern parts of the basin are less than 2 kW/m, indicating the heterogeneity of the basin [106]. The wave power potential in the region is very seasonal, with the Black Sea essentially being almost a lake in summer and having large waves in winter due to Mediterranean cyclones [100].

Almost all studies used the SWAN model, either version 40.91ABC [101,102] or 41.01 [107], but with different calibration approaches. In some studies, the results provided by the wave model are improved through the assimilation of satellite measurements [98], while in others, the altimeter observations are used to calibrate the wave models forced by the regional atmospheric model ALADIN [99] or the regional climate model RCA4 [103]. In addition to the satellite data, validation and calibration of the SWAN modeling system were also carried out using in situ measurements [108]. One study used visual data from the VOS program and teleconnection models to analyze long-term variability in wave climate and wave energy potential in the Black Sea [104], while another study complemented direct observations with actual measured data [109], not just numerical simulations. Data from a wave buoy deployed at Hopa in the study presented in [106] and from both Sinop and Hopa in the study presented in [110] are used to validate the SWAN model results.

For some studies MIKE 21 SW model was chosen to simulate the sea state conditions. As SWAN, this is also a third-generation spectral wave model developed by the Danish Hydraulic Institute (DHI), capable of simulating the generation, propagation, and dissipation of ocean waves, and it was forced with ECMWF wind data in [100]. To evaluate the differences in the mean annual, seasonal, and monthly wave energy potential until the end of the 21st century [102], research also analyzed wave resources in an integrated way, emphasizing the value of hybrid resources (wind + waves) [103].

To simulate the sea state conditions in the Black Sea, the WAM Cycle 4 model was also used, forced with the REMO regional atmospheric model [105]. This wave model was also used for large-scale ocean wave generation, combined with SWAN and forced with wind data from MM5 (mesoscale meteorological model), driven by the GFS (Global Forecast System) atmospheric model in the coastal area of the Iberian Peninsula [112].

In several studies, the impact of climate change on the sea state conditions and wave power was evaluated under various scenarios. The wave models were driven by wind fields simulated under various climate change scenarios that project future greenhouse gas concentrations in the atmosphere, namely Representative Concentration Pathways (RCPs) and Shared Socio-Economic Pathways (SSPs). This way, projections of the sea state conditions were obtained until the end of the 21st century.

RCP4.5 and RCP8.5 are the two most frequently considered climate future scenarios [99,101] suggesting moderate increases in energy potential by 2050 and a possible decline by 2100 [102]. A socio-economic scenario, SSP5-8.5, was used in the study presented in [99] to analyze the impact of climate change on the future state of the Black Sea.

The time intervals range from 15 to 60 years (hindcast), while projections cover the periods 2021–2050 [101] and 2071–2100 [102]. The study in [99] conducted a comparative analysis between the historical reference period (1976–2005) and a near-future interval (2041–2070). Based on a 13-year hindcast dataset from 1996 to 2009, the study in [100] used advanced numerical modeling to identify optimal zones for the development of marine renewable energy. A long-term analysis was conducted in the study presented in [103], which focused on presenting an integrated vision of the renewable energy potential (wind and waves) in the coastal zone of the Black Sea. In the study presented in [104], more than 85,000 visual observation records from 1960 to 2011 were used.

In terms of geographic focus, the studies range from analyses of the entire Black Sea Basin [99,101,102,104,106] to specific coastal sectors. Some studies focused on the Romanian Black Sea coast [103,109] or on the Turkish and Russian sectors of the sea [100]. These studies manage to cover the entire Black Sea region, from the western Black Sea [108] to the southwestern Black Sea [105] and even to the southeastern coast of the Black Sea [110]. Moreover, studies [98,107] explicitly state that they include the Sea of Azov in their analyses, thus providing a broad regional perspective on the available resource.

4.2. Wave Energy Converters

The goal of the wave energy converters (WECs) is to harvest and convert the energy of ocean waves into electricity. Initially, these devices were designed for oceans characterized by stronger and larger waves, which required more powerful and bigger equipment. For the low-energy seas, where the average annual wave power ranges from 2 to 10 kW/m, WECs are generally smaller and suitable for being economically viable [113]. Various studies have evaluated the possibility of using the electricity produced by WECs for desalination, which is a big energy consumer [114], hydrogen production [115], and pumped hydro storage [116], adding to the diversification of renewable sources of energy [117].

According to a study concerning the status and perspectives of the wave energy exploitation in Europe [118], wave energy conversion technologies can be divided into three main categories: shoreline converters, nearshore converters, and offshore converters, as presented in Table 4. Each of these has specific characteristics, and their efficiency is influenced by the location and interaction with the wave conditions, such as wave period and height [119]. All the WEC types present both advantages and limitations, and their suitability depends on the local resource availability and the geophysical features of the site.

