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Review article

Navigating the energy transition: Transdisciplinary insights from marine science, blue economy, energy analytics, and sustainability education

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ABSTRACT

Marine renewable energy (MRE), including offshore wind, tidal, wave, thermal, and biomass resources, can support decarbonization while advancing blue economy objectives, but its deployment requires coordinated ecological, technical, and social strategies. This study synthesizes the interdisciplinary nexus among marine science, blue economy, energy analytics, and sustainability education, and maps the research development using a PRISMA-guided bibliometric review of Scopus-indexed literature. Bibliometric indicators (publications, citations, and collaboration networks) were analysed in order to map research development trends. Findings indicate a rapid growth in MRE research with strong international collaborations, mainly led by offshore wind and tidal technologies, together with persistent concerns related to habitat disturbance, biodiversity impacts, and spatial conflicts. Energy analytics (forecasting, optimization, and grid integration) emerges as key enabler for managing variability and improving system reliability, while sustainability education supports the public understanding, social acceptance, and development of workforce capacity. Accelerating sustainable MRE adoption requires marine spatial planning, robust environmental safeguards, and data-driven grid and system management aligned with equitable governance of blue economy.

1. Introduction

The energy transition, marked by a move towards renewable energy sources and a decrease in dependence on fossil fuels, is reshaping the global energy landscape. Utilizing wind resources far from the coast and beyond shallow water, coastal wind farms have excellent potential for electricity production with the least human intervention and an efficiency benefit (Lüth and Keles, 2024; Edwards et al., 2023). Offshore wind farms generally use turbines with larger installed capacities compared to onshore wind projects, often exceeding the onshore turbine ratings by approximately 1.5–2 times. In addition, offshore wind installations typically achieve higher capacity factors that is commonly ranging from 40% to over 50%, due to stronger and more consistent wind resources, especially in regions such as North Sea, the U.S. Atlantic coast, and parts of East Asia. However, actual capacity factor values vary depending on site conditions, turbine technology, and grid integration characteristics (Musial et al., 2023; Ohunakin et al., 2023; Jung and Schindler, 2022). Nevertheless, integrated assessments linking MRE deployment with ecological trade-offs, governance frameworks, and enabling social mechanisms remains fragmented across disciplines. Climate change, energy security, and economic resilience are accelerating the transition toward renewable energy systems. The world's

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growing population and socio-economic growth increase global energy demand (Khojasteh et al., 2018). Historically, global energy systems have relied heavily on coal, oil, and natural gas. Burning fossil fuels for energy generation contributed to global warming by releasing massive volumes of CO_2 into the atmosphere (Yoro and Daramola, 2020; Hassan et al., 2024). Therefore, marine ecosystems are becoming vital to sustainable energy generation and environmental resilience as the energy transition fosters renewable energy systems to combat climate change and reduce the utilization of fossil fuels (Owusu and Asumadu-Sarkodie, 2016).

The oceans serve as a significant source of renewable energy possessing the ability to store thermal energy (heat), kinetic energy (tides and waves), chemical energy (chemicals), and biological energy (biomass). These renewable energy sources provide opportunities to meet growing energy demands sustainably (Khan et al., 2017; Chu and Majumdar, 2012). The Blue Economy represents a concept focused on the protection of oceans and water resources, emphasizing the equilibrium between economic activities and the sustainable management of ocean ecosystems (Lee et al., 2020). The scope of the blue economy includes various sectors, encompassing traditional industries such as fisheries and marine transport, alongside emerging fields like aquaculture, marine biotechnology, renewable energy, and coastal tourism. These sectors offer substantial opportunities for innovation, promoting sustainability, and combating critical environmental challenges (Martínez-Vázquez et al., 2023). Renewable energies in the Blue Economy promote wealth creation, job opportunities, and local economic growth, especially in coastal and developing areas. In contrast, they require sustainable practices that adhere to marine ecosystem limits to guarantee long-term protection (Hoerterer et al., 2020; Brent et al., 2020; Bordin et al., 2025). Additionally, a major challenge in dealing with the climate crisis involves investing in resilient infrastructure capable of overcoming extreme weather, implementing green infrastructure suited to local needs, and promoting research to create efficient and sustainable technologies (Pires Manso et al., 2023). Assessment of coastal suitability involves a combination of environmental, economic, and social determinants to ensure that coastal development does not compromise ecological integrity (Jattak et al., 2023). These assessment processes provide the theoretical rationale for using effective management processes for the coasts to balance human needs and environmental preservation (Voyer et al., 2020; Demirel et al., 2021). This assessment becomes more urgent with escalating climate change and anthropogenic pressure. The two-pronged threat of environmental degradation and economic needs highlights the necessity of an overall system to incorporate shoreline zoning and marine functional zoning (Liu et al., 2024). Secondly, ecologically sustainable coastal utilization requires an integrated approach for managing industrial expansion, tourism evolution, and protection of biodiversity.

