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Lifecycle analysis of marine renewable energy infrastructures: Sustainable futures

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ABSTRACT

Marine renewable energy (MRE) infrastructures offer significant potential to address global energy needs and mitigate climate change, yet they currently contribute only a small portion of electricity production. The growing reliance on non-renewable resources increases CO_2 emissions, necessitating a shift toward sustainable future solutions. While MRE infrastructures present opportunities for sustainable development, they face interdisciplinary challenges, including high costs, technological barriers, environmental impacts, and governance issues. This review focuses on lifecycle assessments of MRE infrastructures, aiming to reduce their ecological footprint and inform decision-makers. Key challenges include the need for advanced materials, improved resource assessments, and stronger regulatory frameworks. Future collaborative efforts between researchers, policymakers, and industry stakeholders are essential for overcoming these barriers and unlocking the full potential of MRE infrastructures for sustainable energy.

1. Introduction

The Earth's surface is primarily covered by oceans, which account for 71 % of its total area. Additionally, about 40 % of the global population lives within 100 km of the coastline. Coastal zones play a critical role in the global economy, contributing to 70 % of economic activity, with over 80 % of international trade passing through these regions [1]. Traditional ocean-based industries include fishing, tourism, and marine transportation, while emerging sectors such as marine biotechnology, deep-sea mining, aquaculture, and MRE infrastructures are gaining prominence. Tavakoli et al. reviewed the progress and future research directions in ocean engineering, identifying six key research areas: ocean hydrodynamics, risk assessment and safety, ocean climate and geophysics, data and modeling, control and automation, structural engineering for the sea, and MRE infrastructures [2]. Olabi examined sustainable energy sources to promote environmental development and protection [3]. While considerable progress has been made, further research and development (R&D) are essential to addressing energy challenges and reducing harmful emissions to ensure the long-term sustainability of both nature and ecosystems. One of the major challenges of the 21st century is the development of innovative technologies to extract renewable energy. The UN's *sustainable development goals* for the 2030 agenda emphasize this need, with goal-7 focusing on "ensuring affordable and clean energy" and goal-13 calling for "urgent action to combat climate change."

1.1. Renewable energy

Renewable energy is natural resource-based for carbon neutrality. MRE infrastructures are a burgeoning sector that promises to address climate change by providing a clean and sustainable energy source. By curbing greenhouse gas emissions and diverting the energy industry towards a sustainable path, MRE infrastructures have the potential to play a crucial part in climate change mitigation. MRE infrastructures engineering includes power production, distribution, storage, and utilization. Its applications lie in the environment, society, economy, and policy. Renewable energy is harvested through solar, wind, wave, tidal, geothermal, biofuel, and biomass. Such harnessed energy contributes a low-carbon, sustainable source for national grids and remote uses. As a result, it helps to reduce the impact of climate change. However, there are apprehensions about the potential effects of MRE devices and systems on some aspects of the marine ecosystem [4]. Dey et al. presented an overview of renewable energy in India: its current state and prospects in technological advancement and environmentally conscious growth [5]. They pointed out that sustainability is appropriate when managing environmental resources, and their consumption has a minimum

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negative impact on human health. The cost of producing renewable energy is lower than non-renewable energy. Owusu et al. reviewed the analysis of sustainable energy, renewable power, and climate change adaptation [6]. Their findings suggest that the correlation between global decarbonization and decreased reliance on fossil fuels is closely tied to the worldwide diversification of national energy portfolios to mitigate the impacts of climate change. The ocean energy system's executive committee in Portugal presented an annual report on the overview of ocean energy activities in 2019 [7]. The committee conducted several steps last year in different countries to encourage the industrialization of the MRE industry, especially for the MRE devices that harvest energy from the ocean dynamics. Copping et al. investigated the possibility of animal collisions with turbine blades, which is one of the environmental impacts of MRE [8]. They discovered substantial ambiguity concerning the potential for big animals to become entangled in the mooring lines and cables linked to MRE devices.

Pelc et al. studied the growing concern over the threat of global climate change regarding renewable energy from ocean sources [9]. They mentioned that marine energy resources, like thermal, wave, tidal, and wind, offer potential solutions to global climate change. Despite being a valuable energy resource, ocean waves are underutilized due to challenges and limitations in maximizing their potential in the worldwide energy mix. However, the marine environment must be protected, and projects should be sited and scaled appropriately, adhering to environmental guidelines. Wiess et al. demonstrated climate change effects on marine renewable energy resources and environmental conditions for offshore aquaculture in Europe [10]. They estimated that climate change does not directly affect the geographic distribution of potential energy sector regions (wind and wave-based); hence, they do not threaten this Infrastructure. However, long-term environmental changes may demand adaptation in aquaculture and exploitation areas. Girgibo discusses seashore renewable energy resources to provide context for utilizing climate change effects to support shallow geothermal-energy (seaside energy solutions) generation [11]. They found that REIs can be employed efficiently for regional development by exploiting the effects of climate change. Drew et al. introduced the general status of wave energy and evaluated the device types that represent current wave WEC technology, mainly focusing on work undertaken within the United Kingdom [12].

According to their analysis, compared to solar (0.1–0.2 kW/m^2) and wind (0.4–0.6 kW/m^2), the power density of wave energy is significantly higher at 2–3 kW/m^2. The following scale-based categorization of wave energy sources is helpful to highlight: (i) wind-sea waves, which are caused by nearby winds and have periods of 2–5 s or, more precisely, 8 s; (ii) swells, which are caused by far away storms and have periods of 10–20 s; and (iii) tides, which have periods of around 12 h or 24 h. The energy scales and time constants of many waves vary significantly from one another. Effective wave energy harvesting requires several wave energy converter technologies [13]. Hooper et al. investigated how the deployment of floating solar photovoltaic installations is progressing, with varied designs appearing in various marine situations [14]. They concluded that the potential detrimental effects of any installation on marine life must be thoroughly studied, especially in fragile habitats like coral reefs and seagrass. Interactions with other marine users and the elements influencing public perception must be considered early in the project design process.

1.2. Marine renewable energy infrastructures

The oceans possess a wealth of resources of marine habitats, energy, minerals, medicine, water, and space. The demand extends human activity from the continental shelf's coastal areas and shallow waters to deep oceans and polar regions. Moreover, the oceans are becoming increasingly indispensable in national political and economic plans. Various marine infrastructures exist in multiple domains. These infrastructures facilitate the usage of ocean space, the exploitation of resources, and the recovery of energy. REIs are essential for promoting sustainable economic development and ensuring maritime military security. The infrastructures encompass seaports, artificial islands, coastal defense buildings, oil and gas platforms, offshore solar, wind, wave/tidal power installations, maricultural pastures, cross-sea bridges, and subsea tunnels [15]. These large, costly infrastructures function in intricate and challenging situations. Economic losses and environmental degradation can result from the failures and instabilities of marine REIs.