Table 4. WEC projects classified by distance from shore/installation area.

Instalation Area	Converter Name	Developer/Country	Description
SHORELINE	EUROPEAN PILOT PLANT	Instituto Superior Técnico, Lisbon, Portugal	A 400 kW system that was initially designed as a large-scale testing facility but is also used to continuously supply a significant portion of the energy demand of Pico Island.
	LIMPET OWC	Wavegen Ltd. and Queen's University of Belfast, Scotland	A 75 kW prototype was built in 1991, followed by a 500 kW successor aimed at addressing the commercial challenges of this type of device.
	ENERGETECH OWC	Energetech, Australia	A converter consisting of a variable-pitch turbine and a parabolic wall designed to concentrate wave energy. There is a power purchase agreement in place for a 500 kW facility that has a capacity of 1 MW for its MK2 prototype and a planned 2.5 MW capacity for its MK3 prototype. The original MK1 prototype at Port Kembla had a capacity of 450 kW.
	PENDULOR	Japan	This device features a flap mounted on a rectangular structure open at one end. The flap's movement, driven by wave action, powers a hydraulic pump and a generator.
	TAPCHAN	Toftesfallen, Norway	The system operates similarly to a hydroelectric power plant, with 3 ÷ 5 m high walls and a narrowing channel that directs water into a reservoir at the edge of a cliff. Waves increase in height and spill into the reservoir, where the stored water is used to drive a turbine. This empowers a 350 kW generator to supply electricity to the Norwegian grid.

Table 4. *Cont.*

Instalation Area	Converter Name	Developer/Country	Description
NEAR SHORE	Osprey	Wavegen, U.K.	This system includes a 1500 kW turbine and has been upgraded to have a total capacity of 2 MW. Research is being conducted to reduce installation costs and commercialize it.
OFFSHORE	Archimedes Wave Swing	Teamwork Technology BV, Netherlands	An underwater device of 2000 kW that uses hydrostatic pressure to generate energy through the up-and-down movement of a floating part.
	Floating Wave Power Vessel	Sea Power International, Sweden	An overtopping-type device of 1500 kW with a floating basin supported by ballast tanks, oriented toward the direction of the waves.
	McCabe Wave Pump	Kilbaha, County Clare, Ireland	A pump-type converter of 1590 kW with three articulated rectangular pontoons, designed to align with the waves to generate energy.
	OPT WEC	Ocean Power Technology, USA	A buoy-type converter that uses the relative motion between a casing and a float to pump high-pressure oil to a generator and is rated at 20–50 kW.
	Pelamis	Teamwork Technology BV, Netherlands	A semi-submersible articulated device, rated at 375 kW, composed of cylindrical sections connected by flexible joints, resembling a snake and generating energy through the hydraulic motion of its joints.
	Point Absorber Wave Energy Converter	Rambøll, Denmark	A converter that uses a rope anchored to the seabed and a float to activate a piston pump is designed to provide a capacity of up to 450 kW.
	Mighty Whale	Japan Marine Science & Technology Center, Japan	A 120 kW prototype equipped with three in-line OWC systems, operational since 1998 at a distance of 1.5 km from Nansei Town, at a depth of 40 m. The anchoring system is designed to withstand severe storm conditions with a probability of occurring once every 50 years.

Table 4. *Cont.*

Instalation Area	Converter Name	Developer/Country	Description
OFFSHORE	Mighty Whale	Japan Marine Science & Technology Center, Japan	A 120 kW prototype equipped with three in-line OWC systems, operational since 1998 at a distance of 1.5 km from Nansei Town, at a depth of 40 m. The anchoring system is designed to withstand severe storm conditions with a probability of occurring once every 50 years.
	Salter Duck	S. Salter, U.K.	A device that was designed to provide approximately 20 kW and converts both the kinetic and potential energy of waves into mechanical energy, with a theoretical efficiency of over 90%.
	SDE Wave Power Device	S.D.E. Ltd., Israel	An offshore floating device of 40 kW that transforms the hydraulic pressure generated by waves into electricity.
	Wave Dragon	Loewenmark F.R.I. Denmark	An overtopping-type converter of 4000 kW that uses a wave reflector to fill an elevated reservoir and generate electricity using Kaplan turbines.

Figure 8 illustrates the timeline of how wave energy conversion technologies have incrementally but consistently progressed. Over time, the WECs have progressed from first experiments and conceptual designs into increasingly sophisticated and commercially viable technologies.

