

A Review of the Technoeconomic Feasibility of Wave Energy Harvesting for Coastal Power Generation in Saudi Arabia

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Received: 6 April 2026 | **Revised:** 15 July 2026 | **Accepted:** 9 September 2026

Keywords: coastline and oceanography | energy consumption | renewable energy | wave energy converters

ABSTRACT

Saudi Arabia's substantial reliance on fossil fuel-based electrical power generation, combined with rapid growth in population and rising expectations for improved living standards, has led to significant greenhouse gas emissions. Saudi Arabia's energy consumption is anticipated to escalate to 133 GW by 2030, an increase from 84 GW in 2020. The nation intends to produce 50% of its power from green energy by 2030, therefore diminishing its dependence on petroleum and coal. The Saudi government has launched initiatives such as the King Abdullah City for Atomic and Renewable Energy (KACARE) to promote renewable and nuclear energy, but their effectiveness is hindered by factors such as high temperatures, dust storms, and the management of nuclear waste. Wave energy represents a promising renewable energy resource for environmentally sustainable electricity generation; however, its practical deployment in Saudi Arabia depends on site-specific resource conditions, technology maturity, technoeconomic performance, and supportive policy frameworks. Exploring the Saudi clean energy potential from wave energy along the Red Sea coast (Jeddah, Rabigh, and Yanbu) and the Arabian Gulf coast (Dammam, Jubail, and Khafji) is the main goal of this work. The Red Sea exhibits significant wave heights reaching approximately 3 m under energetic sea states, indicating favorable wave resource conditions for future wave energy development. By reducing reliance on fossil fuel sources and creating a more varied and robust energy infrastructure wave energy may be incorporated into the energy mix to help achieve the objectives of Vision 2030. This study provides a comprehensive synthesis of the current state of wave energy research relevant to Saudi Arabia by integrating resource assessment, technology evaluation, technoeconomic analysis, environmental considerations, and deployment strategies within a unified review framework. The findings identify critical research gaps and provide practical recommendations to support future pilot-scale demonstrations, technology development, and policy planning for marine renewable energy deployment in Saudi Arabia. Additionally, this review provides a comprehensive synthesis of the current literature on wave energy technologies, technoeconomic assessment, environmental considerations, and deployment opportunities relevant to Saudi Arabia coastal areas.

1 | Introduction

Global warming and concerns about energy security have led to a search for alternative energy-producing methods, ideally ones

that produce less pollution. The United Nations Framework Convention on Climate Change (UNFCCC) established the Paris Agreement 2015, which calls for countries to expedite their

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energy shift to greener energy generating options in order to retain global warming at a harmless level of “well below 2°C over preindustrial levels and following attempts to restrict temperature rise to 1.5°C beyond pre-industrial levels” at the end of this century. In order to improve energy production dependability, lessen climate change vulnerability via use of renewable energy sources (RESs), along with sustainably meet the rising demand for energy, nations are updating their energy policies and creating new frameworks. The problems modeled by climate change require a concentrated strategy. That may include both adaptation and mitigation measures with a stronger focus on tactical integration initiatives for optimal gains and increased resilience [1, 2]. Saudi Arabia is estimated to be listed as the world’s ninth-largest carbon dioxide emitter due to its heavy reliance upon oil and gas and conventional resources. Saudi Arabia has a \$1,108,150 million yearly GDP and is mostly dependent on fossil fuels, which contributes to significant CO₂ emissions. Fossil fuel production and usage in Saudi Arabia have led to numerous environmental problems, including air and water pollution, which have a detrimental impact on both the environment and human health [3]. Saudi Arabia hopes to reach 58.7 GW of energy through renewable energy means till 2030. According to the energy minister’s 2023 statement, the target is to generate 130 GW of renewable energy per year by 2030. Almost 366 TWh of electricity will be needed if the economy grows moderately and prices remain the same [4]. Saudi Arabia aims to generate 58.7 GW of renewable energy by 2030, with 40 GW coming from solar photovoltaics (PV), 16 GW from wind, and 2.7 GW through concentrated solar power (CSP). Figure 1 depicts Saudi Arabia’s infrastructure and resources for electric power and renewable energy. Saudi Arabia’s goal of reaching net zero until 2060 likewise presents a conflicting obstacle; however, by investing in renewable energy, altering the structure of energy prices, and switching from oil to gas, the country is addressing the issue. The buildup of GHG emissions in the environment is predicted to cause average temperatures to rise, causing Saudi Arabia’s

climate to change more quickly than other parts of the world. Therefore, in line with the Paris Agreement, the nation is dedicated to take action to lessen its reliance on fossil fuels and to minimize its greenhouse gas emissions. The circular economy and renewable energy have emerged as key components of the current strategy used to address energy security, fight climate change, and reach sustainable social, economic, and environmental development. As a result, renewable energy and circular economy work in cycle to achieve environmental objectives while promoting innovation and economic growth for sustainable development [5]. In this approach, achieving global climate and environmental goals and creating robust mechanisms are crucial. Given the diversity of nations’ natural resources, socioeconomic environments, and institutional and technical capabilities, the forces behind the energy transition along with the strategies used to guarantee greener energy-producing possibilities differ from one another. In other words, the factors that affect and characterize the energy shift in nations that produce hydrocarbons may differ greatly from those in nations that import net energy [6]. Saudi Arabia might become a significant provider of green hydrogen due to its essential resources for generating electricity from renewable sources. Furthermore, Saudi Arabia possesses substantial natural gas reserves, extensive expertise for large-scale manufacturing of chemicals and hydrogen, also the ability to absorb and store CO₂, and necessary infrastructure to facilitate growth of blue hydrogen sector. In the Kingdom, because of the dependence on fossil fuel sources, the performance of the national economy is closely linked to the volatility of the world oil market. In order to guarantee a more secure and sustainable economy, Saudi Arabia should consider investing in renewable energy [7]. The legislative and institutional foundation for governing the Kingdom’s nuclear energy industry has been proposed by the Saudi government. The National Atomic Energy Program was started in 2017 by the King Abdullah City for Atomic and Renewable Energy (KACARE), which was founded in 2010 with responsibility of developing technical skills and

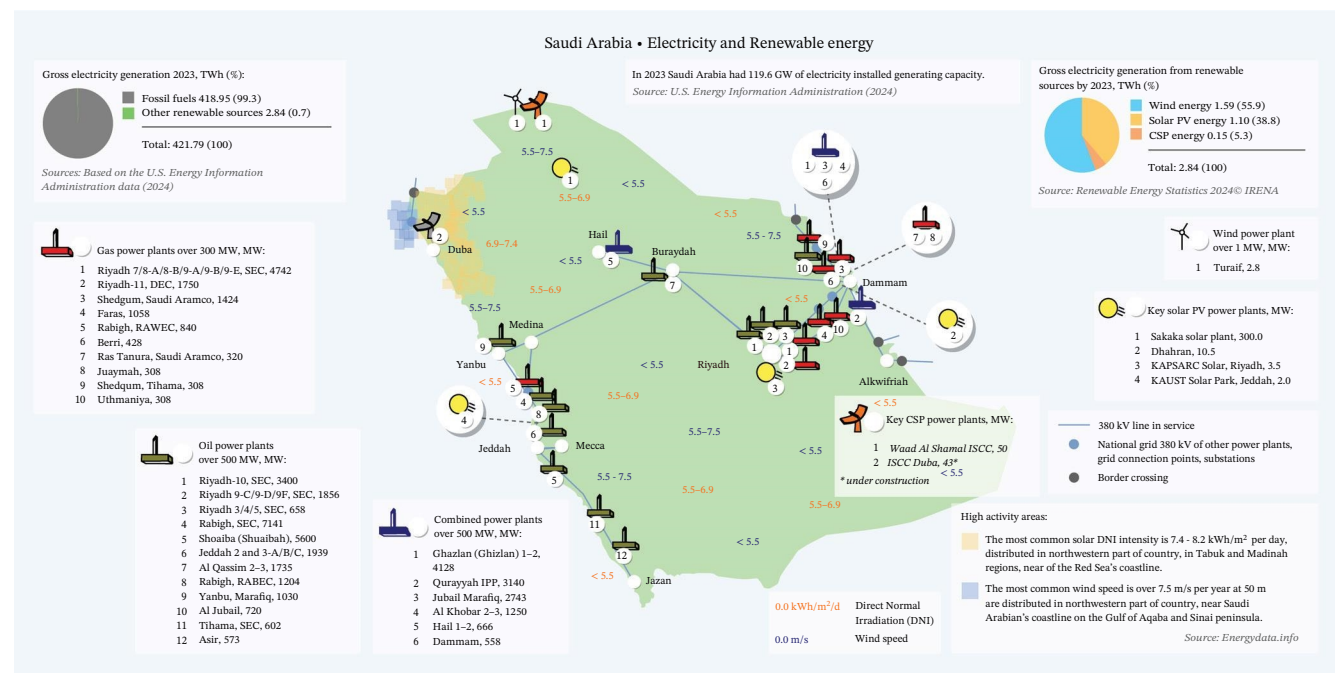


FIGURE 1 | Infrastructure and resource map for electricity and renewable energy [4].

knowledge in the fields of atomic and renewable energy. It created an independent regulatory body, the Nuclear and Radiological Regulatory Commission, to oversee the execution of its nuclear energy program, make sure it conforms with applicable laws, protects people and the environment, and upholds the highest operational safety standards [8]. The Sakaka and Sudair solar plants, which have a significant 1.5 GW capacity, went online in June 2021. Additionally, as part of its efforts to diversify its renewable energy portfolio, Saudi Arabia is now involved in wind-generating ventures. The Dumat Al Jandal wind project is expected to have a planned capacity of 400 MW and is regarded as the nation's first utility-scale wind farm. The success of these efforts is, however, discouraged by numerous factors including high temperatures, dust storms, and nuclear waste. The coasts along the Arabian Gulf and Red Sea are very large, and there is a prospect of existing of wave-power in Saudi Arabia, though still unexploited by any means of serious attempts having been made to develop the solar and wind. Marine energy systems produce clean electricity using renewable energy of the tides and waves. The greatest source of renewable energy is wave energy, which has many advantages compared to other sources of renewable energy. Most maritime countries are at the advantage of being near to RESs, especially the ocean wave energy. Due to increasing demands in the energy market and limited supply of conventional sources, people are seeking sustainable and renewable sources of energy. The use of renewable and sustainable energy sources would not only be useful in meeting energy needs but also reduce carbon emissions. It is believed that there is more than 2 TW of wave energy available around the world, and this energy can someday be economical [9, 10]. Saudi Arabia's vast Red Sea and Arabian Gulf coastlines offer an abundance of wave energy possibilities. However, there are several obstacles in the path of realizing this potential, such as the high cost of infrastructure, the effects on marine habitats, and the requirement for grid integration and supportive regulations. By utilizing its maritime energy sources, Saudi Arabia can enhance its energy mix and move closer to renewable energy targets with the help of the government's strategic support for infrastructure development, technological innovation, and regulatory incentives [11]. According to recent studies, moderately high waves are present in a significant portion of Red Sea with wave heights of normally around 2.0 m in the Red Sea's deep waters are with the center region recording a maximum of 4.5 m. Large-scale seasonal fluctuation is caused by the reversing monsoons. Because of the mountain gap wind jets that blow through the middle region throughout the summer, the Red Sea experiences the highest wave heights. The convergence of the atmosphere throughout the winter caused another noteworthy phenomenon: the convergence of waves across the central Red Sea [12]. As fossil fuels run out and environmental issues become more pressing, there will soon be a greater need for wave energy. Wave energy must be converted by equipment that can essentially operate in three different ways in order to produce the electrical energy that is sent to the grid. (i) Systems powered by the energy of passing waves that take use of the motions or shape deformations of their underlying mechanisms. (ii) Devices that use the weight of saltwater held in a reservoir or the variations in water pressure caused by wave height oscillations; (iii) Devices that transform wave motions into air flow. Wave motion is dependent on the energy transfer between the sea's surface layer and the lower atmosphere. As a result of these interactions, the wind produces waves with the maximum energy content. This

movement creates a mechanism for energy transformation, which leads to an increase in wind energy on the water's free surface. With little energy loss, waves in offshore regions may travel several 100 km once these water masses are moving. The primary forces that contribute to the creation and spread of wave motion are the recall forces, which are represented by the surface tension of water and the ensuing gravity, in addition to the force that is generated. These forces tend to return water to its equilibrium position. Surface tension is the primary recall force for capillary waves with wavelengths less than 1.7 cm, but it is insignificant in comparison to gravity at wavelengths longer than 10 cm [13]. Wave energy converters (WECs) are specifically made to capture low-frequency ocean wave motions and use power take-offs (PTOs) to transform the energy they absorb into electrical power that can be used [14].