Nebot et al. investigated tourism development challenges for the future of ports [16]. Synergic human activities in the marine environment necessitate extensive maritime Infrastructure, potentially leading to multiple negative impacts. Komyakova et al. explored the literature on the ecological impact that is associated with marine Infrastructure, conceptualizing the notion of correlative, interactive, and cumulative effects of anthropogenic activities on the marine environment [17]. They evaluated eco-dynamic development as a crucial approach in the marine sector, integrating economic aspects with ecosystem dynamics. Its development within different governance settings is based on actors, rules, resource division, and discourse sets that foster economic growth. Korbee et al. demonstrated that eco-dynamic development and design is an innovative approach to integrating the financial aspects of port development projects with the dynamics of marine ecosystems [18]. Marine Infrastructure, including platforms, subsea structures, pipelines, moorings, and power cables, is crucial for offshore energy and communication systems. Designing these structures presents unique challenges, often conflicting with water depth and calculated risk factors. The Corporation employs specialists who collaborate with and advise governments and commercial sector clients on essential earth sciences and environmental sustainability issues.

WSP's professionals advise on various topics, including clean air, water, land, biodiversity, green energy, climate change, and environmental, social, and governance challenges [19]. Offshore oil/gas and REIs platforms use plastics to protect against seawater corrosion, but current literature is limited to sea surface environments, requiring a model for subsea degradation. Oluwoye et al. compiled pertinent papers on the degradation of plastics and synthetic polymers in marine environments to get insight into what happens to these materials when left in subsea circumstances [20]. They proposed a novel mathematical model that considers numerous physicochemical changes in the maritime environment as a function of depth to estimate the lifespan of synthetic plastics and the potential development of plastic debris, such as microplastics. Barron et al. studied the critical Infrastructure needed for ocean research and society in 2030 [21]. They conceptualized that marine infrastructure research serves as best practice guidelines by promoting training, offering open access platforms for experiment planning, and sharing documentation and resources.

Bhuiyan et al. reviewed the economic feasibility of MRE. Five major continents are at different development stages of implementing MRE commercialization; Europe is the most advanced, while Africa is in the initial stage. The levelized energy cost is usually used to make decisions and measure the plant's economic feasibility [22]. Low initial investment costs and high capacity factors are necessary for tidal energy projects to be profitable. Most tidal flows worldwide don't move fast enough to power a commercial-scale turbine that uses ocean thermal energy. The cost of offshore wind technology and wind-based MRE prevents its widespread adoption. Considering the superior quality of offshore wind resources, the land scarcity, and the more significant accessible areas in the ocean, investing more in R&D on offshore wind MRE infrastructures and increasing market share is recommended. Although offshore wind energy is more expensive during the asset's lifetime due to higher engineering and licensing costs, higher equipment costs, and a rougher sea surface, it is still economically viable. More research and development, government funding, and feed-in tariffs are necessary for offshore wind MRE infrastructures to become commercially viable. In the years to come, it will be feasible thanks to developments in hydrodynamics, engineering, and operational R&D [22].

This essay evaluates the immediate requirements and technological difficulties in building offshore buildings to provide insights into the future exploitation of the ocean in engineering applications.

1.3. Harsh ocean environments

Wind, waves, currents, and sea ice continuously impact offshore engineering installations, necessitating strong and durable primary structures. Additionally, unforeseen phenomena like earthquakes and tsunamis damage marine infrastructures. Marine infrastructures vary in structure based on water depth and oceanic conditions. Safety assessment requirements for marine REIs are challenging to standardize because building and service activities pose significant risks. The global ocean governance framework is incomplete, with each country handling ocean resource development independently. Scientific progress and ecological conservation are still missing. The primary issue of tidal and river turbines is the possibility of animals sustaining injuries or fatalities due to collisions with moving blades. Additional hazards related to the operation of MRE devices encompass the possibility of turbines and wave energy converters causing disturbances in underwater noise emissions, the creation of electromagnetic fields, alterations in benthic and pelagic habitats, modifications in oceanographic processes, and the entanglement of large marine animals [8]. Li et al. introduced the state-of-art development status of offshore wind energy technology worldwide and then comprehensively analyzed the advantages and constraints of the technology [23]. They concluded that the wind energy conversion system can be land-based or offshore, depending on the installation site. In addition, offshore started later than land-based wind energy technology, but its benefits in wind energy, low wind shear, high power production, and low land occupation rate have garnered attention.

Lee et al. studied the challenges and opportunities related to the blue economy and the United Nations' sustainable development goals [24]. The absence of systematic and rational marine spatial planning has failed to effectively resolve conflicts arising from the development of ocean resources, the conservation of ecological environments, and the clash between short-term economic objectives and long-term living conditions. Modern ocean technology and equipment cannot handle the severe climate and high-risk problems of deep water. It is imperative to promptly enhance public knowledge of the ocean, advance engineering technology through innovation, improve development concepts, create new technologies and equipment, and assist in expanding ocean-related businesses. Boosting scientific development and using ocean resources is crucial for equitable and sustainable blue economic conditions.

The Environmental Protection Agency (EPA) of America briefly explained the effects of climate change on the ocean and marine resources [25]. According to them, the seas' natural environment and sustainable development are at risk due to global climate change and human activities related to the marine ecosystem. Climate change, which encompasses phenomena such as warming, acidification, and low oxygen levels, presents significant dangers to the exploitation and utilization of the ocean. These dangers include the exacerbation of marine pollution and its resulting secondary disasters, the disruption of aquatic ecosystems, and the escalation in the intensity and frequency of extreme sea conditions. The United Nations Assembly convened the conference on the open-ended informal consultative process on oceans and the law of the sea [26]. Global warming is projected to escalate high-intensity storms, perhaps resulting in more frequent and severe destruction caused by abnormal water levels, such as storm surges. Coastal communities are increasingly at risk of floods and beach erosion due to rising sea levels, associated saltwater intrusion, and water pollution. Extreme sea conditions are becoming increasingly common, which poses risks to offshore engineering installations, coastal Infrastructure, and the environment [7].