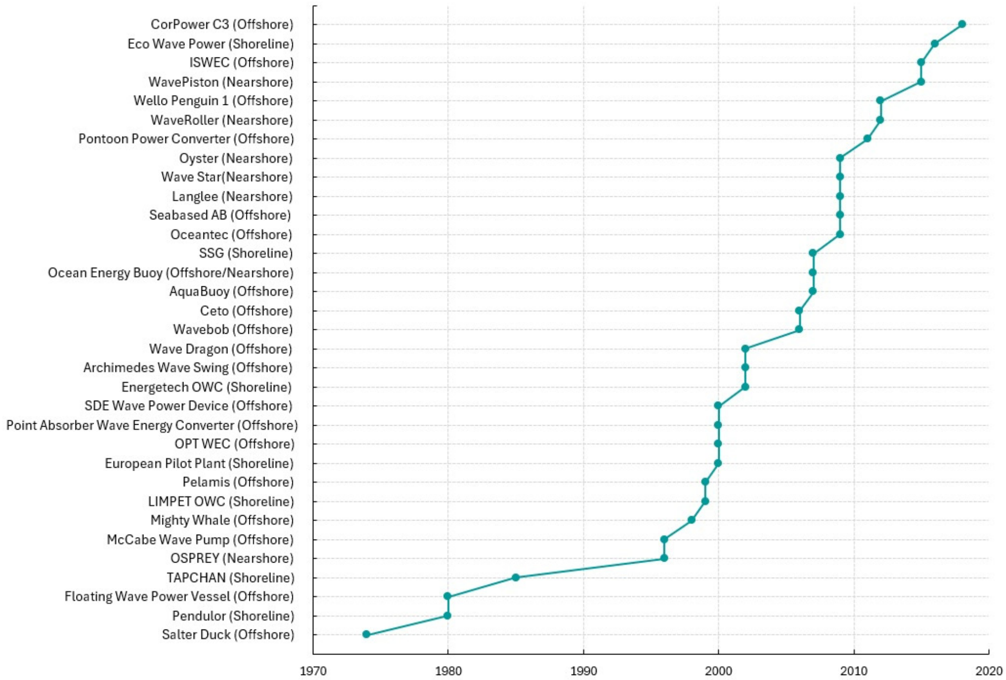

Figure 8. Evolution of wave energy converters (WECs) over time.

WEC development has progressed from conceptualization to fast-tracked development and incremental commercialization, following a typical technology adoption curve. Despite some past setbacks, wave energy may well become an important source of renewable energy in the future years, with advancing technology and reducing costs as the complexity and diversity of WECs grow.

4.2.1. Wave Energy Converters in the Black Sea

Among all types of WECs, in the context of the Black Sea environment, the characteristics and performance of a significant number of WECs have been analyzed, as shown in Table 5.

Table 5. WECs analyzed in the Black Sea context.

WEC Type	[120]	[121]	[122]	[123]
Pelamis (articulated attenuator)	✓	✓	✓	✓
Wave Dragon (overtopping device)	✓	✓	✓	✓
AquaBuoy (point absorber)	✓	✓	–	✓
Oceantec (modern floating buoy)	✓	✓	✓	✓
Pontoon Power Converter (PPC)	✓	✓	✓	✓
Seabased AB (small point absorber)	✓	–	✓	✓
Archimedes Wave Swing (AWS)	✓	✓	–	✓
Langlee (oscillating flap converter)	✓	–	–	✓
Ocean Energy Buoy (OE Buoy)	✓	✓	✓	✓
Wavebob (large point absorber)	✓	✓	✓	✓
Wave Star (multi-float system)	–	✓	✓	✓
Ceto (submerged buoy with pump)	–	✓	✓	-
SSG (Seawave slot-cone generator)	–	–	–	✓
Oyster (shallow-water oscillating flap)	–	–	–	✓
Oyster 2 (shallow-water oscillating flap)	–	–	–	✓
Sea Power (new-generation WEC)	–	–	✓	–
HeaveBuoy (Bottom-fixed)	–	–	–	✓

"✓" = present/analyzed in study, "–" = not present/analyzed in study

Studies [120–122] chose each to analyze 10 WECs. The study in [120] included overtopping converters (Wave Dragon, Pontoon PPC, etc.), oscillating water columns (OE Buoy), and oscillating bodies (point absorbers Pelamis, AquaBuoy, AWS, etc.). The study in [121] replaced some of the lower power devices (Seabased, Langlee, etc.) with others that are presently of interest (Wave Star, Ceto, etc.). The study in [123] expanded the analysis to 15 WECs in the Black Sea, including a shoreline overtopping device (SSG) and two fixed-flap converters (Oyster and Oyster 2), relevant for shallow water areas. The study in [122] selected some of the most advanced WECs globally (referred to as "state-of-the-art"), combining both large-scale devices (Wave Dragon, PPC, Sea Power) and systems below 1000 kW (Pelamis, Wave Bob, Ceto, Seabased, Wave Star).