Table 1 describes the significant regional efforts toward advancing WECs technologies across Europe, the Mediterranean, and the Arabian Gulf. This research work spans from simulation-based feasibility assessments and hydrodynamic modeling to optimization using genetic algorithms. The findings in the table indicated that while wave energy boasts strong technological latency, its economic sustainability is still a hurdle due to higher costs and uncertain resource availability. The region of Mediterranean shows promising potential for coastal and nearshore systems in harnessing efficient energy and stability. For island systems, studies report ~80% energy recovery along with substantial yearly savings. Such intuitions highlight the significance of reliable optimizations along with cost reduction to achieve WEC deployment. This renewable energy could be regarded as financially feasible alternative This work aims to analyze more sustainable and reliable energy solutions for Arabi's energy transition to reduce reliance on fossil fuels by using wave energy, from its Red Sea and Arabian Gulf coastlines. It offers comprehensive study to harness the possibility of wave energy efficiently, also with the analyzes the technoeconomic and ecological possibility of WECs on Red Sea and Arabian Gulf of Saudi Arabia. It also offers real-world vision to investors and representatives for the growth of advanced and modified present technologies. The results of these analyses consider adverse climatic circumstances to diminish global warming phenomena. This will help industrial progress under international environmental guidelines. The author's innovative contribution is its assessment of the capability of establishing WECs in coastal regions, an area that is normally overlooked. This provides important information that may help in achieving 2030 vision of Kingdom to target renewable energy for sustainability. This real-world analysis compares the technical and financial performance of the systems yielding trustworthy scientific findings, which may help directly in the advancement of marine renewable energy as well. The major contribution of this review are as follows:

1. This review systematically examines previous technoeconomic assessments of wave energy projects by comparing key performance indicators including capital expenditure (CAPEX), operational expenditure (OPEX), annual energy production (AEP), capacity factor (CF), project lifetime, discount rate, levelized cost of energy (LCOE), and economic uncertainty factors. The synthesis identifies the primary economic barriers that currently limit commercial deployment of wave energy technologies.

TABLE 1 | Summary of multiple regional studies on WECs [15].

Region/location	Main research focus	Applied methodology	Outcomes/findings	References
Spain	Assessment of technical feasibility and economic potential of WEC systems	Simulation-based analysis	Revealed that WECs possess promising potential, though cost challenges persist. Estimated annual energy generation: 1400 MWh.	[16]
Portugal	Evaluation of the performance of WEC arrays	Combined numerical and experimental investigations	Demonstrated that point absorber configurations provide superior energy output with a LCOE ranging from 70 to 500/MWh.	[17]
Persian Gulf	Exploration of wave energy resources	Integrated resource mapping and technical modeling	Found that the Arabian Gulf exhibits moderate wave conditions, with a capacity factor between 10% and 15%.	[18]
North Sea	Cost-benefit evaluation of WEC deployment	Simulation-driven cost modeling	Despite a declining LCOE, profitability remains marginal, with an estimated annual return of \$1.2 M.	[19]
Mediterranean Sea	Optimization and performance enhancement of multipoint absorber systems	BEM (Boundary element method) and hydrodynamic simulation	Showed that multipoint absorbers enhance power extraction efficiency, achieving an LCOE between 130 and 390/kWh.	[14]
Mediterranean Islands	Sustainable energy integration for isolated systems	Energy sustainability and assessment modeling	Identified feasible renewable energy strategies for islanded grids, yielding an annual energy saving of ~30%.	[16]
Mediterranean Sea (Coastal)	Modeling of wave farms for renewable power	Coastal energy and environmental modeling	Demonstrated that wave farms offer dual environmental and energy benefits, with ~60% wave attenuation.	[19]
European Waters	Economic optimization of WEC arrays	Genetic algorithm-based optimization	Optimal arrangements could cut array costs by up to 25%, producing an annual output of 1800 MWh.	[19]
Mediterranean Sea (Nearshore)	Nearshore wave energy conversion analysis	Wave energy propagation modeling	Found that nearshore installations can capture up to 80% of the offshore wave energy potential.	[14]

2. A structured comparison is developed to evaluate the technical suitability, environmental constraints, infrastructure readiness, wave resource characteristics, and potential deployment challenges across Saudi Arabia’s two major coastal regions. This comparison provides insights into region-specific technology selection and investment priorities.

3. Unlike previous studies [13, 14, 20, 21] that primarily focus on global/regional marine energy resources, this review provides a consolidated assessment of wave energy potential along both the Red Sea and Arabian Gulf coastlines. The analysis highlights regional variations in wave characteristics, resource density, seasonal variability, and suitability for different WEC deployment strategies.

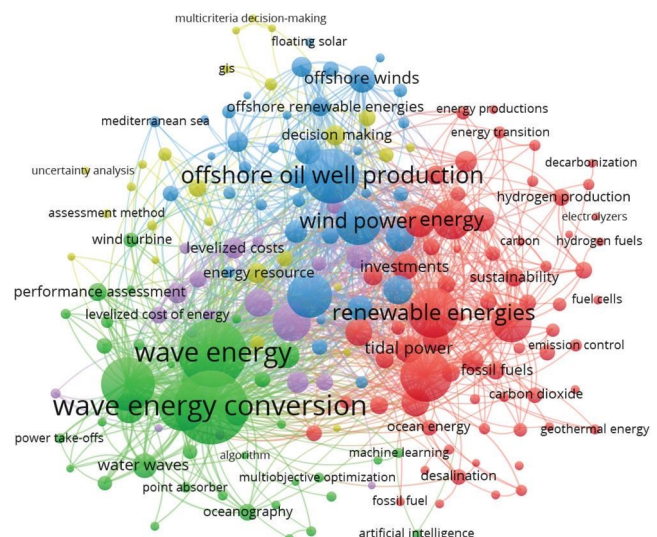
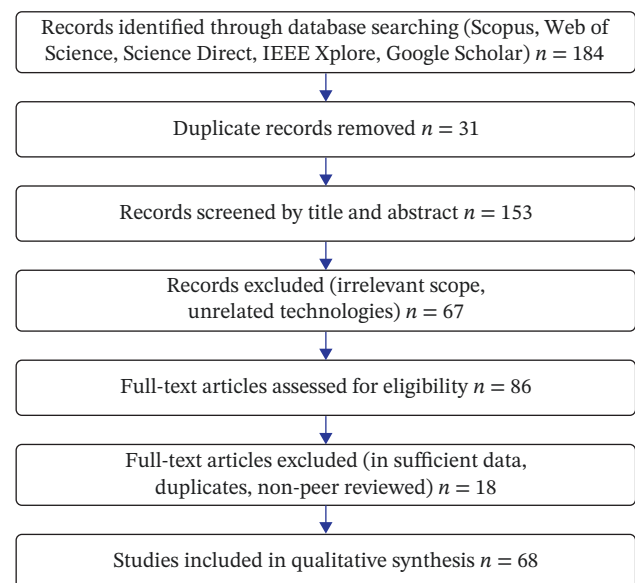
4. The study critically evaluates existing WEC technologies, including point absorbers, oscillating water columns (OWCs), attenuators, oscillating wave surge converters (OWSCs), and overtopping devices, with respect to local operational challenges such as high temperatures, salinity, biofouling, sediment transport, extreme weather events, and maintenance accessibility.

5. The review consolidates technical, economic, environmental, regulatory, and infrastructure-related challenges affecting wave energy deployment in Saudi Arabia. The interrelationships among resource quality, technology maturity, maintenance requirements, grid integration, and investment risk are critically discussed to identify priority areas for future research and development.

6. A strategic roadmap is proposed to support phased implementation of wave energy technologies under Saudi Vision 2030. The roadmap outlines short-term pilot-scale demonstrations, medium-term technology validation and hybrid renewable integration, and long-term commercial deployment pathways for marine renewable energy systems.

7. Based on the reviewed literature and regional assessment, the study provides practical recommendations for policymakers, researchers, investors, and industry stakeholders regarding technology selection, research priorities, pilot project development, economic incentives, and regulatory frameworks required to accelerate wave energy adoption in Saudi Arabia.

To ensure a systematic and transparent review process, a PRISMA-inspired methodology was adopted for literature selection, screening, and synthesis. The following studies were reviewed: wave energy resources, WECS, technoeconomic assessment of wave energy, marine renewable energy devices, and opportunities for wave energy deployment in the Kingdom of Saudi Arabia and similar coastal countries. The literature search was carried out in the major scientific databases such as Scopus, Web of Science, ScienceDirect, IEEE Xplore, and Google Scholar. The publications from 2005 to 2026 were selected to represent both basic and current knowledge on wave energy technologies and technoeconomic evaluations.



energy policies and current renewable energy programs. Section 3 explores the National wave energy potential while analyzing characteristics and physical conditions of coastline. Section 4 describes the comparison of other renewable sources with wave energy in terms of availability and conversion efficiency. Section 5 discusses various present converter technologies of wave energy. Section 6 contains the discussion on implementation of wave energy and environmental benefits. Section 7 contains critical synthesis of existing studies and research gaps. Section 8 describes knowledge gaps and future research directions. Section 9 listed with the suitable WECs for Saudi Arabian coastal conditions. Section 10 presented real-time studies and relevant applications in environmental perspective to Saudi Arabia. Finally, Section 11 concludes the work and suggests future directions.

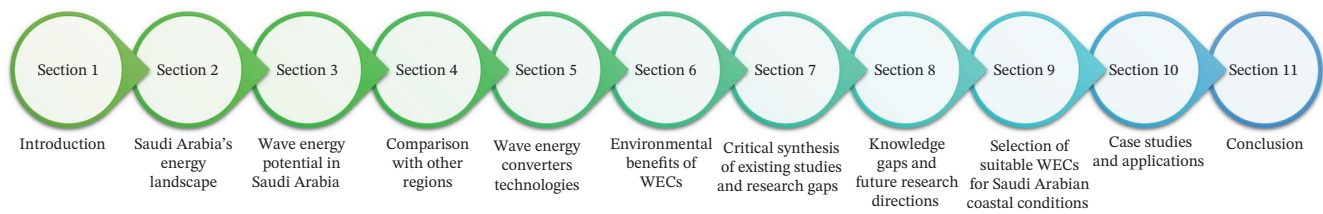


FIGURE 4 | Manuscript organization.

2 | Saudi Arabia's Energy Landscape

Saudi Arabia, which has long been renowned for its massive oil reserves and hold over the world market, is at a turning point in its energy development. The kingdom's economy has always been closely connected to the oil industry, which contributes almost 50% of its GDP and 70% of its export revenue. However, in light of the limited supply of fossil fuel resources, shifting oil prices, and worldwide environmental concerns, this strong dependence on fossil fuels caused a strategic reassessment. According to worldwide data and the global carbon budget (GCB), Saudi Arabia's per capita CO₂ emissions using fossil fuels have significantly increased since 1998 as depicted Figure 5. This shows Saudi Arabia's per capita CO₂ emissions from fossil fuels. The kingdom is utilizing natural gas (63%) and crude oil (36%), as well as about 1% from RESs, for electricity generation; a pie chart is illustrated in Figure 6a. Figure 6b shows energy mix of Saudi Arabia during 2022. By 2030, Saudi Arabia aims to achieve the ideal energy mix for power generation by eliminating petroleum liquids from the system and depending only on gas and RESs, each accounting for 50% of the total [23].

The global energy industry is changing at a very rapid pace, and several factors are driving this faster course. Among these factors, combating climate change is crucial, but governments and policymakers also have other concerns, such as making sure that energy is available at a reasonable price, bolstering energy security, and guaranteeing that everyone has access to energy. Fossil fuels will continue to be used in this context to help meet the

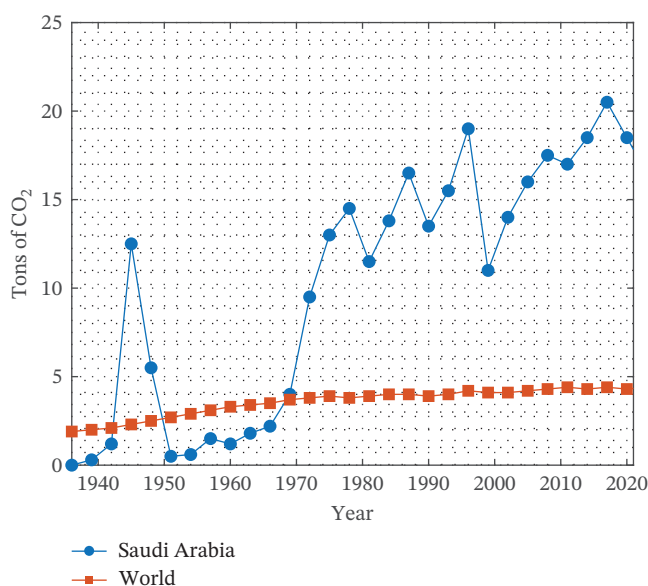


FIGURE 5 | Saudi Arabia's CO₂ emissions per capita from fossil fuels [22].

growing demand for energy in the future. Energy efficiency and renewable energy are two essential energy strategies to meet the objectives of the Paris Agreement. By 2023, Saudi Arabia has made a substantial contribution to the expansion of the world's renewable energy capacity through its strategic efforts. The kingdom is concentrating especially on using solar energy because of its plentiful sunshine, and it is also investigating wind energy because of its expansive desert terrain. Saudi Arabia's larger plan to lead the world in renewable energy includes several initiatives [22].