Energy efficiency, environmental friendliness, and long-term viability are all areas where current ocean exploration systems fall short [6]. A European Union program demonstrated cases of securing human lives and assets in a harsh ocean environment [27]. They concluded that long-term wind data are needed to calculate a structure's forces and predict its lifespan. Predictions and assessments are required to determine a structure's remaining lifetime and plan inspections and routine repairs of recognized weak points. Grech et al. investigated wave energy production in Malta, a small Mediterranean archipelago with wave heights of 0–5.5 m [28]. They examined wave and tidal energy harnessing zones, which are dangerous and difficult to maneuver, making equipment installation challenging and causing harm. About 30 tidal and 45 wave energy firms are technologically advanced. The most significant obstacles for these enterprises are ocean conditions [29]. An expeditious implementation of an efficient, secure, stable, and ecologically advantageous marine development paradigm and framework is urgently required [30]. Prioritizing developing, maintaining, and replacing ocean research infrastructure to maximize its benefits, considering its usefulness, affordability, efficiency, longevity, and potential contributions are the requirements of the present time.

The global transition toward sustainable energy is urgent as the reliance on non-renewable resources continues to drive climate change. MRE infrastructures, including offshore wind, tidal, and wave energy systems, present an emerging solution to this challenge. Despite their significant potential, the contribution of these infrastructures to global electricity production remains minimal, primarily due to technological, economic, and environmental barriers. The structure of this review is as follows: *Section 1* introduces the current topic. *Section 2* provides an account of the difficulties and recent advancements in the use of marine renewable energy infrastructures. *Section 3* expands on the pressing need and potential of LCA for the MRE infrastructures; *Section 4* future prospects of MRE infrastructures; *Section 5* will discuss concluding remarks regarding the future directions for MRE production in the harsh ocean environment.

This study reviews the LCA of MRE infrastructures to evaluate their environmental impacts throughout their lifecycle stages: from manufacturing, installation to operation and the disposal. By focusing on the environmental performance of these infrastructures, we aim to identify strategies for reducing their ecological footprint and improving their feasibility as sustainable energy solutions. The study's objectives are to: Review the environmental assessments of MREs using LCA, discuss the key barriers to the widespread adoption, and to propose solutions for improving their sustainability. A key aim is to highlight the need for collaboration among researchers, policymakers, and industry stakeholders to fully unlock the potential of such infrastructures for sustainable energy production.

2. Literature review

MREs are gaining attention for their potential to mitigate climate change through sustainable energy production [31]. While technologies like offshore wind turbines have made significant progress, tidal and wave energy converters (WECs) remain in early stages of development [32]. Despite the promise of these infrastructures, several challenges persist, including high installation costs, environmental concerns, and regulatory hurdles [33]. MRE infrastructures development is a significant aspect of business and economy, with agreed national and international standards and regulations. In addition, safety is the prime concern of government regulations and is always a part of the institutional framework for energy systems [34]. The advancement of marine engineering relies on six key areas: global climate change and the marine environment, the efficient use of maritime space, the interconnectedness of marine transportation infrastructure, the development of clean, renewable energy sources and maricultural facilities, addressing ecological crises and implementing countermeasures in marine engineering, and ensuring the safety and maintenance of marine infrastructure operations [35]. REI devices' efficiency, capacity factors, and resource potential matter significantly. Every technical device is efficient, like wind turbines in moderate wind (45 %) and solar photovoltaic panels in midday (17 %). As the input arrives without cost from the local environment and is a changing variable, it is best to average over time (per year). Parameters that tell us the annual production of the device terms as the capacity factors. It depends on both efficiency and climate of the site like wind turbines (18 % to 45 %), solar panels (10 % to 40 %), tidal power (25 %), and wave power (30 %). For the review article crisp understanding a framework of the MRE infrastructure in terms of LCA methodology is mentioned in Fig. 1.

A growing body of literature has focused on the potential environmental impacts of MRIs. LCA has become an essential tool for evaluating the environmental impacts of these infrastructures, enabling a comprehensive assessment from manufacturing to end-of-life. Several studies have highlighted the potential for MREs to reduce GHG emissions when compared to fossil fuels. However, the manufacturing, and installation stages present significant environmental challenges, particularly in terms of carbon emissions and resource use [36]. As, studies have shown that these infrastructures offer low emissions during operation, but they can have localized environmental effects, such as disruptions to marine habitats, underwater noise, and the potential for collisions with marine life [37,38]. These impacts are often site-specific and require careful evaluation through comprehensive Environmental Impact Assessments (EIA) [38]. The economic feasibility of these infrastructures remains a significant challenge. While the cost of offshore wind has decreased in recent years, wave and tidal energy technologies still face high costs of development, installation, and maintenance [39, 40]. Technological advances, particularly in materials, energy storage, and grid integration, are essential to improving the economic viability of such infrastructures [40]. LCA has emerged as a critical tool for evaluating the environmental impacts of these infrastructures from cradle-to-grave [41]. Several LCA studies have been conducted on wind turbines, tidal, and wave energy systems, but comprehensive assessments for integrated MRE infrastructures are limited [42]. Studies are lacking of integrated LCA approaches that assess the full environmental footprint of MREs when deployed in combination [43].

An "artificial reef" at the base of offshore wind turbines supports marine life. Wind turbines can be painted black to deter birds. Australian governments want an offshore wind industry. Dr. Taylor said Australia, like Europe, needs continuing regulation and monitoring to decrease wildlife hazards. Australia must have its marine life environmental monitoring schemes [44]. China started a $7.7 billion green energy project to power Beijing. Shanxi Daily reports that the project in northern China's Shanxi province will include 6 gigawatts (GW) of wind and solar capacity and 3.4 GW of energy storage. On this, the state-owned Jinneng Holding Group company started construction. The project will power Beijing, Tianjin, and Hebei provinces by connecting to the grid next year. The Datong-Tianjin ultra-high voltage power line will link it to those locations. A former coal mine is hosting the renewables facility. The COP28 climate meeting in Dubai endorsed China's agreement with the USA to treble renewable energy capacity by 2030.

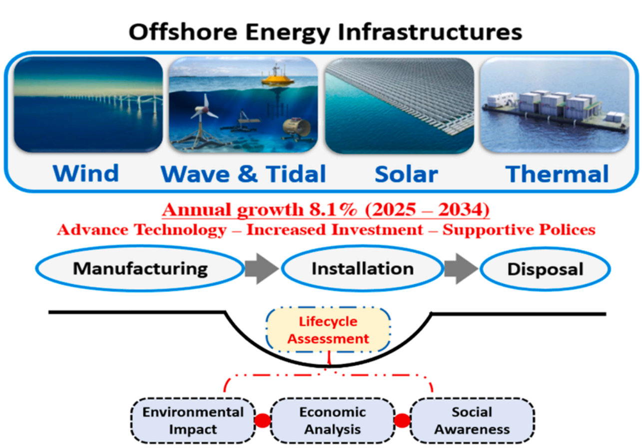

Fig. 1. Framework diagram of the MRE infrastructure in terms of LCA methodology.