Although each study addresses the topic of wave energy converters differently, there are both common elements and notable differences. All four studies have six devices in common, considered representative of their categories: Pelamis, Wave Dragon, Oceantec, PPC, OE Buoy, and Wavebob. AquaBuoy, Seabased AB, AWS, and Wave Star appear in three out of four studies, indicating continuity. The study in [122] introduced the Sea Power converter, a new generation WEC, and a similar study [121] analyzed Wave Star and Ceto converters, reflecting technological advancement. The study in [123], focused on the Black Sea and analyzed a total of 15 WECs, effectively including all of the above and adding devices relevant for shallow waters: SSG (a fixed structure with an integrated shoreline overtopping system) and Oyster/Oyster 2 (oscillating flaps mounted on the seabed at shallow depths).

Point absorber-type converters have been the subject of multiple studies in the context of the Black Sea, analyzed from various perspectives, criteria, and purposes. These range from feasibility studies [124] to long-term analyses [125], in both low-wave conditions [126] and extreme wave conditions [127], as well as customized variants aimed at parametric optimization [128].

Because the Black Sea has moderate-to-low wave energy, which is substantially lower than in oceans, the wave energy converters (WECs) that were created for strong wave areas are not suitable there. To function effectively here, they must make significant adjustments. As highlighted in [129], adapting to such environments requires the downscaling of existing technologies, while novel and innovative concepts are also being explored for offshore applications [130]. Multiple studies focused on the Black Sea [120–123] emphasize that traditional WECs show diminished efficiency in this basin due to limited wave heights and periods and seasonal variability.

Under these conditions, the design and deployment of downscaled WECs, specifically tailored for low-energy seas, emerge as both a technical necessity and an economically viable solution. Researchers have suggested customizing key design parameters, such as resonance frequency, capture width, and mooring system configurations, to align with the local wave spectrum of the Black Sea [120,129]. Additionally, the use of modular and smaller-scale devices may enable phased implementation, reduce initial investment risks, and offer practical platforms for hybrid integration with offshore wind technologies.

The case for adopting scaled WECs becomes even stronger with findings indicating that poor spectral matching is a critical factor limiting the effectiveness of standard converters in the region [121,128]. Therefore, custom-made designs and performance-optimized systems are essential for unlocking the Black Sea's real wave energy potential and ensuring sustainable energy extraction in this unique marine environment.

4.2.2. Parameters Analyzed in the Evaluation of WEC Performance

The evaluation of the WEC performances involves both quantitative technical indicators (which describe how much energy the device delivers and how efficiently it does so) and qualitative/impact parameters (which assess how well the technology integrates into and performs within operational, economic, and social environments).

Quantitative technical parameters directly quantify the energy performance of WECs under certain sea state conditions, which are measured or numerically simulated, allowing for objective comparisons between devices or scenarios.

- Electric power output represents the energy extracted from waves and converted into electricity by the WEC. The reviewed studies estimate the generated power using the converter's power matrix (performance curve based on significant wave height and period) applied to the wave climate of each studied location [120]. For example, the average power output of three WECs (AquaBuOY, Pelamis, and Wave Dragon) is calculated in three different coastal environments using bivariate Hs–Te distributions derived from simulations with the SWAN model. While in high-energy areas (e.g., the Northeast Atlantic, Western Europe), waves deliver average powers of ~40–60 kW/m, allowing large WECs (>2 MW) to generate hundreds of kW on average [121], in low-energy seas like the Black Sea (~2–5 kW/m [110]), the average output of a WEC drops to tens of kW or less. A study shows a gradual decrease in resource intensity along the Turkish Black Sea coast from ~3 kW/m to even lower values, reflecting a reduction in the capturable power by WECs [131].