Saudi Arabia's goal of reaching net zero until 2060 also presents a conflicting obstacle. The country is addressing this by shifting from oil to gas, investing in renewable energy, and altering the structure of energy prices. Furthermore, consideration is being given to carbon capture and storage (CCS) and potential transitions to hydrogen as a renewable energy resource (for example, bidding projects with a 20 GW target in 2024). The renewable energy industry offers opportunities for economic expansion and employment development in keeping with the country's reform plan. Saudi Arabia's energy sector is going through a tremendous upheaval that will have a big effect on both the kingdom and the entire rest of the world.

According to International Energy Agency (IEA) report 2022, to diversify its economy, Saudi Arabia has started a number of projects. The Vision 2030 initiative is the most prominent of them, aiming to lessen the nation's reliance on oil while establishing other industries including technology, entertainment, and tourism. The government has also made significant investments in infrastructure projects that are intended to draw in foreign capital and generate employment, such as the Red Sea Project and the building of the NEOM megacity. Saudi Energy Efficiency Center's Energy Efficiency Action Plan, which seeks to cut power intensity by 30% by 2030, and NEOM project featuring green hydrogen factory of 4 GW show commitment to technical innovation and sustainability by Saudi Arabia. The Riyadh Urban Project is among Saudi Arabia's biggest Vision 2030 initiatives, with the goal of developing and improving Riyadh while also offering its citizens numerous services and enhancements. Building hospitals, schools, shopping malls, and public centers; expanding green areas; improving existing housing; improving roads and transportation systems; and reducing pollution in building by using renewable resources. Additionally, the Red Sea Project is one of the biggest tourism initiatives in the Kingdom and is a component of Vision 2030 of Saudi Arabia. It will be a Red Sea tourist resort situated between the two towns of Umluj and Al-Wajh on Saudi Arabia's western coast. 90 natural islands, hilly areas, and deserts are included in the project, which helps Saudi Arabia achieve its main goals of boosting tourism, protecting the country's natural terrestrial and marine habitats, and

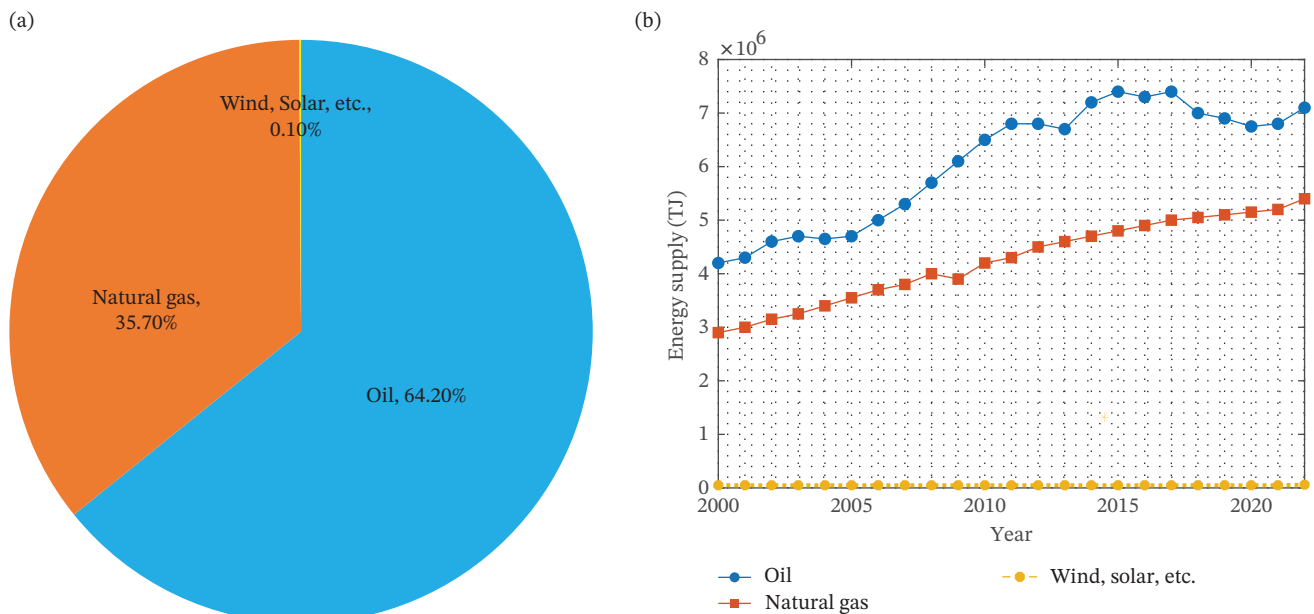


FIGURE 6 | Energy utilization profile and primary energy supply trends in Saudi Arabia. (a) Contribution of major energy sources to national CO₂ emissions, highlighting the dominant reliance on oil (64.2%) and natural gas (35.7%), with renewable energy sources accounting for less than 0.1% of the total energy mix. (b) Historical evolution of Saudi Arabia's primary energy supply from 2000 to 2022, showing the continued growth in oil and natural gas consumption and the comparatively limited contribution of renewable energy resources [22].

creating a large number of work opportunities. An important advancement for Saudi Arabia's renewable energy initiative is Dumat Al Jandal, the largest wind farm in the Middle East. When completed, the farm is expected to produce 400 MW of electricity, enough to power thousands of homes and significantly reduce carbon emissions. Major projects started by Saudi Arabia under vision 2030 are summarized in Table 2. Among the various alternative energy sources, solar and wind energy are rising to the top and are increasingly being used in a wide range of applications [25]. In desert areas, a number of environmental issues, including dust, air pollution, and shadow, have an impact on solar photovoltaic panels. In Saudi Arabia's desert regions, a variety of photovoltaic systems are adversely affected by dust, sun radiation, carbonate coatings, and relative humidity. These issues, which have a significant impact on the surfaces of photovoltaic panels and wind turbines, were outlined in order to determine if solar as well as wind energy systems might be established in Saudi Arabia. Since the aforementioned environmental issues make photovoltaic (PV) cells unsuitable for the Kingdom of Saudi Arabia, alternative RESs are seen to be more practical. Wind-driven sand can damage a wind turbine's blades, reducing efficiency and increasing maintenance expenses. Wind turbines must therefore be built to resist this abrasive effect. The transportation and installation of wind turbines in remote desert areas require significant infrastructure development, from building roads to ensuring a stable electricity grid connection, and the initial cost for wind farms is another obstacle. While wind energy may be less expensive than solar energy in some areas, Saudi Arabia must maintain the profits of its current oil economy while managing the fluctuations in the universal energy market to ensure a return on its green energy investments [26, 27]. Additionally, heat can damage electronic and mechanical components, thus it's critical to develop heat-resistant materials and designs. Extended exposure to sunshine and high ambient temperatures both increase the effect of temperature on PV cell

efficiency. Higher cell temperatures cause atoms to vibrate more (phonons), which hinders the flow of charge carriers and reduces cell efficiency. It is crucial to have knowledge of these environmental issues in a particular area in order to set up renewable energies and estimate their production and efficiencies. Additionally, understanding these difficulties is important for climatology, air quality research, and atmospheric energy balance. It is also necessary for the design and modeling of all wind and photovoltaic systems [28, 29].

Figure 7 illustrates the spatial distribution of wave energy potential along the Saudi Arabian coastline, emphasizing the promising regions for marine renewable energy development. The wave energy per meter of wave crest (kJ m^{-1}) overlaid with mean sea-level pressure is illustrated in Figure 7a and the distribution according to significant wave height (H_s , m) is depicted in Figure 7b. The maps reveal that the southern Red Sea and parts of the Arabian Sea exhibit comparatively high wave energy densities, indicating favorable conditions for WEC deployment. Although the central and northern Red Sea and Arabian Gulf show moderate to low energy levels due to limited fetch and enclosed geography, these areas still offer steady and predictable wave patterns suitable for small- to medium-scale energy applications. This accentuates Saudi Arabia's emerging potential to harness wave energy as a complementary renewable resource. This will help in supporting its long-term vision for sustainable and diversified energy generation. Furthermore, the Gulf Cooperation Council (GCC) nations are working to meet their stated 2030 energy goals, which average roughly 26% with Saudi Arabia and the UAE and Oman reaching 50% and 30%, respectively. The emphasis on sustainability in Saudi Arabia's Vision 2030 makes it stand out because it successfully creates a roadmap and maintains its leadership position [7]. The Kingdom of Saudi Arabia has set a goal of achieving net-zero GHG emissions by 2060, including 50% renewable energy goal and a cut of 278 million tons of CO₂

TABLE 2 | Saudi Vision 2030 major projects [24].

Project	Area occupied (km ²)	Date of announcement	Expected completion	Cost
New Taif project	1250	1-Mar-17	2020	\$3 billion
Diriyah Gate project	1.5	20-Jul-17	2030	Unknown
Al-Qiddiya project (Al-Qiddiya, southwest of Riyadh)	334	8-Apr-17	2022	\$2.7 billion
Al-Faisaliah project (West of Makkah)	2450	26-Jul-17	1st phase will be completed by the end of 2020	Unknown
Downtown Jeddah	5.2	27-Sep-17	1st phase will be completed by the end of 2022	\$4.8 billion
NEOM (Tabuk)	26,500	24-Oct-17	1st phase will be completed by the end of 2025	\$500 billion
Renewable energy project	Unknown	27-Mar-18	2030	\$200 billion
Amaala project (Along the Red Sea)	3800	26-Sep-18	1st phase will be completed by the end of 2020	Unknown
King Salman Energy Park (between Dammam and Al-Ahsa)	50	5-Dec-18	1st phase will be completed by the end of 2021	\$1.6 billion
Al-Ula Vision	22,500	11-Feb-19	2030	Unknown
King Salman Park, Sports Boulevard, Green Riyadh, and Riyadh Art	>149	19-Mar-19	Unknown	\$23 billion
Great Mosque of Mecca	0.250	2017	Mid-2018	\$21.3 billion
Mall of Saudi	8.666	2017	2022	\$3.2 billion
The Red Sea project	28,000	2018	1st phase will be completed by the end of 2022	3.2–3.7 billion

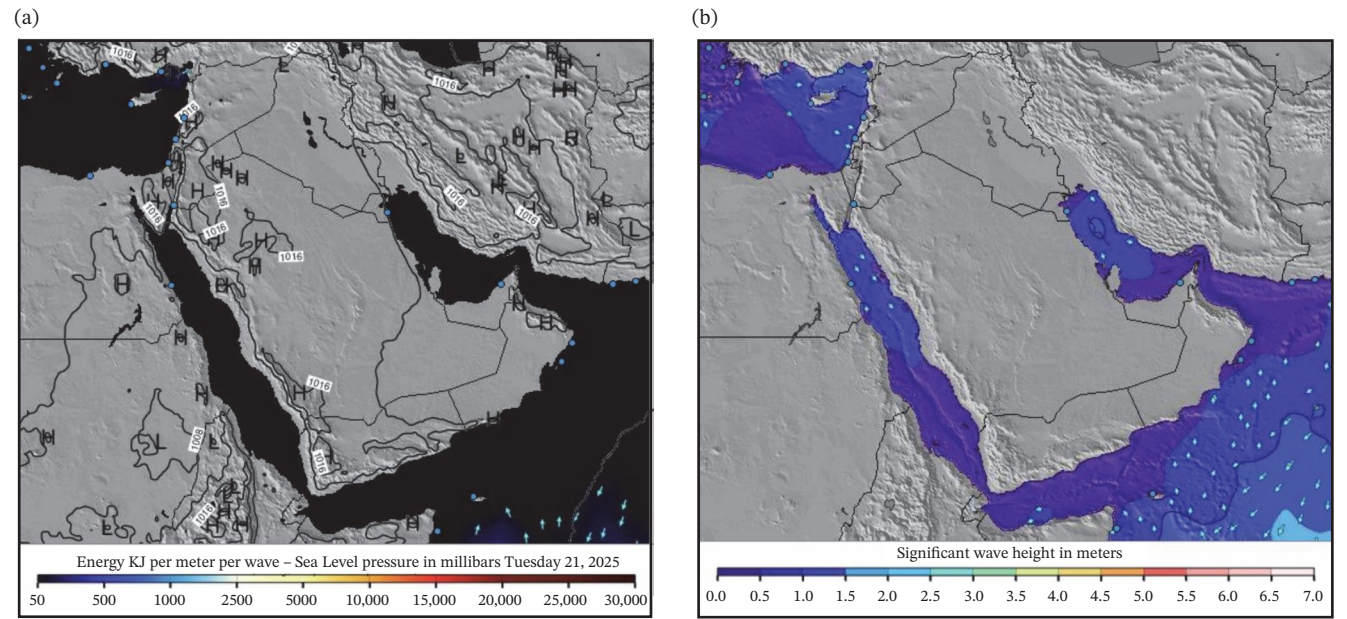


FIGURE 7 | Spatial distribution of wave conditions in the Red Sea and Arabian Gulf illustrating (a) Wave energy per meter of wave crest (kJ m^{-1}) overlaid with mean sea-level pressure (hPa) and (b) Significant wave height (H_s , m). The figure represents a regional wave snapshot obtained from the ECMWF numerical weather prediction system (Tuesday, 21 January 2025) using gridded meteorological and wave model data.

equivalent annually by 2030 [16, 30]. This vision places an emphasis on financial diversification, global participation, and better life quality. The energy sector is crucial to the carbon neutrality effort

that intends to reduce emissions by 55% by 2030, with 90 GW of built-in capacity by 2020 [31]. Energy Efficiency Action Plan by the Saudi Energy Efficiency Center, which aims to reduce power

intensity by 30% by 2030, and the NEOM project. This includes a 4 GW green hydrogen factory, which is an example of Saudi Arabia's commitment to sustainability and technological innovation. This research linked to energy policies of Saudi Arabia's has previously focused on oil production and exports rather than a more comprehensive analysis of sustainability and economic diversification. Given the importance of the kingdom's energy transition, research trends followed these changes and focused more on Saudi Arabia's attempts to broaden its economy and lessen its reliance on oil earnings.