China wants to achieve its carbon emissions peak by 2030 and reach net zero by 2060 [45]. A new analysis suggests China could create 863 GW of floating solar to supply green energy to land-scarce cities like Beijing. Last month, academics suggested China promote floating solar to "preserve finite land resources" in its population-dense east and south. China installed 392 GW of solar and 365 GW of wind power by 2022, accounting for one-third of world capacity. Last year, Rystad Energy predicted China would reach 500 GW and 1 TW by 2026 [46]. In response to industry concerns about a wind turbine "arms race" among manufacturers, China's Mingyang at its Shanwei manufacturing base showcased a 20 MW offshore monster that exceeds European rivals' capacity [47].

International Energy Agency (IEA) report says 50 % growth last year keeps hope of achieving the COP28 climate target of tripling clean energy capacity. Fatih Birol, the IEA's executive director, said: "The combination of higher interest rates and supply chain costs has forced some developers to cancel big offshore wind projects and raised concerns over the future of the technology" [48]. Saudi Minister of Economy and Planning said the kingdom wants 50 % of its energy from renewable sources by 2030. This strategy move supports environmental goals and shows the country's commitment to renewable energy, which investors like [49]. Chinese researchers examined 875 reservoirs and discovered that floating PV technology could generate 1423.8 TWh annually. The researchers stated that floating photovoltaics (FPV) offer a viable solution to address the conflict between the growing demand for solar energy and the limited availability of land, particularly in eastern China. "The three northern regions possess abundant land resources, but their potential for generating solar energy using FPV systems is restricted." FPV can potentially alleviate land limitations in developing solar power in East and South China [50]. China will add 56 % of renewable energy capacity in 2023–28, according to the IEA's renewables 2023 report. IEA data shows that China will build 2060 GW of renewable capacity, and the rest will build 1574 GW [51].

Identifying potential zones for MRE infrastructures and offshore aquaculture can improve decision-making and help manage short- and long-term marine economies [10]. Switching to electric boats benefits the marine ecosystem and carbon-conscious clients. The vessels reduce port community air pollution and marine ecosystem sound pollution by using 100 % electric or hybrid systems. In addition, this eco-friendly solution reduces GHG emissions by 1560 tons (t) and operations costs by up to 80 %. Due to climate change, green energy options for maritime transportation are becoming more critical. Developing and using clean energy will reduce ship-related air and water pollution and increase marine safety [52]. Successful health and safety management principles require policy, planning and implementation, reviewing performance, occupational auditable standards, and risk assessment [53]. In this respect, it is necessary to do the whole LCA of the MRE infrastructures. With the help of techno-economic LCA study, it is possible to get insight into the affordability and clean technological assessment and environmental impacts. There are international guidelines for the LCA method: ISO (14,040, 14,044) [54,55].

2.1. Technological advancements

Experienced and competent personnel can solve scientific and technological obstacles, increasing output and productivity. A more significant number of researchers improves the likelihood of various specialties, resulting in a more thorough and multidisciplinary R&D strategy. It allows researchers to discover new options and solve challenges creatively. An extensive worldwide digital repository encompasses over 1000 offshore wind projects across 36 countries, with China, Denmark, Germany, the Netherlands, and the UK being the main markets. The wave energy development in Canada is now at a comparable level to that of tidal energy, with minimal ongoing effort. Due to the nascent stage of the sector, there is a lack of clearly defined criteria. The technology is still advancing, making it challenging to anticipate the future direction of these requirements [56]. Coal-fired power will cost more than solar photovoltaic (PV) panels by 2030. Solar PV costs $3.55 per kilowatt-hour (kWh) at life, while coal costs $116.25. Although solar PV power seems more environmentally effective than coal-fired power in the life span, results showed the high external environmental cost of producing PV modules, reminding us to consider the environmental impact when analyzing renewable technologies' cost-benefits. The actual costs of REI technology are underestimated without environmental expenses [57].

The Australian government conducted environmental assessments under the "Environment Protection and Biodiversity Conservation Act of 1999″ and granted marine energy approval under the "Coastal Management Act 1995″. Canada's province of Nova Scotia introduced the "Marine Renewable Energy Act" for sustainable sector growth in 2015. The legislation aims to enhance the development of marine renewable energy resources, such as waves, tidal range, in-stream tides, currents, and wind. China's renewable energy law (2009) accelerates and promotes renewable energy initiatives. MRE infrastructures initiatives received special financing from the Ministry of Finance in 2010. Under the Ministry of Finance and State Oceanic Administration (SOA), the Administrative Center for MRE infrastructures coordinates and manages the unique financial program.

In 2016–2020, the SOA introduced the China 13th Ocean Energy Development five-year plan, which aims to utilize and advance various MRE resources such as tidal barrage, current, wave, ocean thermal, salinity gradient, and island MRE infrastructures. Denmark enacted the energy bill for the 2020–2024 period in 2018. As stated in the agreement, the Danish electricity demand may be met through renewable energy sources by 2030. REIs are financed to reach 55 % share in 2030. The arrangement includes three 2400 megawatts (MW) offshore wind projects that can power more than all Danish households. Several EU directives affect maritime energy project development, monitoring, and consenting. EU member states must change their laws and policies. These include renewable energy (directive 2009/28/EC), maritime spatial planning, environmental impact assessment, strategic environmental assessment, birds (2009/147/EC), habitats (92/43/EEC), and water framework. The French government changed offshore farm developer selection in 2017. The 2018 legislation and its accompanying regulation on MRE shift a significant portion of the responsibilities to be addressed before the issue of permits. It reduces the risk for project developers, provided that the project's technical specifications remain consistent with the initial proposals regarding technological advancements and environmental effects. MRE in India is still being tested. No marine energy project has a specific ecological clearance process [58].

Ireland must develop a national energy and climate plan (NECP) per the European Union's governance of the energy union and climate action policy for 2021–2030. In 2017, the Department of Communications, Climate Action and Environment released comprehensive advice on the Environmental Impact Assessment (EIA) and National Infrastructure Statement (NIS) preparation for MRE projects. Depending on the characteristics of the ocean energy device, such as its nature, size, and location, both EU and national legislation may require an EIA for its deployment. If a development is close to a natural protected site as defined by the EU habitats regulation, it may be necessary to conduct a suitable evaluation. County council planning clearance is essential for onshore developments. The 2018 third basic plan on ocean policy by Japan's cabinet office incorporated the development of MRE.