- Capacity factor (CF) is a standardized energy performance indicator, expressing the percentage of time (or number of hours annually) a WEC would need to operate at full capacity to produce the actual energy obtained. While CF values can be relatively high in oceanic regions, they drop significantly in low-energy seas [120]. For example, Oceantec reached 11% in the Black Sea [121], compared to values over 40% in areas of the UK or North America [122], while Wave Dragon achieved a CF of 28% in the Black Sea [121].
- Capture width (CW) is an important parameter for evaluating the performance of a WEC as it indicates how well a device can extract energy from waves. It serves as a basis for comparing the performance of different WEC designs. Wave Dragon can reach up to 74 m, even in low-energy areas, while Oceantec and Pelamis show CW values of up to 11 m in the Black Sea, which is remarkable for their size [121]. In other regions, these same converters exhibit different values: Wave Dragon reaches up to 111 m in Asia, while for Pelamis and Oceantec vary between 6 and 16 m, being highly efficient in moderate wave conditions. AquaBuoy, analyzed in another study, shows a CW of 1.5 m [120].

Overall, the global efficiency of conversion is limited by hydrodynamic [132,133] and technical factors. In practice, no WEC captures 100% of wave energy; hydrodynamic efficiencies are often below 50%. For instance, even Wave Dragon, with a CW of ~70 m and a device width of ~170 m, captures about 40% of the wave front energy (hydrodynamic efficiency ~40% in the Atlantic) [120]. When internal conversion losses (generator, hydraulic losses, etc.) are added, the wave-to-wire efficiency decreases further. Additionally, WECs must be tuned to the local spectrum, as the study in [121] highlights, and smaller systems tend to have higher CFs in winter, suggesting they approach resonance under specific conditions. A WEC optimized for a certain spectrum will perform well there but may underperform in a different wave climate (lack of spectral adaptability). Therefore, the studies emphasize the importance of compatibility between technology and wave climate in achieving a good conversion efficiency.

Qualitative and impact parameters consider the environmental, economic, and operational characteristics of WEC deployments. They are not explicitly measured in terms of a specific metric but, instead, look at the impact and suitability of the technology for field deployments.

- Adaptability of WECs to local conditions is crucial to their performance because existing technologies, specifically designed for ocean environments, are not effective in marine environments characterized by low energy, such as the Black Sea. A study shows, through parametric optimization in the Black Sea, that tailoring the design to the local wave spectrum can greatly enhance a WEC's efficiency [128].
- Installation and maintenance costs are among the main barriers to the commercial adoption of WECs, as both capital expenditures (CAPEX) and operational expenditures (OPEX) are high compared to other renewable energy technologies. The levelized cost of energy (LCOE) of wave energy is currently estimated at 2–3 times the cost of wind or solar energy [134], although these are anticipated to decrease as the technology develops. Studies [129,135] identify that cost-cutting through innovation, modularization, and the integration of other infrastructure is required to keep WECs competitive. A comprehensive performance analysis of the systems must include both technical and economic factors to demonstrate the true cost-effectiveness of the systems.

- Environmental impact. Due to its reduced environmental footprint and lower carbon footprint on operation compared to other means of power generation, such as hydropower stations or offshore wind farms, wave energy conversion is considered a clean technology [135]. Although the deployment of WEC has short-term effects on ocean ecosystems, during the construction and installation phases, it has a front-end carbon cost [136]. Such systems are thought to have a lesser likelihood of collision with marine animals compared to other technologies, and they can also develop into artificial reefs that enhance biodiversity in the long run [135]. WEC zones might even aid in the recovery of ecosystems by limiting human activity, while underwater noise and visual effects are controllable and detectable.
- Grid integration and operational reliability are essential aspects in evaluating the real-world performance of WECs, as they influence the continuous and high-quality delivery of energy to the grid. This includes the importance of optimal control systems for energy converters [137], the calculation of failure rates (hazard rate), and the availability of the overall energy system that includes WECs [138]. According to [129], in calmer seas such as the Black Sea, WECs can operate more stably, with a lower risk of major damage.

These parameters highlight that a technically efficient WEC must also be practically feasible. Adaptability to local conditions is essential: a design tailored to the target environment can make the difference between a capacity factor of 5% and 20% [120]. Costs remain the main challenge: without reductions in CAPEX and OPEX, even the most efficient WECs will result in an uncompetitive LCOE [128]. At the same time, the environmental advantages (zero emissions, moderate ecological impact) give WECs strategic potential in the future energy mix, especially if smart integration with the grid and other maritime uses is achieved [139].

WECs have been analyzed not only from a technological perspective, as demonstrated by the studies mentioned earlier, but also from other viewpoints. The performance of WECs depends on their layout and spatial configuration [140]. Furthermore, they have also been studied in the context of port infrastructure design [141], or as an integrated component of multifunctional breakwaters [142].

Considering one of the key reasons driving the need for these technologies, reducing carbon emissions, the assessment of their impact on the marine environment [143] and on the Romanian coastline in the case of a wave farm implementation [144] represents a crucial aspect in the development of this type of renewable energy. In this regard, there is a wide range of studies exploring the social and economic perceptions of wave energy [145].