3 | Wave Energy Potential in Saudi Arabia

3.1 | Coastline and Oceanography

2320 km of Saudi Arabia's coastline stretch across the Arabian Gulf (560 km) and Red Sea (1760 km). With a normal range of up to 1 m, the northern Red Sea's tides are semidiurnal. Moreover, across the central Red Sea, seasonal fluctuations in water level of 0.2–0.3 m are noted. In the northern Red Sea, extreme sea levels are thought to range from 0.5 to 2 m. Because of the Gulf's size and shape, a complicated system of standing waves exists. The wave characteristics of the Gulf differ, with diurnal, mixed, and semidiurnal tides occurring in different places. Sand makes up 99% of Saudi Arabia's coastline, with rocky headlands in between. Mangrove forests (35 km²) dotted throughout the Red Sea coast and vast surrounding coral reef habitats (1480 km²) make up the most important coastal habitats on the Saudi coast. Many coastal interferences have been carried out in last few decades along coastline of nation's major economic hubs (Jeddah, Khobar, Dammam, Jubail, etc.) due to the thriving economy and expanding tourism industry. These interventions were motivated by the need to increase the amount of space available for urban, industrial, and recreational purposes. Currently, in order to stimulate economic activity and the rise of tourism, beachfront developments (such as NEOM, Red Sea Development Project, and Economic Cities) have been planned and constructed, primarily at sparsely populated and pristine locations. An intelligent, future-proof coastal front design combined with the preservation of these coasts' distinctive physical and ecological features is a top priority for developers and stakeholders. The primary wind systems in the Red Sea strongly characterize the wave climatology. Northwestern to northern wave directions are dominant while considering frequency. The wave height (H_s) mean stays around 1 m throughout the year in northern Red Sea. Furthermore, waves having swell characteristics that are linked to the southeast wind in the southern Red Sea make their way northward. For the high percentages from October to April, energy via southerly waves is particularly important. In the northern Red Sea, wave height trends are declining, according to a 30-year hindcast (around 5–6 cm for northern waves vs. 1 cm for southern waves). There is also evidence of a decline in annual storm events associated with northern and southern waves. Following the direction of wind, the predominant direction of wave above the Gulf is northwest to north. Throughout the Gulf, monthly average Wave height is less than 1 m, with the central Gulf region experiencing the highest values during months of June and February [32]. One of the worst effects of warming is sea level rise (SLR), which can cause freshwater pollution, beach erosion, coastal flooding, habitat loss, elevated soil salinity, and the possibility of coastal infrastructure damage. The

Kingdom of Saudi Arabia's (KSA) Jeddah Province is one example of how SLR has major physical effects in coastal regions and cities, mostly in the form of floods and inundation threats [33]. Figure 8 illustrates the multiple SLR levels in Arabian Gulf and Red Sea along KSA.

3.2 | Wave Energy Resources

Wave energy potential along Saudi Arabia's whole coastline is 58 TWh/year. Even after accounting for real-world limitations, a mere 5% of theoretical capacity would still generate about 3 TWh annually. Wave energy can therefore offer a reliable and sustainable source of energy, especially for the coastal areas where 45% of population of Saudi Arabia lives. Wave energy may diversify the renewable energy mix with its more consistent energy generation profile than solar as well as wind sources. Furthermore, continuous operation of wave energy plants could provide baseload power that aids in grid stabilization. Wave energy is therefore a useful complement to the current energy mix, particularly with regard to energy security and dependability. Also, building marine energy infrastructure would establish Saudi Arabia as a Middle Eastern front-runner in maritime energy, advancing global transition to cleaner energy sources. In light of the nation's strategic drive for sustainability, investigating wave energy for Saudi Arabia has two advantages: it advances the development of RESs while utilizing a resource which has previously been mainly untapped. By reducing reliance on fossil fuel sources and creating a more varied and robust energy infrastructure, wave energy may be incorporated into the energy mix to help achieve the objectives of Vision 2030. Around 2.5 kW/m is the yearly average wave energy power along Saudi Arabia's Gulf Sea coastline. This potential is appropriate for large-scale energy harvesting since it is constant and dispersed over wide regions. For irregular waves, the average wave energy density per unit horizontal surface area is expressed as in Equation (1),

$$E = \frac{1}{16} \rho g H_s^2 \quad (1)$$

In above equation, E is the wave energy density (J m⁻²), ρ is the seawater density (kg m⁻³), g is the gravitational acceleration (9.81 m s⁻²), and H_s is the significant wave height (m). The wave power flux, representing the rate of energy transported per meter of wave crest, is calculated as Equation (2) [35],

$$P = \frac{\rho g^2 H_s^2 T_e}{64\pi} \quad (2)$$

Here, the P is the wave power flux (W m⁻¹) and T_e is the energy period (s). Unlike wave energy density, wave power flux represents the available wave energy transported through a vertical plane of unit crest width and is therefore the preferred parameter for assessing wave energy resources. The energy period (T_e) is adopted because it provides a more representative measure of energy transport in irregular sea states than the peak period (T_p) and mean period (T_m). Consequently, T_e is widely used in wave resource assessments and technoeconomic analyses of wave energy projects.

The waves in the Gulf Sea are high enough in height and duration to provide enough energy to generate electricity. Wave energy, a comparatively unexplored resource, as a reliable and sustainable

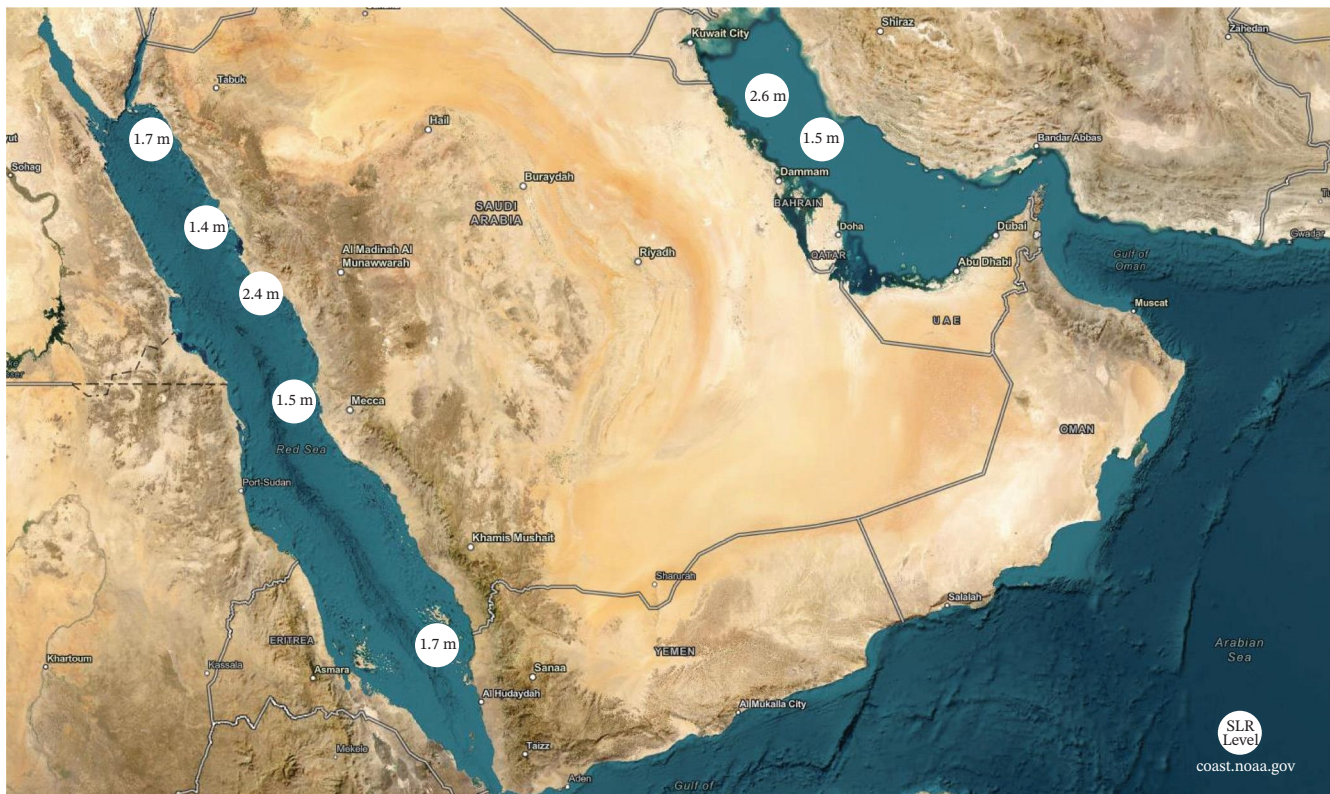


FIGURE 8 | Projected sea-level rise scenarios for selected coastal locations along the Saudi Arabian Red Sea and Arabian Gulf [34].

energy source to supplement wind and solar, offers a chance to include it in renewable energy policy of Saudi Arabia. Coastal areas of Saudi Arabia with more than 2500 km of shoreline can accommodate a number of wave energy projects, strengthening the country's grid's resilience and lowering its need on fossil fuels [15]. In the majority of the Red Sea, the waves are moderately high. Significant wave heights in the Red Sea's deep waters are normally around 2.0 m, with the center region recording a maximum of 4.5 m. Large-scale seasonal fluctuation is brought on by reversing monsoons. The Red Sea's highest wave heights are caused by summertime mountain gap wind jets that blow across the central region and throughout the Red Sea's width. Another noteworthy phenomenon that happened during the winter months as a result of the atmospheric convergence is the wave convergence at the center Red Sea. Additionally, the local breezes along the eastern Red Sea give a certain volume of wave energy. Deep waters of the Red Sea have a noticeable range of wave power, up to 4.5 kW/m, with the central Red Sea having the highest mean wave power. Seasonally, winter dominates the higher wave power, reaching up to 6.5 kW/m, followed by postwinter (up to 5.0 kW/m), summer, and postsummer (up to 4.5 kW/m). One significant feature is the seasonal fluctuations in highest mean wave power, which take place in the central and southern Red Seas during the winter, in the central Red Sea during the post-winter, in the central and lower northern Red Seas during the summer, and in the southern Red Sea during the postsummer [12].

4 | Comparison With Other Regions

By 2030, the nation wants to produce 58.7 GW from renewable sources, of which 16 GW will come from wind and 40 GW from

solar. The nation's dedication to sustainable energy development is demonstrated by important projects like Dumat Al Jandal Wind Farm (400 MW), Sakaka Solar Plant (300 MW), and Neom Solar Project [36]. In spite of these developments in wind and solar, although wave energy is still mostly unexplored, vast coastlines of Saudi Arabia across the Arabian Gulf and the Red Sea offer a potential possibility. The overall length of Saudi Arabia's coastline is 2640 km. The estimated potential for wave energy along these shorelines is almost 58 TWh/year based on the currently available data. 3 TWh/year would still be generated as a mere 5% of theoretic capacity, even after accounting for practical limitations. Accordingly, wave energy may be a reliable and sustainable energy source, especially for the coastal areas where 45% population of Saudi Arabia lives [9]. In contrast to wind and solar, wave energy offers a more stable power generation profile, which could diversify the renewable energy mix. Several studies conducted for WECs in other parts of the world place Saudi Arabia's wave energy potential in a global framework, taking use of current developments while taking into account regional elements like the economic climate and wave characteristics of the Gulf Sea. Wave energy in the UK might realistically reach 7–10 GW. The overall grid capacity in the UK is 80 GW, and peak demand is stabilized at about 65 GW to put these numbers into perspective. Therefore, wave energy has the potential to meet up to 15% of the present electricity demand in the UK; when paired with wave energy generation, this amount might reach up to 20%. China possesses a wave energy density of 6 kW/m over its expansive 14,500 km coastline, having 43% of its population living close to the sea. Theoretically, this could produce 762 TWh annually, which is a substantial 1/10th of the country's electricity requirements. H_s and P_w have similar spatial and temporal distribution features, and their levels are progressively declining from offshore to nearshore,

TABLE 3 | Comparative assessment of wave energy resource characteristics and deployment potential across Saudi Arabia and neighboring GCC countries [12, 35].