In 2019, the Ministry of Economy, Trade, and Industry enacted a law to encourage using sea areas to develop power generation facilities utilizing MRE infrastructures. The land, Infrastructure, transport, and tourism minister also allowed MRE development in a port region by amending the Port and Harbor Act. Mexico's energy industry, namely renewable energy, is regulated by the laws of sustainable energy use, renewable energy usage, and the financing of energy transition. The legislation for the energetic transition has recently superseded the law for the funding of energy transition. The Singapore Power Group issues worldwide renewable energy certificates to monitor and record the utilization of renewable energy. Enterprise Singapore has established a working committee to deliberate on international standards for wave, tidal, and other water current converters in the field of MRE [58]. Depending on location, Federal, state, and municipal agencies will regulate MRE projects. Details of the USA are in the handbook of marine hydrokinetic regulatory processes (2020). The guideline document specifically addresses the regulations and standards imposed by federal agencies for projects conducted in federal waters, as these requirements vary from those imposed by state authorities. The National Energy Regulatory Commission oversees maritime and hydrokinetic projects in the USA. It utilizes its powers under the Federal Power Act to regulate and provide licenses for hydroelectric projects located within three nautical miles of the shoreline and those connected to an onshore power system. The Bureau of Ocean Energy Management oversees marine activities on the outer continental shelf, located beyond three nautical miles from the shoreline. These two entities collaborate to authorize the development of MRE infrastructures [59].

Further, as researchers present, time requires a boost in competition, cooperation, and R&D innovations [60]. So, new amendments and legislative directives can be implemented. Renewable energy, globalization, technical innovation, and sustainable forest management can help the country reach net zero emissions [61]. Wave energy converters transform wave energy into electricity. They harvest wave energy using point absorbers, oscillating water columns, attenuators, stream generators, barrages, and wind turbines.

A comparison of WEC's new technologies with existing MRE infrastructures on the market is concluded, along with an economic overview of building wave energy converters with a brief LCA considered among its monetized environmental cost [62]. Zhai et al. examined the stages and procedures of the life cycle, focusing on the three primary functional modules—the mooring, generator, and buoy. Based on the energy and material usage, the manufacturing stage of the WEC was the primary contributor to the environmental impact [63]—micro-grid technology results in a significantly higher carbon reduction potential at 23.8 % compared to the baseline. Optimization through technology by altering the grid structure, such as by substituting conventional fuel with renewable energy, the emission of 0.05 kg of CO_{2eq} greenhouse gas per kWh of electricity generated can amount to 7.9 % of the baseline [64]. An analysis of the energy consumption and CO_2 emissions related to the initial generation of ocean turbines was presented through LCA.

The comprehensive evaluation includes the CO_2 and embodied energy for device installation and operation and those for decommissioning, component materials, and production. The study demonstrates that, even with the early stages of development and under relatively conservative assumptions, the corresponding energy and carbon intensities—214 kJ/kWh and 15 gCO_2/kWh, respectively—are comparable to large wind turbines and extremely low when compared to the 400–1000 gCO_2/kWh typical of fossil fuel-fueled generation. The payback period for energy is roughly 14 months, while for CO_2 is approximately eight months [65]. An analysis was conducted to determine the LCA of a replicable module of WECs about GHG emissions during the stages of building, installation, maintenance, and operation. The avoided emissions resulting from the implementation of an operable module (with a carbon footprint of 1.08 tCO_{2eq} and an environmental investment of 0.48 tCO_{2eq}) and electricity production (12.6 MWh/year per module) would offset the environmental costs (carbon footprint and ecological investment) within a period of 13–25 months, respectively [66]. MRE projects do not harm the marine environment or its resources.

The EU has a clear framework for its energy and climate policies up to 2020, but the debate has begun on adapting it to meet 2030 goals. European Council member states pledged in 2009 to cut EU greenhouse gas emissions by 80–95 % below 1990 levels by 2050. In 2011, the European Commission produced the energy roadmap for 2050. The roadmap examines the challenges of achieving nearly carbon-free energy production in the EU while maintaining supply security and competitiveness. The roadmap evaluates various scenarios to assess the effects of decarbonizing the EU energy system and identify policy needs. Given that the energy policies of 2020 will only achieve half of the 2050 greenhouse gas reduction goal, the roadmap urges immediate action to create a 2030 EU energy agenda that outlines the path to achieving the 2050 goal [67].

2.2. Environmental repercussions

Polluted oceans are a significant threat to the Earth's environment. Pollution (or marine pollution, intentional discharge, oil spills, littering, ocean mining) combines waste and chemicals, i.e., chemicals and debris washed, blown, or poured into the water [68]; because of this, different environmental factors affect marine creature development, survival, and production in our oceans. These include light, oxygen, water flow, salinity, density, and pH. Such parameters vary by habitat and support or hinder marine species' life processes [69]. High dissolved salt levels characterize marine ecosystems. These include open, deep-sea, and coastal marine environments with different physical and biological properties. Scientists classify marine habitats into numerous significant categories, but the source varies. Many marine ecosystems are agreed upon: estuaries (ocean meets rivers), salt marshes (land near estuaries), mangrove forests (in tropical areas), coral reefs (bit farther out into the tropical sea), open ocean (beyond the coral reefs lies), and deep-sea ocean (darker, colder, and with less available oxygen) [70].

Plastic comprises 80 % of marine detritus from surface to deep-sea sediments. Plastic trash entangles and injures marine creatures, killing them. Plastic pollution harms food, health, coastal tourism, and climate change. Many countries lack sanitary landfills, incinerator facilities, recycling capacity, circular economy pathways, and waste management and disposal methods to prevent plastic pollution. It causes 'plastic leakage' into oceans and rivers. The legal and criminal worldwide plastic garbage trade harms ecosystems [71]. Plastic pollution is rapidly becoming one of the most dangerous threats to marine life. It harms animals more than oil spills, heavy metals, or toxins. Large pieces cause damage when they are eaten or become entangled in animals. Microplastics are far more difficult to remove from the environment. When animals swallow plastic fragments, their nutritional intake is lowered. It can affect anything from microscopic zooplankton to larger species like fish and shellfish. Toxic chemicals can accumulate in larger animals that swallow their tiny particles and potentially threaten health [72].