5. Wind–Wave Hybrid Solutions

Several studies have shown that different areas of the Black Sea Basin, especially its western part, have significant potential for harnessing wind [146] and wave energy [147] or implementing hybrid solutions to mitigate the variability of these resources. Figure 9 presents an evaluation of the wind and wave potential based on data also covering 30 years.

The volatile and unsteady nature of the renewable energy resources can lead to grid imbalances, resulting in additional costs as well as even greater carbon emissions in certain situations. That is why the emphasis has been put on the development of sophisticated forecast models as accurately and reliably as possible, facilitating the successful integration of renewable sources of energy into energy systems [148].

However, due to the variability of the renewable energy sources in the marine environment, the main solution represents a hybrid system. Hybrid marine renewable energy systems integrating two or more marine-based renewable energy sources are indicated to be installed to improve power generating efficiency, dependability, and sustainability [149].

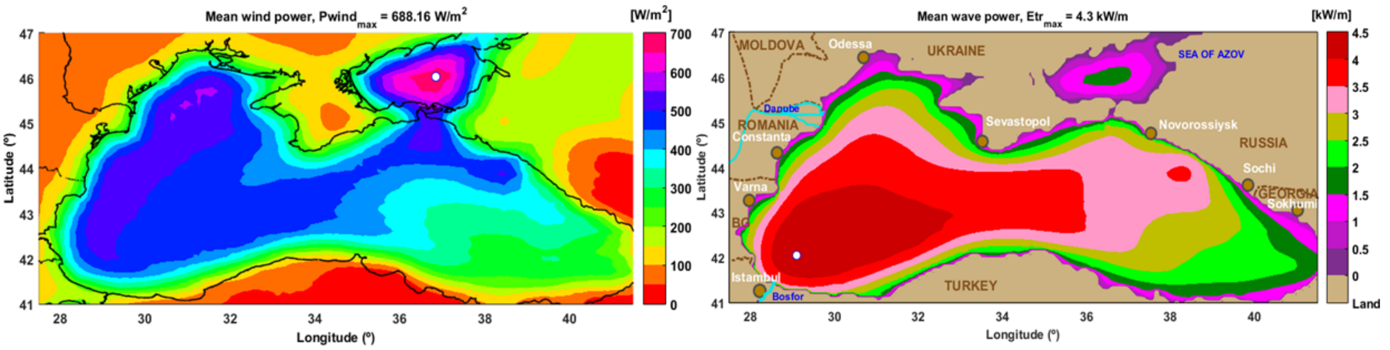

Figure 9. Mean wind power density at 80 m (**left panel**) and mean wave power (**right panel**) over 30 years (1987–2016). Adapted from [34].

The aim of developing such systems is to leverage the synergistic attributes of various maritime resources (including wind, wave, solar, and tidal energy) and to minimize the variability of electricity fed into the power grid. Given that tidal energy is insignificant in the Black Sea, a brief analysis of the hybrid solution defined by the wind–wave couple will be conducted.

Wind and wave power are among the most recognized types of marine renewable energy sources. Offshore wind turbines are installed on fixed or floating structures, with floating structures providing access to stronger winds in deeper waters. Wave energy converters (WECs) are less developed than wind turbines, but integrating them into hybrid platforms can offer both technical and economic advantages, such as cost savings and enhanced reliability [150].

The wave and wind energy potential in the Black Sea has been assessed over extended periods (20-year [151] or 30-year [152] periods), with a focus on the possibility of joint exploitation of these resources. Studies analyze the synergies between offshore wind and wave energy, identifying some potential integration methods and the associated technological aspects [153].

To enhance energy efficiency and reduce the infrastructure costs, [154] proposes the co-location of WECs in front of the wind farms. Even though wind turbines dominate in terms of energy output, WECs have the potential to complement their operation in hybrid scenarios [155]. The possibility of implementing WECs alongside wind turbines was also explored in the North Sea to maximize renewable energy extraction from the marine environment and reduce infrastructure costs by using existing installations [156], as well as in the Adriatic Sea, where hybrid solutions were explored to optimize the integration into the energy system [157].

"Wind complementary to wave" conditions are more frequently encountered, thus ensuring continuous energy exploitation when one of the sources is inactive. Although positive correlations between wind and waves are predominant, and complementarity is favorable [158], high-frequency dynamic responses must also be taken into account. Fatigue analysis has shown that high-frequency dynamic forces at the turbine tower tip significantly shorten the structure's lifespan [159].