Parameter	Saudi Arabia	Oman	UAE	Qatar	Kuwait	Iran (PG coast)
Mean wave power flux (kW/m)	2.5–6.5	6–15	2–5	1–4	1–3	3–8
Significant wave height (m)	1.0–4.5	1.5–5.0	0.8–3.0	0.5–2.5	0.5–2.0	1.0–4.0
Wave period (s)	5–8	6–10	4–7	4–6	4–6	5–8
Seasonal variability	Moderate	Moderate–High	Moderate	Moderate	Low–Moderate	Moderate
Typical water depth	Shallow–Moderate	Moderate–Deep	Shallow	Shallow	Shallow	Moderate
Grid accessibility	High	Moderate	High	High	High	Moderate
Technology readiness	Emerging	Pilot-scale	Emerging	Emerging	Emerging	Pilot-scale
Major environmental constraints	High salinity, biofouling, elevated temperature	Cyclones, deep water	High salinity, sediment transport	High temperature	Sedimentation	High salinity, seismic activity
Most suitable deployment	Hybrid systems, desalination, ports	Offshore wave farms	Hybrid systems, desalination	Nearshore pilot projects	Pilot-scale deployment	Hybrid offshore systems

according to the analysis. In other words, the relationship between water depth and H_s and P_w values is inverse. In the study area, the mean H_s of the majority of waves ranges from 0.2 to 1.4 m. The eastern and southern regions of Taiwan Island have the greatest mean H_s , which surpasses 1.5 m. A comparable location has the largest wave energy flux, which is more than 16 kW/m [37]. Portugal is a great place to produce wave energy because of its striking 1793 km of coastline and high percentage of 70% coastal residents. With an average wave energy density of 25 kW/m², the theoretical annual potential is an astounding 390 TWh, which is eight times the present electricity usage. One of the biggest wave energy resources across continental Europe can be found at WECs along the Portuguese mainland's coast. The coastal region of Figueira da Foz in central Portugal is a very suitable site for WEC deployment, as evidenced by the CF, good capture width (CW) values, and significant AEP (over 4 GWh) [17].

To provide a consistent and objective assessment of Saudi Arabia's wave energy potential, a comparative evaluation was conducted using a common set of technical and technoeconomic indicators, including mean wave power flux, significant wave height, wave period, seasonal variability, water depth, grid accessibility, technology readiness, environmental constraints, and suitable deployment scenarios.

Table 3 compares these indicators for Saudi Arabia with neighboring GCC countries and the Arabian Gulf region, providing a regional context for evaluating wave energy development opportunities. The comparison indicates that although Saudi Arabia possesses more moderate wave resources than high-energy oceanic regions, it benefits from relatively stable wave conditions, extensive coastal infrastructure, and strong integration opportunities with desalination plants, ports, and offshore facilities. These characteristics suggest that the Red Sea and Arabian Gulf are particularly well suited for pilot-scale demonstrations, hybrid renewable energy systems, and niche coastal applications rather than immediate large-scale commercial wave farm deployment. Such a phased deployment strategy is expected to reduce technical and economic uncertainties while supporting the Kingdom's long-term renewable energy objectives under Vision 2030.

Remark 1. It is important to note that the values provided in Table 3 are not deterministic but are more representative ranges compiled from published studies. Climatic variations are due to time differences, wave data sets, numerical modeling methods, seasonal differences, and site-specific environmental factors. The estimated wave resource assessment of the theoretical wave energy potential along the Saudi Arabian coastline is ~58 TWh/year [15] (with variations reported based on temporal variations, assessment methodology, and site-specific environmental conditions).

5 | Economic and Technical Challenges in Wave Energy Conversion

WECs are devices that capture and transform ocean wave energy into electrical power. WECs draw energy from variations in water pressure beneath the ocean's surface or from the motion of surface waves. The kinetic energy of the surface waves or pressure changes is transformed into electrical energy by means of a generator or PTO device such as attenuators, point absorbers, and

OWCs. Every technology has pros and cons. While terminators and attenuators should be oriented in the direction of the predominant waves, point absorbers, for instance, can produce electricity irrespective of the direction of the waves. Different WEC kinds have different efficiency and physical principles. Based on the local requirements and features of the specific coastal region, including the bathymetry, wave climate, shoreline attributes, and marine life, the best kind for deployment should be chosen for the given place [38, 39]. Numerous studies on the properties and workings of various WECs have been conducted by researchers (Table 2).

5.1 | Reliability and Predictability

Wave energy uses the force of the ocean's waves to create electricity. They employ water's mechanical motion to power energy converters like turbines. Significant energy from wind is carried by ocean waves and is transmitted to the water's surface. Many technologies, including attenuators, point absorbers [40], and OWCs transform this energy into useful electricity. Because of its high energy density and dependability, wave energy is a viable renewable resource. Ocean waves can be predicted with great precision on a day-by-day scale, and this predictability is generally extremely good [11]. It derives from the fact that swells tend to include a significant portion of wave energy after being produced by wind at a remote site and traveling coherently over long distances. Given the wide variety of production sources, loads, and storage needs of the contemporary electrical grid, predictability is an especially alluring feature [41]. Wave energy is gaining popularity worldwide as sustainable energy solutions become more and more important. Wave energy provides a stable and dependable source of electricity, particularly for coastal areas, and is a potential supplement to wind and solar power as nations want to diversify their power portfolios and cut carbon emissions. The necessity to shift to cleaner energy sources globally in order to lessen dependency upon fossil fuels and mitigate environmental effects like greenhouse gas emissions is what is driving its increasing significance [15]. Furthermore, the predictability of wave energy is one of its unique benefits. Ocean waves follow predictable and persistent patterns, unlike other RESs like sun and wind, which are influenced by the fluctuations of the weather. This dependability translates into a steady and reliable electrical supply, which is essential for energy planning and grid stability. Since tides are dependable and predictable, wave energy serves as a potential ocean power source. Electricity can be produced in large quantities by carefully positioning wave turbines in locations with high wave currents. This approach has many benefits, such as job generation potential, dependability, and minimal environmental effects. Successful wave energy harvesting projects have shown the technology's feasibility and scalability, including Scotland's MeyGen project. Taking the energy by ocean waves and turning it into electrical power is known as wave energy conversion. This approach has a lot of potential because waves are a reliable and plentiful energy source. Projects using wave energy have demonstrated encouraging outcomes in terms of both environmental effects and power generation. For instance, Portugal's Pelamis WEC was able to supply thousands of homes with electricity. Wider use, however, requires addressing issues including high upfront costs and the requirement for maintenance in challenging marine settings. Wave generator output is dependent on wave height and period, and

because these factors vary greatly, the power generated by them varies as well. Therefore, reliability is affected in electric networks that use huge wave generators [42]. In many sectors, reliability analysis is a sophisticated statistical method used to forecast installation performance. WECs require reliability evaluations because of the potential for restricted accessibility in the event of maintenance and failure. Reliability factors can be used to adjust these failure rates. Reliability can be estimated using two distinct methods: probabilistic reliability theory and so-called classical reliability theory. Estimating the failure rate of mechanical and electrical components is frequently done using the classical reliability theory, while structural components are typically handled using the probabilistic reliability theory. Together with structural elements, mechanical and electrical components are crucial for WECs. Consequently, it is necessary to integrate both dependability theories into WEC designs, advancements, and enhancements [43, 44]. WECs come in a wide variety today, but their extraction costs are still far higher than those of other established RESs. LCOE, which is the sum of CAPEX, OPEX, and decommissioning cost and AEP, discount factor, and project lifespan, is one of the best measures for estimating the price of producing wave energy. However, there is debate with the LCOE results; therefore, it is crucial to investigate how much wave energy costs using the WEC, looking possible methods to cut costs, and then comparing it to other RESs [45]. Table 4 listed the existing research in the field of WECs.

5.2 | Scalability and Cost-Effectiveness

The kinetic energy which waves create when wind hits the ocean's surface is used in the wave-energy conversion process. This energy source can be successfully integrated into the power grid because of its great regularity and predictability [55]. Wave energy conversion has a bright future despite the difficulties brought on by the adverse marine atmosphere and higher price of these devices. When coupled with encouraging legislation and ongoing research and development, this technology has the potential to be extremely important in the shift to renewable and sustainable energy sources. WECs use water's oscillating motion in a chamber to power air turbines. They are beneficial for commercialization since they are scalable and quick [56]. WECs can be categorized as oscillating body, OWCs, and overtopping devices based on their operating principle. Wave energy is captured by the energy capture device, transformed into mechanical energy, and then transmitted to the PTO for additional electrical energy conversion. Table 5 lists the typical types of WECs [57]. An oscillating body-type WEC produces electricity when wave motion is converted into device oscillations. In order to absorb more energy, certain oscillating WECs are designed with many modes. The OWC system uses specially made air turbines to create wave-induced air pressure inside a chamber. The airflow then drives the turbine connected with an electric generator, enabling the production of electricity [50]. There are three major subcategories according to the primary oscillation mode of the WEC: (1) a heaving body that oscillates vertically due to wave action; (2) an OWSC that revolves about a hinged axis parallel with the wave crests; and (3) an articulated body that is oriented parallel to the direction of the waves and creates relative rotation between neighboring segments. WECs can be divided into three categories according to their size and orientation in relation to the wave front: terminator, attenuator, and point absorber (PA). The PA's dimensions are significantly less

TABLE 4 | Research works in field of WECs.

References	Year	Findings
[46]	2017	To improve the efficiency of the raft-type WEC, a combined hydrodynamic and hydraulic power take-off unit model was proposed. This study also compares the performance of a linear power take-off unit with a hydraulic power take-off unit using this integrated model.
[47]	2024	In a CFD-based simulated wave tank, the controllable-valve buoy (CVB) movement in waves was simulated, and wave energy was converted to electrical energy using a direct-drive WEC. Even in harsh sea conditions, WEC with a CVB can reliably produce electricity and link to the grid, suggesting a great deal of room for growth and use.
[48]	2022	Wave energy converter (WEC) scalability was examined, and the results indicated that while terminators could reach MW scale by employing a high characteristic dimension, point absorber units would have trouble doing so due to their lack of scalability.
[18, 49]	2023	Model-test, numerical, and semianalytical techniques for multipoint absorbers were summarized. The LCOE analysis and control techniques for multipoint absorbers were succinctly reviewed.
[50]	2024	Highlighted significant difficulties in creating and implementing effective PA-WECs. investigated how PA-WEC performance can be enhanced with the incorporation of AI and machine learning.
[9]	2022	The regulation of wave energy power-take-off and controllers for the grid power converters, as well as the performance of wave energy converters in array topologies, were studied.
[51]	2015	A study on the applicability of WECs in various climates came to the conclusion that the primary objective of WEC design should be a structure that is both appropriately sized and highly adaptable to wave climate.
[52]	2020	The study evaluated the effects of wave energy conversion on morpho dynamics and found that it frequently lessens coastal erosion.
[40]	2023	The study included a thorough examination of hybrid MPPT strategies for energy extraction optimization and maximum power point tracking (MPPT) methodologies for wave energy conversion.
[41]	2021	This work outlined a straightforward yet effective method for modeling wave energy dynamics and designing an impedance-matching-based control system. Causal impedance matching feedback controllers are capable of power absorption performance that is nearly at the theoretical limit.
[53]	2024	This research proposes a revolutionary built-in wave energy converter (BIWEC) that may be incorporated with current floating platforms to lower building costs. A broad effective wave frequency capture range and good energy conversion efficiency are demonstrated by the research findings for BIWEC.
[54]	2023	To study the hydrodynamic properties of the system, a hybrid WEC system including an OWC and a point absorber device was introduced. At various wave-numbers, the hybrid scheme that was introduced performs better.

than those of the incoming wave. An attenuator is a device that is parallel to the direction of waves and has a length that is equal to or greater than one wavelength. A terminator is positioned perpendicular to the direction of the waves and has a width that is equal to or greater than the incidence wavelength [48]. Multiple types of WECs and their characteristics are listed in Table 5, and their summary is listed in Table 6.

Figure 9 describes the classification of WECs. In the context of scalability, we are interested in whether the power output will increase as the size of each individual device unit increases. WECs' scalability is complex and varies by kind, in contrast to wind turbines, whose energy absorption rises with turbine diameter. Though the ideal capture width ratio (CWR) can surpass 100%, it is shown that the point absorber (PA) WEC is not scalable and has a small theoretic CW. While the CW shows scalability with increasing device width for terminator as well as length for attenuator WECs, there are 50% and 100% CWR restrictions. The results indicate that the PA unit finds it difficult to reach MW scale because to its lack of scalability, whereas the terminator was

able to do so by utilizing a high characteristic dimension greater than 100 m. In laboratory experiments, up to 80% of hydrodynamic efficiencies have been achieved for the PA OWSCs, suggesting that PA functions more efficiently compared to the terminator and attenuator [48]. Sea waves are less variable than wind energy with an elevated energy density and effective forecasting. This is due to the fact that originally wind-driven waves linger longer as they disperse and spread much beyond the boundaries of the actual storm where they originated. Although wave energy has the potential to increase the penetration of RESs and reduce intermittency, the sector is still in the early stages and has fallen decades behind more established renewables like solar and wind. With over 1000 ideas already patented, there are numerous WEC techniques available today, but none are developed enough to be commercialized. The underlying causes, which translate into high risk for investors, are expensive CAPEX, unsuccessful development projects, and technology limitations [16]. Although WECs like RM5 and RM6 have the capacity to provide electricity, their present economic performance is inferior to that of more well-established

TABLE 5 | Common wave energy converter types their characteristics.