Renewable energy has zero emissions, efficient clean techniques (does not release air pollutants), and is based on green energy (from natural resources) concepts. Most green energy sources are renewable, but not all are green. Hydropower is renewable, but some claim it is not green because erecting hydro dams deforests and industrializes the environment. Clean energy appears to be the future for humanity's power needs worldwide as reliance on fossil fuels continues to decline. Preserving natural resources and mitigating environmental disasters such as fuel spills and gas leaks is crucial. Cost reductions are inherent because there is no need to extract and transport fuels such as oil or coal. After all, the resources replenish themselves spontaneously [73].

Sites using MRE devices saved larval particles of pelagic organisms that would have been lost at sea. In addition, they supplied the coasts with larvae [74]. Climate change is undoubtedly one of the most serious threats to our oceans. Rising sea temperatures and acidification are already impacting marine habitats, fauna, and the coastal communities that rely on them [75]. While energy installations are blocked to fishing and maritime traffic, some species shelter under and around them, undisturbed, hiding from predators and feeding and breeding. The "artificial reef effect" occurs when organisms colonize buildings, attracting fish and other creatures. Many fish, crayfish, and mollusks live on energy devices, much as sunken shipwrecks and offshore wind turbines increase biodiversity. These devices' total greenhouse gas amounts vary between 15 and 105 gCO_2-eq. kWh^{-1}. All device types' average global warming potential is 53 ± 29 $gCO_{2\text{-eq}}$ kWh^{-1}. The study's results are consistent with previous research, indicating that the environmental effects of these devices are similar to those of other REIs and can potentially enhance the sustainability of the supply chain [76].

Human-caused noise, i.e., machine-generated noise, is barely audible above ambient sea noise and much below ship and vessel noise. Based on the analysis of available data, it is determined that underwater noise produced by MRE devices, electromagnetic fields emitted by cables, alterations in benthic and pelagic habitats, and changes in oceanographic systems will not have any noteworthy impacts on marine organisms and environments [8] - fossil fuel damages fur-bearing species like sea otters and birds' feathers, exposing them to harsh weather. Without water repellence and insulation, birds and mammals die from hypothermia [77]. Increased MRE infrastructures, i.e., offshore wind farms, may coincide with existing and future marine protected areas, posing conservation challenges. Both will restrict fishing to variable degrees; therefore, a framework is needed to examine stakeholder and ecosystem health trade-offs. Using ecosystem health and productivity indicators, a spatially explicit trophic model can read ecosystem response to several spatial closures to the southern North Sea fisheries [78].

Ocean pollution is pervasive, worsening, and uncontrolled in most countries. Its complicated composition is toxic metals, plastics, manufactured chemicals, petroleum, urban and industrial wastes, pesticides, fertilizers, pharmaceutical chemicals, agricultural runoff, and sewage. Over 80 % comes from land. It enters seas via rivers, runoff, air deposition, and direct discharge. It is usually densest and most concentrated on the coasts of low- and middle-income countries. Plastic pollution is rising and apparent in the water [79]. Large-scale initiatives might impact ocean ecosystems. Wave energy devices covering huge ocean surfaces might harm marine life and change ocean-atmosphere interactions, which could have broader impacts [9]. Healthy oceans provide food and jobs and are crucial to cultural traditions. Climate change exposes societies that rely on the sea to hardship [25].

Higher CO_2 concentrations lower ocean pH, changing the carbonate chemistry. It may harm the many planktonic creatures that utilize calcium carbonate for skeletons [80]. Sperling, a Stanford scientist of geological sciences, said they've never better understood how and why different stressors affected different sections of the global ocean. "This was thrilling to see" [81]. The solution to ocean pollution is to avoid contamination by reducing chemical fertilizer use, opting for reusable bottles and utensils, and properly disposing of plastics and other trash [68]. This review identifies key gaps in the LCA of MREs, particularly the lack of integrated assessments for hybrid systems combining different MRE technologies. It also underscores the need for more geographically-specific studies to account for local environmental and economic conditions.

3. Methodology: lifecycle assessment

This study employs a comprehensive LCA methodology to evaluate the environmental impact of MRE infrastructures. The LCA methodology follows the *ISO 14,040* and *ISO 14,044* standards, which outline the principles and framework for assessing the environmental impact of products throughout their lifecycle, from raw material extraction to end-of-life disposal [54,55]. The following steps are outlined to provide clarity on the methodological approach.

3.1. Goal and scope definition

The goals and scope of the study by Guercio et al. are to estimate the possible environmental effects of the production process of the energy system and to find the production process's hotspots [82]. The primary goal of this study is to review the MRE infrastructures, specifically the wave, tidal, and offshore wind systems, in terms of environmental hazardous potential, resource use, and overall sustainability. While the scope of the study discusses the influence of LCA on the current offshore technologies for the generation of MRE.

The functional unit of such studies were defined as the production of 1 kWh of electricity generated by these infrastructures over their entire lifecycle [83]. It allows for comparing results from various LCA studies for product systems with similar functionalities. The main purpose of MRE infrastructures are to produce electricity. As a result, most of the chosen LCA studies define the functional unit as kWh of electricity generated [76]. It means that the studies measure the environmental impact of producing one kWh of electricity and supplying it to the national grid. Some studies also consider the entire power system for internal analysis. However, a few studies do not explicitly state the functional unit, but they still use per-kWh electricity measurements to calculate energy and carbon intensities. The study concludes that one kWh of electricity is the most suitable for such investigations [84].

3.2. Lifecycle inventory

Data collection for the lifecycle inventory (LCI) phase involves gathering quantitative data from multiple sources [85], including:

- Manufacturers' specifications for energy-producing components (e.g., turbines, wave converters).
- Environmental data for the production and transport of materials (e.g., steel, concrete, composites).
- Operation data, such as energy production rates and maintenance intervals, sourced from existing MRE installations.
- Decommissioning data, including recycling rates and disposal costs.

Where primary data is mostly limited, while the secondary data from literature sources and established databases (e.g., the Ecoinvent database) were used. These data sources were chosen based on their relevance to MRE technologies and consistency with international standards. While, different short-term and long-term lifecycle stages: manufacture, assembly, deployment, maintenance and operation, and decommissioning were considered for the "short-term" and "long-term" criteria [56].

3.3. Impact assessment

At this stage the environmental impacts of each MRE system can access through different impact assessment models like CML/Global warming potential method, which calculates impacts across several categories like acidification, eutrophication, ecotoxicity, human toxicity, GWP etc [86]. These categories were selected based on their relevance to the marine environment and the typical materials used in MRE systems [87].