A well-developed methodology enhances the understanding of the technological solutions and the factors that can either accelerate or hinder industry development, thereby supporting strategic planning and informed decision-making. A comprehensive evaluation of lifecycle costs for offshore hybrid energy systems can only be provided by a methodology that covers all stages: concept, design, development, manufacturing, installation, operation, and decommissioning [160]. The analysis of hybrid systems, such as W2Power and Poseidon, is discussed in [161], which highlights both the advantages and the challenges of integrating offshore wind energy with wave energy.

The wind variability in the Black Sea also strongly influences the wave regime. The wave fields produced are closely dependent on the local conditions (wind direction, duration, and force), especially in the coastal areas, as suggested by the study presented in [162]. The findings confirm that coastal areas with high wave and wind resources are often subjected to extreme environmental conditions. For this reason, the marine energy farms should be prepared to cope with such harsh conditions, especially in the context of climate change, which indicates an intensification of extreme events [163].

The utilization of conventional sources of energy, as well as pollution in the Black Sea region, is a condition that necessitates immediate focus on the reduction of energy-related emissions. This includes investments in energy-saving technology and the strengthening of environmental protection legislation [164].

6. Risks and Environmental Impacts Associated with Renewable Energy Extraction in the Black Sea

The Black Sea's discovery of renewable energy sources presents riparian nations with significant opportunities for their energy transition. Nonetheless, the procedure has clear advantages but also some risks that must be properly controlled to guarantee the long-term viability and sustainability of such projects. In Table 6, some positive and negative impacts are presented.

Table 6. Positive and negative impacts based on [165–170].

Positive Impacts	*Negative Impacts*
• Offshore wind and wave power generate electricity with *zero* direct CO_2 emissions, helping mitigate climate change. • Wind turbine foundations and wave devices act as artificial reefs, attracting marine life. Studies report increased shellfish and reef species on turbine monopiles, which, in turn, attracts fish and predators. This enhances local biodiversity in the farm area. • The extraction of marine energy may possess obvious industrial applications and could aid in coastal protection in regions susceptible to wave erosion. • Development of sustainable infrastructure for nautical tourism and recreational transport, supported by green energy and environmental policies.	• With the installation of new offshore systems comes the risk of migratory birds and marine mammals colliding with wind turbines or becoming entangled in the underwater structures of energy devices. • Man-made structures brought into the sea can act as artificial reefs, affecting the behavior and habitats of marine organisms. • Submarine noise associated with MRE device installation and operation can affect marine mammals and fish and disrupt their communication and navigation behaviors. • Possible changes in sea currents and sediment transport patterns could damage coastal regions. • Noise and visual pollution may affect ecosystems and tourism if not properly managed.

The analysis examines offshore wind energy and wave energy in the Black Sea, along with the hybrid scenario combining both of them. Global benefits, such as reduction of CO_2 emissions, must be weighed against local environmental impacts, and the planning of offshore projects should incorporate measures to protect biodiversity and coastal processes to minimize risks [171]. Finally, a clear and stable legislative framework is crucial to supporting the development of the renewable energy sector at a commercial scale [172].

7. Conclusions

The extensive analysis presented in this paper aimed to synthesize, analyze, and evaluate the energy potential of the Black Sea, with a focus on renewable marine sources, especially offshore wind and wave energy, in the current context of the energy transition and European climate goals.

Regarding the offshore wind potential in the Black Sea region, it can be noticed that a substantial energy resource awaits exploitation. It is also emphasized that the northwestern sector of the Black Sea, especially Romanian and Ukrainian waters, holds the highest wind potential in the entire basin. Analyses based on historical climate data, in situ observations, and numerical model simulations (ERA5, ERA-Interim, RCA4) show a favorable wind speed distribution, particularly during the cold season. Climate projections up to 2100 indicate a possible moderate increase in wind intensity by 2050, followed by a potential slow decrease toward the end of the century under high emission scenarios (RCP8.5). The study highlights significant technological progress in offshore wind turbines, analyzing the performance of a wide range of turbines in the specific context of the Black Sea.

By contrast, the wave energy potential in the Black Sea is moderate to low. Nevertheless, wave energy still plays a significant role in combating climate change, which makes it difficult to ignore. There are notable spatial variations; for instance, along the southwestern coast, the average annual wave power reaches ~4–5 kW/m (with peaks of ~10 kW/m in winter and ~1 kW/m in summer), while in the northern and eastern sectors, including Romania's Exclusive Economic Zone, average values are below 2 kW/m. This confirms the highly seasonal nature of the wave climate: generally calm in summer and energetic in winter. An analysis of the energy potential in the context of climate change, along with evaluations of some future climate scenarios, indicates a likely increase in wave energy potential until mid-century, followed by a possible slight decline toward the century's end.