Type	Description	Working principle	Advantages	Examples
Point absorbers	Floating devices that capture energy from the vertical (heave) motion of waves at a single point on the water surface. They are relatively small compared to the wavelength.	A buoy moves up and down with wave motion, driving a power take-off (PTO) system (hydraulic pump or linear generator) that converts mechanical motion into electrical energy.	Omnidirectional energy capture Suitable for deep-water deployment Modular and scalable for arrays	PowerBuoy (USA), Wavebob (Ireland), AquaBuOY (USA)
Oscillating water column	A partially submerged chamber trapping air above the water column; usually built into a shoreline or breakwater.	Incoming waves cause the internal water column to rise and fall, compressing and decompressing the trapped air. The airflow drives a bidirectional turbine (Wells turbine) connected to a generator.	Simple structure, few moving parts Onshore/nearshore construction reduces maintenance Proven, commercialized technology	LIMPET (Scotland)–500 kW, Mutriku (Spain)–296 kW (16 turbines)
Oscillating wave surge converter (OWSC)	Hinged flaps or panels fixed near the seabed in shallow waters (10–20 m depth) that utilize horizontal (surge) motion of waves.	Waves push the flap back and forth. The motion activates hydraulic pistons or mechanical linkages, which power a hydraulic motor or generator to produce electricity.	High efficiency in nearshore conditions Robust in rough seas Suitable for array installation	WaveRoller (Finland), Oyster Device (UK)
Attenuators	Long, jointed floating structures aligned parallel to wave direction that harness energy from bending motion between segments.	Waves cause flexing at the joints; hydraulic or mechanical systems at these joints pressurize fluid to drive generators. Power is transmitted to shore via subsea cables.	Performs well in deep waters Smooth, continuous power output Easily scalable in farms	Pelamis (UK/Portugal), Sea Snake (Pelamis variant)
Overtopping devices	Collect seawater into an elevated reservoir above sea level, using the potential energy of the stored water to generate electricity.	Waves overtop a ramp into the reservoir; water returns to the sea through low-head hydro turbines.	Simple and durable construction Based on proven hydroelectric principle Provides steady output despite wave fluctuations	Wave Dragon (Denmark), TAPCHAN (Norway)
Submerged pressure differential devices	Devices placed below the water surface that exploit pressure variations caused by passing waves.	Changing wave pressure acts on a flexible membrane or buoyant chamber, driving a hydraulic or direct-drive system to produce electricity.	Submerged: minimal visual impact Storm-safe and reliable Ideal for nearshore installation	CETO System (Australia)

TABLE 6 | Comparison summary.

Type	Installation	Wave motion used	Example	Advantage
Point absorber	Offshore	Heave	PowerBuoy	Compact, omnidirectional, simple, few moving parts, efficient in shallow water
Attenuator	Offshore	Flex/Bending	Pelamis	High power output, steady power, durable
Pressure differential	Submerged	Pressure change	CETO	Hidden, storm-resistant

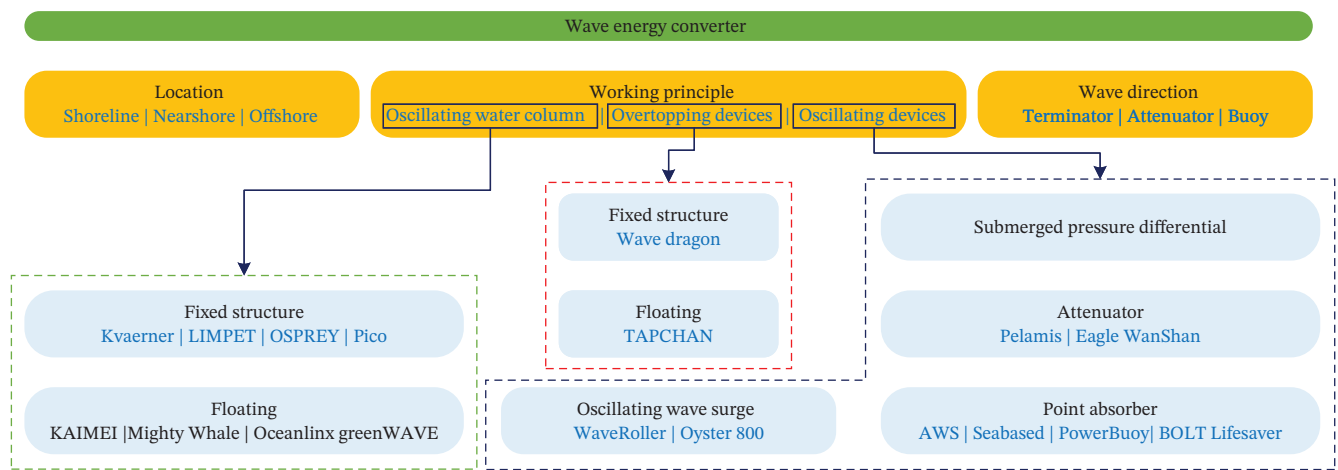


FIGURE 9 | Classification of wave energy converters [56].

renewable technologies like PV solar and wind turbines. Because of their higher LCOE and high initial expenditures, marine energy systems have longer payback times and are therefore less appealing from a short-term financial standpoint. Nonetheless, WECs might grow more competitive in future, especially in coastal areas with abundant wave resources, with further technological developments, cost savings, and supportive incentives for marine energy [15]. High LCOE and CAPEX sometimes interfere with WECs' economic viability. The commercial feasibility of WECs can be greatly increased by implementing several measures to lower these costs, including policy-based incentives and technology breakthroughs. WEC technological developments are essential for cutting expenses and enhancing efficiency. PTO systems are one of the biggest expense drivers, making up between 30% and 50% of the device's entire cost. The total economic feasibility of WEC projects is significantly impacted by the efficiency of PTO systems, which are in charge of transforming mechanical wave energy into electrical energy. It has been demonstrated that innovations like direct-drive PTO systems, that do away with intermediary mechanical components, improve reliability and lower operating losses. This highlights how crucial it is to optimize PTO systems for economical WEC implementation as it could result in an 8%–12% reduction in LCOE [18]. The use of scalable and modular WEC designs is another revolutionary strategy. Modular components increase the cost-effectiveness of production and maintenance procedures by simplifying them. In addition to lowering CAPEX by roughly 10% to 15%, this scalability makes it simpler to integrate WECs into a variety of marine situations. By using prefabricated modular designs, point absorbers have shown notable cost savings while retaining similar energy output. Additionally, this flexibility facilitates simpler component replacement and repair, reducing downtime and guaranteeing steady energy output. Advanced manufacturing processes and materials also help to lower costs and improve the longevity of WECs [15]. Enhancing WEC power absorption requires the use of specialized controllers that can maximize energy extraction from wave resources while minimizing component damage within the confines of device-specific physical limitations. It has been shown that appropriate control technologies can double the energy yield from WECs. A key component of optimizing energy absorption across many WECs is dynamically responding to wave conditions [58–60].

5.3 | Technoeconomic Assessment of Wave Energy Projects: A Literature Review

The commercial deployment of wave energy technologies depends not only on resource availability and technical performance but also on their economic competitiveness relative to established renewable energy technologies. Consequently, technoeconomic assessments have become an essential tool for evaluating the feasibility of WECs and wave farm projects. Several studies have investigated the economic performance of wave energy systems using indicators such as CAPEX, OPEX, AEP, CF, LCOE, net present value (NPV), internal rate of return (IRR), and payback period [20, 21, 61, 62]. Despite significant technological advancements, economic viability remains one of the principal challenges limiting large-scale commercialization of wave energy technologies. A comparison is listed in Table 7. Economic assessments conducted in Portugal demonstrated that wave farms located in high-resource regions can achieve favorable energy yields; however, project viability remains highly sensitive to installation costs, maintenance requirements, financing assumptions, and device reliability. Comparative studies evaluating wave energy against other renewable technologies reported that the current LCOE of wave energy systems remains higher than mature solar photovoltaic and onshore wind technologies due to lower technology readiness levels and elevated deployment costs. Recent research has expanded traditional technoeconomic frameworks by incorporating additional societal and environmental benefits. In particular, dual-purpose wave farms designed for both renewable energy generation and coastal protection have shown improved economic performance when avoided coastal damage costs and shoreline protection benefits are included in the assessment. Such integrated approaches are particularly relevant for coastal regions facing erosion and sea-level-rise challenges. Sensitivity analyses reported in the literature consistently identify CAPEX, CF, device availability, maintenance frequency, discount rate, and grid connection costs as the most influential parameters affecting project feasibility. Furthermore, offshore installation logistics, harsh marine environments, and survivability under extreme sea states continue to contribute significantly to project uncertainty and investment risk. For Saudi Arabia, technoeconomic evaluation is particularly important because the wave climate of the Red Sea and Arabian Gulf is generally moderate compared with Atlantic Ocean locations where most commercial demonstrations have been conducted.

TABLE 7 | Comparison of wave energy technoeconomic studies.

Study	Region	Technology	Capacity factor (%)	Lifetime (years)	LCOE	Main finding
[61]	Coastal regions	Dual-purpose WEC farms	18.34	25	Improved economics when coastal protection benefits included with reduces LCoE from 193 to 115 €/MWh.	Multibenefit projects enhance feasibility. Also wave farm deployment enhanced sediment retention and reduced erosion by up to 50.4% while generating 5623 MWh/year from 10 WaveRoller devices.
[62]	Coastal protection applications	Integrated WEC farms	18.34	10–20	Lower effective LCOE with 49.9% capture efficiency	Coastal protection should be included in valuation
[21]	Portugal	Wave farm	25–35	20–25	Reported competitive performance in high-resource areas with the best value of 316.90 €/MWh	Resource quality strongly affects viability
[20]	Global	Multiple WECs	20–45	20–25	Higher than solar/wind between 471.25 and 709.18 €/MWh	Cost reduction needed for commercialization
This review	Red Sea and Arabian Gulf	Candidate WEC systems	Moderate	20–25	Requires detailed site studies	Strong potential for future deployment

Therefore, future deployment strategies should focus on selecting suitable WEC technologies, optimizing installation locations, reducing maintenance costs, and exploiting synergies with large-scale coastal developments associated with Vision 2030 initiatives such as NEOM and the Red Sea Project. Comprehensive site-specific technoeconomic studies incorporating uncertainty analyses and lifecycle costing will be necessary to establish realistic pathways for commercial wave energy deployment in the Kingdom.

Furthermore, RM3, RM5, and RM6 WECs are suitable for Red Sea coastal area to harvest wave energy. The RM3 device is a heaving buoy equipped with a hydraulic drivetrain and has a diameter of 20 m and a mass of 687 metric tons. It employs a floating foundation with slack mooring, is constructed from A36 steel, and has a rated capacity of 286 kW. The RM5 is an oscillating surge wave converter that also utilizes a hydraulic drivetrain. It has a diameter of 25 m, a mass of 800 metric tons, and is supported by a floating foundation with taut mooring. The device is primarily made of fiberglass and A36 steel and has a rated capacity of 360 kW. The RM6 is a backward bent duct buoy floating oscillating water column system that incorporates a Wells air turbine as its PTO. It has the largest dimensions among the selected WECs, with a diameter of 27 m and a mass of 1809 metric tons. Similar to RM3, it uses a floating foundation with slack mooring, is constructed from A36 steel, and has a rated capacity of 350 kW. Together, these three WECs represent diverse energy conversion technologies, PTO systems, and structural configurations suitable for comparative performance evaluation [15]. Table 8 contains the technical specification and technoeconomic parameters considering RM3, RM4, and RM5.

The commercial feasibility of wave energy depends on achieving a balance between energy production, lifecycle costs, and long-term

operational reliability. Unlike mature renewable technologies such as PV and onshore wind, wave energy systems operate in harsh offshore environments, where installation, maintenance, and survivability requirements significantly increase project costs. Consequently, technoeconomic feasibility is governed by multiple interrelated parameters rather than by the LCOE alone [63]. The literature consistently identifies CAPEX as the dominant economic component of wave energy projects. CAPEX includes the WEC, PTO system, mooring and foundation systems, offshore installation, electrical infrastructure, and grid connection. Among these components, PTO systems may account for ~30%–50% of the total device cost, while offshore installation and mooring systems represent a significant fraction of the remaining investment due to the need for specialized vessels, subsea infrastructure, and challenging marine operations [35]. Operation and maintenance (O&M) costs are also substantially higher than those of solar and wind because of corrosion, biofouling, fatigue loading, accessibility constraints, and survivability requirements under extreme sea states [64]. In addition to engineering costs, project financing plays a critical role in determining economic viability. CF, AEP, project lifetime, discount rate, and device availability strongly influence the resulting LCOE. Studies consistently demonstrate that increasing device reliability and operational availability has a comparable economic impact to reducing initial capital costs because higher AEP lowers the effective cost of electricity throughout the project lifetime. Although wave energy possesses several technical advantages, including high energy density, excellent predictability, and complementary generation profiles with wind and solar resources, it remains less commercially mature than other renewable technologies [65]. This is primarily attributed to the relatively low technology readiness level, limited commercial deployment, absence of large-scale manufacturing, immature supply chains, and reduced opportunities for economies of scale.