3.4. Interpretation and sensitivity analysis

In the interpretation phase, the results were analyzed to identify key environmental hotspots, or stages of the lifecycle that contribute most significantly to the environmental impact. Many different energy and environmental markers use to study the "hot spots" in the energy systems [88]. In addition with the shortened LCA, it is possible to show how the materials used in a product can significantly impact how well it works with the environment. A meticulous LCA study could even help you make a sound wave energy gadget for the climate [89]. LCA techniques for biofuels and bioenergy technologies are expanding rapidly, making methodology development difficult [90], primarily for comparing consumer goods' environmental implications [91]. LCA research has relied on scientific consensus for two decades, as shown by reports from SETAC, UNEP, ISO, and the joint research center. Without scientific consensus, firms could exploit LCA for greenwashing by choosing the evaluation technique that benefits their product, putting LCA's scientific credibility at risk. The "scientific consensus agenda" may also be driven by LCA's goal to solve environmental issues [92].

LCAs are needed for the latest updates related to MRE devices, including all suggested technologies, to understand better their environmental consequences and how they may help preserve the energy supply. Uihlein studied ILCD recommendations and cradle-to-grave life cycle phases. The database includes 83 tidal devices from 36 developers, 103 wave devices from 50 developers, 49 horizontal and seven vertical axis turbines, 53 point absorbers, and 16 oscillating wave surge converters [76]. A few essential suggestions include increasing the accessibility of MRE infrastructures' strategic framework source data. Grid connection investigations to determine what grid upgrades are required for each primary resource area. Gather site-specific data and analysis for all theoretically feasible resource areas—examine the likely interactions between large-scale arrays and the maritime environment. Create a well-defined strategy or program to develop primary resource regions for arrays with a capacity of up to 30 MW (the expected maximum limit for revenue subsidy). This strategy should be the focus of a strategic environmental evaluation [93]. The most significant LCA impact can be achieved through indigenous training in the LCA practice of renewable energy and comparing various infrastructures and technologies [94]. Municipal wastewater management, excessive nutrient enrichment, habitat degradation in the coastal zone, and marine trash containing novel chemicals are among the issues designated for priority attention [95].

Pehnt investigated a dynamic approach towards the LCA of REIs and proved that for all energy chains, the inputs of finite energy resources and emissions are extremely low compared with the conventional system [96]. Dahlsten performed the LCA of a hypothetical prototype wave power plant [97]. LCA compared the two technical systems intended to harvest the MRE infrastructures-wave infrastructure [98]. Wave and tidal energy systems were commonly examined through LCA for their environmental impact [99]. The potential ecological impacts were computed per kWh of wave-power electricity supplied to the utility. In particular, the production of steel and parts dramatically contributes to the overall results.

The Maltese government has unveiled plans to tap into offshore opportunities to maximize the benefits. Their MRE infrastructures' goals are facilitating the launch of offshore wind and solar power projects; encouraging investment in offshore wind and solar power; conducting assessments of wind resources and bathymetry to identify potential development areas; managing and planning maritime resources; guiding investors towards efficient renewable technology; strengthening R&D and innovation in offshore wind and solar power infrastructures; generating economic growth through the creation of new green job opportunities; and, finally, the creation of jobs in a variety of sectors, such as manufacturing, construction, operation, and maintenance of REIs; developing supply chain facilities to support services; transportation [100]. To chart a course towards climate neutrality, Spain has compiled several legal and strategic documents into the strategic framework for energy and climate. This framework includes documents such as the integrated national energy and climate plan 2021–2030, long-term decarbonization strategy 2050, climate change and energy transition law, transition strategy, and strategy against energy poverty [101].

The LCA results show that offshore wind systems exhibit the lowest environmental impact in terms of carbon emissions when compared to tidal and wave energy systems. However, the manufacturing and disposal stages of all MREs contribute significantly to their overall environmental footprint. The production of steel and composite materials for turbines, as well as the transportation of equipment, were identified as the most energy-intensive processes [102]. While, the potential to recycle materials from disposed-off MRE devices, such as metals and composites, could reduce the environmental impact significantly.

Tidal and wave energy systems, while promising, face higher installation and operational costs, primarily due to technological constraints [40]. However, these technologies have the potential to offer significant environmental benefits once technical challenges are addressed. The co-location of different MRE technologies could increase efficiency and reduce costs, providing a promising area for future development [103]. One key finding is the importance of location in determining the environmental impact of MREs. Factors such as local marine biodiversity, installation depth, and the energy potential of specific sites play a significant role in influencing both the environmental and economic feasibility of these systems. Future studies should focus on more geographically-specific LCAs to optimize the design and deployment of MREs.

Furthermore, the integration of different MRE technologies (e.g., wind, tidal, and wave) in hybrid systems presents a promising avenue for reducing overall costs while maximizing energy production [104]. Future research should investigate co-location strategies that combine different renewable energy technologies to benefit from complementary energy generation patterns. While sensitivity analysis conducts to determine the robustness of the results under varying conditions, such as:

- Changes in material efficiency or energy conversion rates.
- Variations in operational lifespan (e.g., from 20 to 30 years).
- The impact of technological improvements (e.g., next-generation turbines or more efficient storage solutions).

The results can be compare with the environmental performance of traditional fossil fuel-based power generation (coal, gas) and other renewable energy sources (solar, hydro, wind) based on available literature and existing LCA studies [105]. These comparisons allow us for an understanding of how MREs contribute to reducing the overall carbon footprint and other environmental impacts associated with global energy production. It provides insight into the reliability of the results and the potential for reducing environmental impacts through technological advancements or design improvements.

4. Future scope and limitations

It is critical to address present issues and investigate novel solutions as the world moves faster and faster towards renewable energy, especially in maritime areas. However, considerable technical difficulties exist in overcoming the switch from non-sustainable to sustainable energy.

4.1. Advancements in research and infrastructure

Research into new materials that are more resistant to corrosion and biofouling and have improved durability must continue. Practical MRE infrastructures are necessary to investigate marine-specific polymers, coatings, and nanomaterials. The potential for increased use of renewable energy sources, including floating solar, offshore wind, tidal, and wave power, is enormous. Future research can concentrate on improving the co-location of these technologies to increase energy output while minimizing environmental impact. Advancements in energy storage technology are crucial to guarantee the dependability and grid integration of renewable energy systems in the challenging ocean environment. Potential areas of further study include the creation of innovative battery chemistries, methods for storing hydrogen, and compressed air energy storage systems designed specifically for use in maritime environments. It is essential to implement advanced remote monitoring and maintenance systems to guarantee the security of MRE infrastructures. Possible sensors for real-time monitoring and predictive maintenance applications include autonomous drones, underwater robots, and similar technologies.