A significant number of the analyzed studies indicate that wave energy could be efficiently exploited, especially in joint projects with offshore wind energy. Such an approach allows the limitations of each energy source to be mitigated; for example, periods of low wind can be compensated for by background waves, ensuring a more stable and reliable energy output. Hybrid projects thus emerge as some of the most promising innovations in the exploitation of wind and wave renewable energy resources, particularly in the western and northwestern sectors of the Black Sea. However, it is noted that wave energy technologies will require appropriate adaptation to local conditions.

An essential aspect addressed in the study concerns the risks and impacts associated with the exploitation of the marine renewable resources in the Black Sea, with a focus on the need to maintain a balance between energy benefits and ecological, technical, and strategic challenges. In addition to the high energy potential identified, the study highlights that offshore infrastructure development can exert a significant pressure on the marine ecosystems, especially through underwater noise, sediment disruption, and biodiversity disturbance, risks that may be amplified in sensitive areas such as the Romanian coastline. Importantly, these risks can be effectively managed through the use of advanced technologies that support sustainable and responsible marine energy development in the Black Sea Basin.

In light of the gaps and opportunities identified, several key future research directions can also be outlined. A first direction would be to deepen the detailed assessment of the wind and wave resources in the Black Sea by expanding the network of in situ measurements, improving numerical models, and using satellite data to obtain more accurate potential maps and predictions. Another direction of interest is the development and pilot-scale testing of conversion technologies adapted to Black Sea conditions: for example, prototypes of floating wind turbines suitable for greater depths and local weather conditions, respectively, and new types of low-power WECs optimized for the Black Sea wave spectrum. Such pilot projects would provide real data on performance, costs, and environmental impact, reducing uncertainties for future commercial investments. Interdisciplinary research on environmental impact and solutions to reduce it, as well as the integration of artificial intelligence systems, are also aspects that deserve attention and must be studied and deepened in conjunction with research on the potential for renewable energy in the Black Sea.

In conclusion, the present analysis has demonstrated that the Black Sea region holds a significant potential for the exploitation of renewable energy resources, and an integrated and responsible approach is needed to capitalize on this. Offshore wind and wave energy, together with emerging technologies and hybrid solutions analyzed here, can place the Black Sea on the map of the green energy transition process. For this to happen, technological development must be complemented by strategic measures, and the technical, financial, geopolitical, and environmental challenges must be carefully managed. By implementing the recommendations and continuing the proposed research, riparian countries can sustainably capitalize on their natural heritage of the Black Sea, contributing both to their energy security and the global efforts to combat climate change.

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Nomenclature

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
ALADIN	Aire Limitée Adaptation dynamique Développement InterNational
ANM	The National Meteorological Administration of Romania
AVISO	French Active Archive Data Center for multi-satellite altimeter missions
CAPEX	CAPital EXpenditure
CFSR	Climate Forecast System Reanalysis
CMIP	Coupled Model Intercomparison Project
CNRM	Centre National de Recherches Météorologiques, France
CoE	Cost of Energy
CORDEX	COordinated Regional climate Downscaling EXperiment
DHI	Danish Hydraulic Institute
EU	European Union
EC-EARTH	Earth system model developed by a European consortium
ECMWF	European Centre for Medium-range Weather Forecast
ERA5	ECMWF RE-analysis, fifth-generation
ERA-Interim	ECMWF RE-analysis Project
EURO-CORDEX	European branch of the international CORDEX initiative
FOWT	Floating Offshore Wind Turbine

FPV	Floating Photovoltaic
FPVs	Floating Photovoltaic Systems
GFS	Global Forecast System
GHG	Greenhouse Gas
GWEC	Global Wind Energy Council
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost of Energy
MIKE 21 SW	MIKE 21 Spectral Waves
MM5	Fifth-Generation Mesoscale Meteorological
NCEP	US National Centers for Environmental Prediction
NREL	National Renewable Energy Laboratory
OPEX	OPerational EXpenditures
OWT	Offshore Wind Turbine
RCA4	Rossby Centre regional atmospheric model
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
REMO	Regional Climate Model from the Max Planck Institute, Hamburg, Germany
SMHI	Swedish Meteorological and Hydrological Institute
SSP	Shared Socio-Economic Pathway
SST	Sea Surface Temperature
SWAN	Simulating WAves Nearshore
VOS	Voluntary Observing Ship
WAM	Wave model, third generation wave model
WEC	Wave Energy Converters

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