TABLE 8 | Comparison of representative WECs and their technoeconomic characteristics.

Parameter	RM3	RM5	RM6
Technical specifications			
WEC type	Heaving buoy	Oscillating surge converter	Backward bent duct buoy
Power take-off (PTO)	Hydraulic drivetrain	Hydraulic drivetrain	Wells air turbine
Rated capacity (kW)	286	360	350
Diameter (m)	20	25	27
Mass (Metric tons)	687	800	1809
Foundation type	Floating	Floating	Floating
Mooring system	Slack mooring	Taut mooring	Slack mooring
Primary structural material	A36 steel	Fiberglass + A36 steel	A36 steel
Technoeconomic characteristics			
Total device cost (USD)	14,953,843	15,808,750	27,249,256
Balance of system (BoS) cost (USD)	10,170,905	9,971,182	10,160,306
Total financial cost (USD)	2,201,779	2,259,195	3,278,345
Annual O&M cost (USD/year)	1,366,374	1,356,698	1,352,679
Total project cost (USD)	27,326,527	28,039,127	40,688,586
Inflation rate (%)	2.5	2.5	2.5
Real discount rate (%)	5.5	5.5	5.5
Nominal discount rate (%)	8.14	8.14	8.14
Income tax (%)	11	11	11
Sales tax (%)	5	5	5
Technoeconomic assessment			
Key strength	Low fabrication complexity	Highest rated capacity	Robust offshore concept
Primary limitation	Lower energy output	Higher structural complexity	Highest CAPEX and installation cost
Potential application	Nearshore deployment	Commercial wave farms	Offshore and hybrid systems

Consequently, investment risks remain comparatively high, resulting in higher financing costs and discount rates than those associated with established renewable technologies [66].

Remark 2. The quantitative resource estimates provided in this review article have been derived from the existing wave resource assessment studies undertaken for the Red Sea and Arabian Gulf. These values are reported here to offer a comparison baseline of the literature available but are not intended to offer a new numerical simulation or site-specific resource calculation. The original study period, data source, and assessment process are specified in the discussion and references [12, 15, 20, 21, 35, 45, 61–72].

5.4 | Grid Integration and System-Level Value of Wave Energy

The utility of wave energy goes beyond electricity generation and will rely on the successful integration of wave energy into the larger power system. Wave generation can sometimes have

different seasonal and diurnal trends as compared to solar PV generation, which operates only during daylight hours, and wind generation, which is very variable in time. Wave power, when combined with solar and wind power, can therefore enhance the overall stability and reliability of renewable electricity generation by minimizing the overall generation variability. Coastal wave energy systems are especially appealing for Saudi Arabia as potential sites are close to major coastal cities, desalination plants, ports, industrial sites, and offshore infrastructure that already have electrical networks. This geographical proximity could make the transmission requirements less than in remote projects in the interior, where there are more RESs. However, further grid hardening, subsea cable infrastructure, and more flexibility in operation will likely be necessary for commercialization to take place, to cater for variable renewable generation.

Another important consideration is renewable energy curtailment. In times of strong renewables supply and low demand, there may be curtailment if there is not enough storage or

transmission capacity. Hybrid renewable energy systems combining wave, PV, wind, and battery storage are a promising solution for reducing the curtailment and improving the system utilization. Moreover, integration of wave energy with desalination plant or hydrogen production helps make the electricity demand variable to accommodate excess renewable energy generation and enhances the value of the wave energy projects, thus helping to achieve Saudi Arabia's energy diversification and decarbonization goals in the long term. A quantitative comparison among multiple renewable energy resources is listed in Table 9

[11, 15, 67]. Furthermore, a conceptual framework integrating renewable energy generations is illustrated in Figure 10.

6 | Environmental Benefits of WECs

In the energy industry, sustainability emerged as the top priority. The fields of innovation and energy production have lofty objectives and are highly ambitious. Additionally, their primary objective with renewables is to completely rely on clean renewable resources in

TABLE 9 | Quantitative comparison of system-level integration characteristics of wave energy with other renewable energy sources.

Parameter	Wave energy	Solar PV	Wind energy
Forecast horizon accuracy	24–72 h	6–24 h	6–24 h
Capacity factor (%)	20–45	18–30	30–45
Grid connection distance (km)	5–30	10–100	20–100
Energy availability (%)	Up to 90	20–30	25–45
Energy density (kW/m ²)	2–3	0.1–0.2	0.4–0.6
Typical curtailment risk	Low–moderate	High (midday peaks)	Moderate–high
Generation complementarity	High	Daytime only	Seasonal/Weather dependent
Transmission requirement	Medium	High	High
Energy storage requirement	Low–moderate	High	Moderate–high
Grid balancing requirement	Low	High	Moderate
Power output variability	Low–moderate	High	Moderate–high
Typical grid connection	Nearshore/offshore	Land	Land/offshore
Grid integration cost	Moderate	High	Moderate
Storage requirement	Moderate	High	Moderate
Levelized value of energy (LVoE)	High	Moderate	Moderate
Renewable complementarity index	High	Medium	Medium

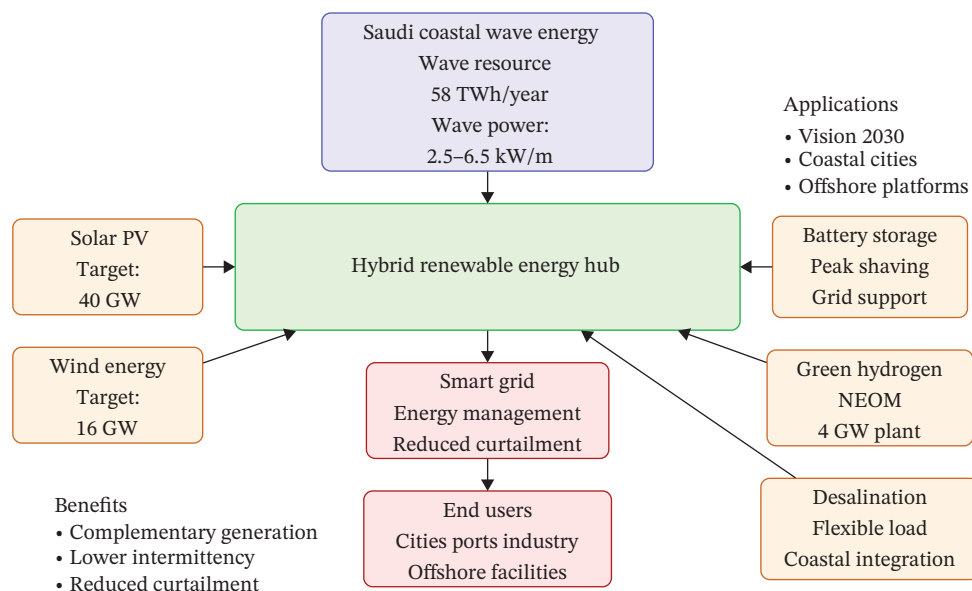


FIGURE 10 | Conceptual framework illustrating the integration of Saudi Arabia's coastal wave energy resource with solar PV, wind energy, battery storage, green hydrogen production, and desalination facilities through a hybrid renewable energy hub [11, 15, 67, 68].

order to achieve zero net carbon emissions. These days, the majority of electrification is based on dirty energy, which perpetuates the myth that electricity is bad for the environment. However, numerous instances demonstrate the adverse effects of electrification through the use of carbon-releasing energy. This assertion is not totally accurate; according to game theory, electrification can coexist with net-zero carbon emissions and produce a win-win situation. The IEA predicts that until 2026, the capacity of renewable energy will increase by greater than 1800 GW. Approximately 95% of the total increase in global power capacity is anticipated to come from this increase in renewable capacity. These high energy levels and energy growth projections are a sign of the significant effects that will lead to the electrification objectives by considering the benefit of a harmless environment in reaching a net zero carbon goal, which will improve all aspects of global warming and pollution, as well as to reach even more significant environmental milestones like a sustainable ecosystem and the achievement of high-quality constructions, life, and mobility. When compared to conventional fossil fuel-based power generation, the WEC's environmental impact from ocean wave energy conversion is extremely encouraging. Because point absorbers have few moving parts and require little maintenance, their lifetime can have a favorable effect on their overall environmental impact. Wave energy's advantages for the environment are just as strong as its capacity to produce electricity. In sharp contrast to the damaging history of fossil fuels, wave energy generation is an environmentally friendly resource that produces no greenhouse gas emissions or waste byproducts. Often buried beneath the water's surface or blending in perfectly with the maritime environment, the infrastructure needed to fully utilize wave energy is made to have as little visual impact as possible. Because WECs blend in so well with the marine environment, they usually have a minimal environmental impact. Wave energy devices are also known for their quiet and discreet operation, which prevents any disturbance to the tranquil atmosphere of the ocean. Because of these characteristics, wave energy is among the most environmentally friendly methods of producing electricity that are currently accessible. We can protect the ocean's inherent beauty and peace while also utilizing an endless and sustainable energy source by utilizing the power of the waves. When wave power is properly positioned, deployed, operated, maintained, and decommissioned, it has the potential to be among the most environmentally friendly electrical generation technologies. It is expected that wave power projects will involve field research and coordination with federal, state, and municipal entities. Environmental benefits from establishing WECs could include creating fishing exclusion zones that would allow endangered fish populations to recover.

7 | Critical Synthesis of Existing Studies and Research Gaps

The review of the existing literature [45, 69–71] reveals broad agreement that wave energy represents a promising renewable resource capable of contributing to future low-carbon energy systems. Most studies agree that wave energy possesses higher energy density and greater predictability than several other renewable resources, particularly when compared with solar and wind systems. Similarly, there is consensus that WECs have demonstrated technical feasibility under controlled experimental and pilot-scale conditions. Despite these common findings, significant differences exist among previous studies regarding resource estimation, technology

performance, and economic feasibility. Resource assessments often employ different methodologies, including satellite observations, numerical wave models, buoy measurements, and hindcast datasets. Consequently, estimated wave power densities can vary considerably for the same geographical region, introducing uncertainty into AEP calculations and subsequent economic evaluations.

From a technoeconomic perspective, nearly all studies identify CAPEX as the dominant factor affecting project viability. However, considerable variation exists in the assumptions used for maintenance costs, project lifetime, discount rates, device availability, and CFs. As a result, reported LCOE values differ substantially across studies. This variability highlights the importance of standardized technoeconomic assessment methodologies and sensitivity analyses when comparing different wave energy projects. Another important observation is that many studies focus primarily on European and Atlantic Ocean deployment environments, where wave resources are considerably stronger than those observed in the Red Sea and Arabian Gulf. Consequently, the direct transfer of performance and economic results to Saudi Arabia may not be appropriate without adjustment for local environmental conditions. High salinity, elevated temperatures, biofouling, sediment transport, and limited regional operational experience may significantly affect long-term device reliability and maintenance requirements.

Furthermore, the uncertainty associated with reliability and survivability remains one of the major obstacles to commercial deployment. Although several WEC technologies have demonstrated encouraging performance during pilot projects, long-term operational data remain limited. Failures associated with harsh marine environments continue to increase project risk and contribute to elevated maintenance costs. In literature, the primary barriers to large-scale deployment can be grouped into four categories:

1. High capital and maintenance costs.
2. Limited long-term reliability and survivability data.
3. Uncertainty in resource assessment and energy yield predictions.
4. Lack of dedicated regulatory and investment frameworks for marine renewable energy technologies.

Therefore, future research should prioritize site-specific technoeconomic assessments, long-term reliability testing under local environmental conditions, standardized economic evaluation methodologies, hybrid renewable energy integration strategies, and pilot-scale demonstrations along the Saudi coastline. Addressing these challenges will be essential for reducing uncertainty and establishing commercially viable wave energy projects capable of supporting Saudi Arabia's renewable energy transition. Table 10 summarizes the critical synthesis of findings, uncertainties, and research gaps.

8 | Knowledge Gaps and Future Research Directions

Although significant progress has been achieved in wave energy research over the last two decades, several critical knowledge gaps

TABLE 10 | Critical synthesis of findings, uncertainties, and research gaps identified in the reviewed literature.

Aspect	Areas of agreement	Areas of uncertainty or disagreement	Implications for Saudi Arabia
Wave resource assessment	Moderate to high wave potential exists in selected coastal regions	Different datasets and modeling approaches produce varying estimates	Need for long-term high-resolution resource assessment
WEC Technologies	Technical feasibility has been demonstrated for multiple technologies	No consensus on the optimal WEC technology for commercial deployment	Technology selection must be site-specific
Economic feasibility	CAPEX and OPEX strongly influence project viability	Large variation in LCOE estimates and economic assumptions	Saudi-specific technoeconomic assessment required
Reliability and survivability	Marine environment significantly affects system performance	Limited long-term operational data available	Local testing under Red Sea and Arabian Gulf conditions necessary
Environmental impacts	Generally lower emissions than fossil-fuel systems	Limited regional environmental assessments available	Need for ecological impact studies before deployment
Commercial deployment	Pilot-scale projects demonstrate potential feasibility	Commercial-scale success remains limited globally	Phased demonstration projects are recommended

continue to limit large-scale commercial deployment. A review of the existing literature reveals substantial variations in resource assessment methodologies, technoeconomic assumptions, and technology performance metrics, making direct comparisons among studies challenging. One of the primary sources of uncertainty originates from wave resource characterization. Different studies employ satellite observations, buoy measurements, numerical wave models, and hindcast datasets, often resulting in variations in estimated wave power densities and AEP. Consequently, the reliability of resource assessments remains strongly dependent on data availability, temporal coverage, and model resolution. Similarly, considerable uncertainty exists in technoeconomic analyses. While CAPEX and OPEX are consistently identified as dominant economic factors, the reported values vary substantially among studies due to differences in technology maturity, deployment scale, maintenance strategies, project lifetime assumptions, and discount rates. As a result, LCOE estimates reported in the literature span a wide range, highlighting the need for standardized assessment frameworks.