4.2. Policy and collaboration for development

For policy and decision-making purposes, individual and comparative technology evaluations should estimate and discuss criteria, including the application scale, size, and weight per unit of energy production, economics, efficiency, and level of technological development. Also, data analytics and artificial intelligence (AI) algorithms can significantly assist in understanding how to optimize and operate renewable energy systems in marine environments. Improving operational efficiency, decreasing downtime, and maximizing energy production could be the subject of future research involving AI-driven prediction models. The demand for thorough EIAs is rising with the number of offshore renewable energy projects. Future studies might concentrate on creating more sophisticated modeling methods to evaluate the ecological impacts of MRE infrastructure's in the ocean on marine ecosystems, biodiversity, and habitats. It is critical to set up robust legislative and regulatory frameworks adapted to the specific difficulties of offshore developing renewable energy sources. To create policies that effectively balance environmental protection, economic development, and energy security, researchers, policymakers, and industry stakeholders may need to work together in the future. The widespread use of renewable energy sources makes it all the more important to encourage cooperation and the exchange of information worldwide. Facilitating relationships between nations, institutions, and industry players to exchange lessons learned, technical advancements, and best practices in offshore renewable energy development should be the focus of future research efforts.

4.3. Limitations

While this study provides a comprehensive LCA of MRE infrastructures, several limitations should be acknowledged:

Data uncertainty: MRE technologies are relatively new, there is limited historical data on their performance, lifespan, and maintenance needs, leading to uncertainty in predictions. Marine conditions such as tidal strength, wave patterns, and local ecosystems vary greatly across locations, adding unpredictability to the performance of MRE systems. Rapid developments in MRE technology introduce uncertainties, as new materials and improvements in design may change lifecycle data assumptions. Variability in material sourcing, manufacturing processes, and operational conditions (such as energy production based on fluctuating marine conditions) contribute to data uncertainty. These uncertainties affect the reliability of the LCA, particularly in terms of estimating environmental impacts, energy production, and material use. Sensitivity analyses are often used to assess how changes in data assumptions affect the outcomes of the LCA.

Regional differences: The environmental impacts of MRE technologies can vary depending on the health and sensitivity of local marine ecosystems, including biodiversity, species interactions, and ecosystem services. The potential for energy generation from MRE technologies depends on regional marine conditions, such as tidal currents or wave heights, which affect efficiency and output. The availability of materials and the transportation required for constructing MRE infrastructure can differ by region, influencing overall environmental impact and carbon footprint. Different regions have varying environmental laws and regulations that affect the construction and operation of MRE technologies, impacting project costs and complexity. The impact on local communities, such as potential disruptions to industries or benefits like job creation, varies by region. Public acceptance of MRE technologies also influences their success. Harsh environmental conditions, such as extreme weather, can affect the durability and operational efficiency of MRE systems, while climate change impacts may increase maintenance or adaptation costs.

Technological evaluation: As MRE technologies evolve, innovations in design and materials can improve efficiency, reduce environmental impacts, and increase energy production. These advancements can lead to updated lifecycle data, making earlier projections less accurate. Technological improvements can lower the carbon footprint of MRE systems by increasing energy efficiency and using sustainable materials, thus altering lifecycle impact assessments. As more MRE systems are deployed, the industry gathers valuable operational data, improving the accuracy of performance projections and refining LCA models over time. Technological advancements, such as predictive maintenance and autonomous operations, can reduce operational costs and downtime, positively influencing the LCA results. Evolving technologies allow MRE systems to adapt to environmental shifts and regulatory requirements, helping to reduce their environmental impact and enhance sustainability. Technological advancements lead to decreasing capital costs, making MRE systems more economically viable and improving the economic side of the LCA. Given the rapid technological developments, LCA projections may become outdated, requiring periodic updates to reflect the latest data and advancements.

5. Conclusion

This review explores the current practices and challenges in electricity generation through MRE technologies, emphasizing both their significant potential and the barriers impeding their widespread adoption. Key obstacles include rising production costs, technological constraints, complex regulations, and environmental impacts. Overcoming these challenges is crucial to fully unlocking the potential of wind, solar, and wave energy sources.

Despite these hurdles, opportunities for innovation exist. Advancing MRE technology and infrastructure requires collaboration among researchers, policymakers, and industry stakeholders. Computational fluid dynamics, experimental studies and LCA are vital for understanding energy flows and environmental impacts. China has made notable progress with MRIs, including wind power and floating photovoltaics, while offshore aquaculture holds considerable commercial potential. To enhance MRE technologies' efficiency, reliability, and cost-effectiveness, research should focus on advanced materials, optimized energy conversion systems, and novel deployment methods. Improved resource assessment techniques and site characterization are essential for accurate energy potential estimates. Additionally, future studies should explore grid management, smart grid technologies, and energy storage systems to ensure seamless integration of MRE into existing power grids. Environmental considerations remain paramount in MRE development. While MREs hold substantial potential for sustainable energy production, their deployment faces significant environmental and economic challenges. The application of LCA across MRE systems demonstrates their environmental advantages over fossil fuels. Future research should prioritize improving recyclability and reducing lifecycle energy consumption and carbon emissions.

Additionally, offshore wind farms, marine protected areas, and habitat restoration initiatives are essential for minimizing environmental impacts and promoting ecosystem resilience. Effective maritime space planning is critical to balance exploitation and conservation. Environmental monitoring around offshore energy projects will provide valuable data to guide policy decisions. Supportive policies, such as feed-in tariffs and streamlined permitting processes, are vital for incentivizing investment and promoting MRE deployment. Future efforts should focus on developing policies that balance environmental protection, economic growth, and energy security. Collaboration across disciplines and sectors is essential to overcoming MRE adoption barriers. By aligning efforts on technology, regulatory frameworks, and market conditions, we can unlock MRE systems' full potential, ensuring a sustainable, low-carbon energy future. This includes enhancing energy storage and grid integration capabilities for MRE scalability and reliability.

Abbreviations

MRE	Marine renewable energy
MRIs	Marine renewable energy infrastructures
CFD	Computational fluid dynamics
LCA	Lifecycle assessment
R&D	Research and Development
EPA	Environmental Protection Agency
EU	European Union
RE	Renewable energy

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CRediT authorship contribution statement

Muhammad Tamoor: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Chunwei Zhang:** Writing – review & editing, Visualization, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sftr.2025.101393.

Data availability

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding authors.

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