The review also confirms that there is no single technology which is optimal for all WECs. While point absorbers typically have higher hydrodynamic efficiency and modularity, OWCs have simpler structure and lower maintenance needs. However, the performance of the technology is still very site-specific, and long-term reliability information in extreme environments is still limited. In the case of Saudi Arabia, further problems include salinity, high temperatures, biofouling, sediment transport, and a lack of operational experience with marine renewable energy systems. The Red Sea, in comparison, has more of a wave resource than the Arabian Gulf; however, detailed site-specific feasibility studies are required prior to commercial deployment in both areas. R&D directions for future research will be highlighted as,

1. High-resolution wave resource mapping using long-term observational and numerical datasets.
2. Site-specific technoeconomic feasibility studies for major coastal locations.

3. Reliability and survivability assessment of WEC technologies under Red Sea and Arabian Gulf environmental conditions.
4. Development of hybrid renewable energy systems integrating wave, solar, and wind resources.
5. Advanced uncertainty and sensitivity analyses to identify critical economic risk factors.
6. Pilot-scale demonstration projects to validate performance and maintenance requirements under local operating conditions.
7. Development of regulatory frameworks and investment incentives supporting marine renewable energy deployment.

Addressing these research gaps will be essential for establishing a technically reliable and economically viable wave energy sector capable of contributing to Saudi Arabia's long-term renewable energy and sustainability objectives.

9 | Selection of Suitable WECs for Saudi Arabian Coastal Conditions

The choice of an adequate WEC is very context-sensitive and can be determined by local wave climates, bathymetry, coastal facilities, and operational needs. The Red Sea and Arabian Gulf have moderate wave power, low mean wave heights, and short wave periods in general, whereas the high-energy Atlantic coastlines have resulted in good performance with large attenuators and floating devices. Therefore, selection of technology should focus on those that can operate under moderate wave climates with a low installation and maintenance cost. One of the most promising technologies for Saudi Arabian waters is the point absorber, which has a modular design, can harvest energy in all directions, and installation is relatively easy. They are small enough to be deployed in medium wave climates and can be phased expanded to larger sizes using array configurations. Likewise, the RM6

type, known as OWCs, are well suited for integration in the existing coastal infrastructure, such as breakwaters, ports, and seawalls, which offer at the same time coastal protection and generation of renewable energy. In addition, overtopping devices are another option that is attractive because they can be combined with rubble-mound breakwaters and shoreline protection structures. Recent studies have proven that overtopping WECs can also provide coastal protection from wave run-up as well as generate electricity, leading to dual-purpose effectiveness and consequently a decrease in the effective LCOE [72, 73]. Such systems are particularly attractive for Saudi Arabia, where large investments are being made in coastal infrastructure associated with Vision 2030 developments.

On the other hand, RM5 are example of OWSCs that may also provide favorable performance in shallow nearshore waters where moderate wave climates dominate. Their seabed-mounted configuration reduces visual impact and facilitates maintenance compared with floating offshore systems. In contrast, large attenuator-type devices are generally optimized for energetic Atlantic wave climates and therefore may not achieve comparable economic performance under the moderate wave conditions of the Red Sea and Arabian Gulf. Considering the regional wave climate, extensive desalination infrastructure, expanding ports, offshore industrial facilities, and coastal mega projects, hybrid deployment strategies integrating WECs with solar photovoltaic, offshore wind, and desalination systems represent one of the most promising pathways for future commercialization [74]. Such integrated systems can improve overall renewable energy utilization while increasing energy security and reducing dependence on fossil-fuel-based electricity generation. A selection of WEC technology according to Saudi Arabia wave climate is illustrated in Figure 11.

10 | Case Studies and Applications

Many developed nations today prioritize producing electricity from safe, clean, and sustainable energy sources in order to fulfill rising energy demand and lower CO₂ emissions. Surface ocean waves are a very promising renewable resource that might produce a significant amount of clean energy. Research has shown that it is potentially beneficial to use all techniques available to

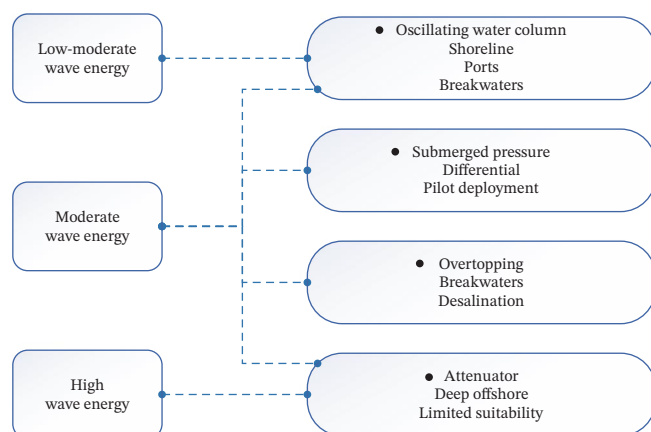


FIGURE 11 | Selection of representative WEC technologies for Saudi Arabian coastal environments.

obtain energy from water. The fact that some regions in the world are ready to adopt these kinds of technologies makes this feasible. The six categories of plants that can take use of the oceans that we have examined till now are waves, tides, salt gradients, ocean currents, and ocean thermal energy conversion. Sea wave is one of these that has the most promise for the future. According to current international assessments, the overall estimated wave energy capacity is ~32 PWh/year, which is higher than the global displacement rate. Researchers expect that sea waves will be sufficient to cover a sizable portion of this amount, which is equivalent to the annual energy requirement of electricity [13]. Numerous installations of wave energy systems with a range of capacities and performances have been made throughout the world. Located at the Portugal coast, Pelamis WEC is one prominent example. One of the earliest wave power plants on a commercial basis, it has a 750 kW capacity. Mutriku Wave Power Plant (300 kW) operating in Spain is another notable project that has been in service since 2011. This plant, with its OWCs, uses the sea's oscillations to create more than just electricity. It is a symbol of sustainable progress. These columns function as lungs, transforming kinetic energy into electrical power as they breathe in and out with the waves. It sets the standard for upcoming wave energy projects and is a proud example of Spain's and Europe's larger commitment to utilizing renewable energy. The MeyGen Project in Scotland adds 6 MW to the grid by combining wave energy. Wave energy's promise as a practical renewable energy source is demonstrated by these facilities. The Sihwa Lake tidal Power Station in South Korea is one of the biggest tidal power plants globally, supplying thousands of families with clean electricity. The Wave Hub project, located in Cornwall, UK, is another example. It is a testing ground for various wave energy technologies [15]. At Sotenäs, Sweden built one of the biggest commercial wave energy systems in the world, which has 42 devices and generates 1.05 MW of power. Ghjana also saw the installation of another project that had six 400 kW devices. These measures were later implemented by the Norwegian government. Considerable work was done in 1985 to construct two real-size converters with rated powers of 350 kW and 500 kW on the coast close to Bergen, Norway. The most noteworthy accomplishment of this era is a small-scale OWC constructed on Islay, Scotland, in 1991. Around the same period, two OWCs were installed in Asia: a 125 kW bottom-standing power plant in Trivandrum, India, and a 60 kW converter with a breakwater in the port of Sakata, Japan [75]. The development of ocean energy and its possible influence on conventional energy systems are illustrated by these case studies. Saudi Arabia's vast Red Sea and Arabian Gulf coastlines offer substantial wave energy possibilities. By 2032, the power consumption of Saudi Arabia is expected to surpass 120 GW, and according to KAUST resources, the country serves as one of the most driven and committed countries to meet the goal of renewable power production. Saudi Vision 2030 establishes sustainable and renewable energy projects to reduce the consumption of liquid fuel while achieving 9.5 GW of cleaner and sustainable energy through natural gas and RESs by 2030. Average wave power density of the Arabian Gulf coast is 5–25 kW/m per year, whereas the Red Sea coast has an average wave power density of 2.5–20 kW/m per year. Wave traits, marine environment, and economic viability are some of the elements that determine which wave energy technology is most suited for Saudi Arabia. While attenuators and overtopping devices are better suited for the Arabian Gulf, OWCs and point absorbers are thought to be appropriate technology for the Red Sea. Thus, Saudi Arabia has a lot of potential for

the development of marine energy, especially in the area of wave energy. However, the environmental effects, technological viability, and economic feasibility must all be carefully considered before implementing marine energy technology in the nation [11]. Significant infrastructure development is needed for the implementation of marine energy technology, including the building of subsea cables, onshore facilities, and wave energy-generating devices. Major improvements to the current infrastructure are also necessary for the integration of maritime energy with the national grid. In recent years, Saudi Arabia has expanded its networks for transmission and distribution, among other major investments in its electricity infrastructure. To incorporate marine energy to the grid, more funding is necessary. For marine energy to be successfully deployed in Saudi Arabia, appropriate marine energy technologies that take into account the local wave characteristics must be developed.

11 | Conclusion

This review critically evaluated the technical, environmental, and technoeconomic feasibility of wave energy harvesting for coastal power generation in Saudi Arabia. The main focus is on harvesting energy from the Red Sea and Arabian Gulf coastlines. The review finding reveals that wave resources in Saudi Arabia are more moderate than those in traditional high-energy wave areas like Atlantic Ocean; however, the Red Sea has wave characteristics which are favorable for certain wave energy applications. Comparative analysis shows that the suitability for use of WECs is largely a function of local wave climate, coastal infrastructure, and technoeconomic factors. Point absorbers, OWCs, OWSCs, and overtopping devices were found to be the most appropriate technologies for the coastal environment in Saudi Arabia integration with ports, breakwaters, desalination plants, and hybrid renewable energy systems. The major factors which influence the commercial viability of wave energy are identified in the technoeconomic review as CAPEX, OPEX, device reliability, CF, technology maturity, and LCOE. For Saudi Arabian coastal deployment, representative WECs could achieve CFs of 18%–35%, project lifetimes of 20–25 years, CAPEX of USD 27.3–40.7 million, and LCOE values of 131–536 \$/MWh. Additionally, this review also suggests that although the technologies under development are currently less economically competitive than solar and wind technologies, their future potential remains significant. The integration of hybrid renewable energy systems, dual-use coastal protection, site-specific selection, and optimized deployment of WECs can substantially enhance the economic competitiveness of these technologies. Overall, the conclusions of this review indicate that wave energy is currently not an alternative source of energy for current energy technologies in Saudi Arabia. Instead, it is a complementary renewable energy resource with significant potential to be implemented at the pilot scale, integrated into coastal infrastructure, and applied to niche applications where moderate wave resources, energy security, and multifunctional benefits are useful to enhance project feasibility. The detailed synthesis included in this review can guide the development of future technologies, the formulation of policies, and technoeconomic assessments of specific sites to support the Kingdom's Vision 2030 renewable energy goals. Phased commercialization strategies, development of supply chain, offshore installation logistics, and investigation of local manufacturing capability to support large-scale deployment of

the technologies of WECs will be investigated and implemented in the laboratory scale for real-time investigation and implementation in future works.

Nomenclature

AEP:	Annual energy production
CAPEX:	capital expenditure
CCS:	Carbon capture and storage
CF:	Capacity factor
CSP:	Concentrated solar power
GCC:	Gulf Cooperation Council
GHG:	Greenhouse gas
EA:	International Energy Agency
IRR:	Internal rate of return
LCOE:	Levelized cost of energy
NPV:	Net present value
OPEX:	Operational expenditure
OWC:	Oscillating water column
OWSC:	Oscillating wave surge converter
PTO:	Power take-off
PV:	Photovoltaic
RES:	Renewable energy sources
SLR:	Sea-level rise
TRL:	Technology readiness level
WEC:	Wave energy converter

Symbols

H_s :	Significant wave height
T_e :	Energy period
T_m :	Mean wave period
T_p :	Peak wave period.

Author Contributions

Hasnain Ahmad: writing – original draft, conceptualization, methodology, writing – review and editing, data curation, formal analysis. **Muhammad Ahmad:** writing – original draft, project administration, validation, methodology. **Muhammad Majid Gulzar:** writing – review and editing, supervision. **Md. Shafiullah:** writing – review and editing, supervision. **M. M. R. Ahmed:** writing – review and editing, supervision.

Acknowledgments

The authors express their profound gratitude to the Interdisciplinary Research Center for Sustainable Energy Systems (IRC-SES) and King Fahd University of Petroleum and Minerals for their unwavering support. The provision of administrative, technical, and financial resources has been indispensable to the advancement of our research activities.

Funding

No funding was received for this review paper.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Authors elect to not share data.

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