Coastal areas are hubs for local fisheries, aquaculture, port activities, and investments in renewable energy, and therefore, their sustainable management is critical to maintaining long-term economic and environmental resilience (Butt et al., 2024; Wibisono, 2024; Hridoy et al., 2026a). Strategic land use planning, habitat conservation, and adaptive management strategies are necessary to minimize the adverse effects of urbanization, pollution, and habitat loss in coastal areas. Ecosystem-based approaches and nature-based solutions can also enhance coastal resilience while supporting socio-economic development (Wu et al., 2024; Hridoy et al., 2026b). Combining science-based decision-making and regional stakeholder participation ensures that coastal resources are utilized optimally without impairing their future sustainability.

Energy analytics, an approach based on data for optimizing energy systems, is vital for the integration of renewable energy into existing grids and for enhancing efficiency (Ahmad et al., 2022; Panda and Das, 2021; Al Mamun Hridoy et al., 2025a). Predictive modeling in energy analytics enables the forecasting of marine energy generation by analyzing wave and wind patterns, identifying optimal sites for energy projects, and balancing grid loads to maintain system stability. These tools offer insights for long-term energy planning, enhance reliability, and reduce operational costs (Simbolon et al., 2024; Afridi et al., 2024; Masoumi, 2023; Hridoy et al., 2025a). Utilizing analytics enables stakeholders to cope with the variability and unpredictability associated with MRE, facilitating effortless integration and enhancing system performance (Khalil and Sheikh, 2024; Yousef et al., 2023).

Sustainability education is a multidimensional concept that extends beyond technical skill-building to encompass environmental literacy, civic engagement, ethical reasoning, and systems thinking (Rieckmann, 2018; Pavlova, 2008). In the context of the energy transition, sustainability education promotes public understanding of renewable energy technologies, fosters critical thinking about environmental impacts, and enhances community resilience through informed participation and social acceptance (Kellberg et al., 2023; Fan and Fan, 2024). Moreover, it equips individuals with not only the technical competencies to implement and maintain clean energy systems but also the social and civic capacities to advocate for equitable and inclusive energy policies (Tran, 2024; Altassan, 2023; Hridoy et al., 2025c). By integrating environmental knowledge with democratic participation and innovation, sustainability education serves a transformative function, empowering both individuals and societies to actively engage in shaping a sustainable, low-carbon future (Akour and Alenezi, 2022). Therefore, the objectives of this review are to evaluate how MRE technologies contribute to a low-carbon transition while addressing ecological trade-offs, to analyze the socio-economic and policy dimensions of the blue economy, and to assess the enabling roles of energy analytics and sustainability education in improving integration, public awareness, and innovation. The conceptual interactions among these domains are summarized in Fig. 1. The study also analyzes the socio-economic and policy dimensions of the blue economy, emphasizing the need for inclusive and equitable energy development. Furthermore, it investigates the critical roles of data-driven energy analytics and sustainability-focused education in enhancing public awareness, policy responsiveness, and technological innovation. By integrating these domains, this review provides a roadmap for advancing MRE within sustainable development agendas.

1.1. Contribution and advancement of knowledge

This study advances the existing literature in three main directions.

First, it goes beyond a purely sectoral or fragmented analysis by structuring marine renewable energy within an explicitly integrated transdisciplinary decision architecture. Such architecture connects ecological constraints, governance mechanisms, energy analytics, and societal enabling factors within one coherent framework. In this way, the work does not treat these domains as parallel or isolated dimensions, but rather as interacting components that must be considered simultaneously.

Second, the study reframes marine renewable deployment from a resource-potential narrative towards a systems-readiness perspective. Instead of focusing only on theoretical availability of resources, the analysis emphasizes operational feasibility, spatial trade-offs, and adaptive governance mechanisms. This shift of perspective is important, since technological potential alone does not guarantee implementable solutions in real-world contexts.

Third, by combining bibliometric mapping with critical synthesis, the study identifies persistent fragmentation across disciplines and proposes an integrative pathway which can inform policy design, marine spatial planning, and data-driven energy optimization strategies. The objective is not only to map research evolution, but also to highlight structural gaps that limit coordinated development.

Rather than introducing a new technological model, the main contribution lies in conceptual integration and decision structuring — addressing the gap between technical potential and implementable sustainability. In this sense, the value of the work is not in proposing

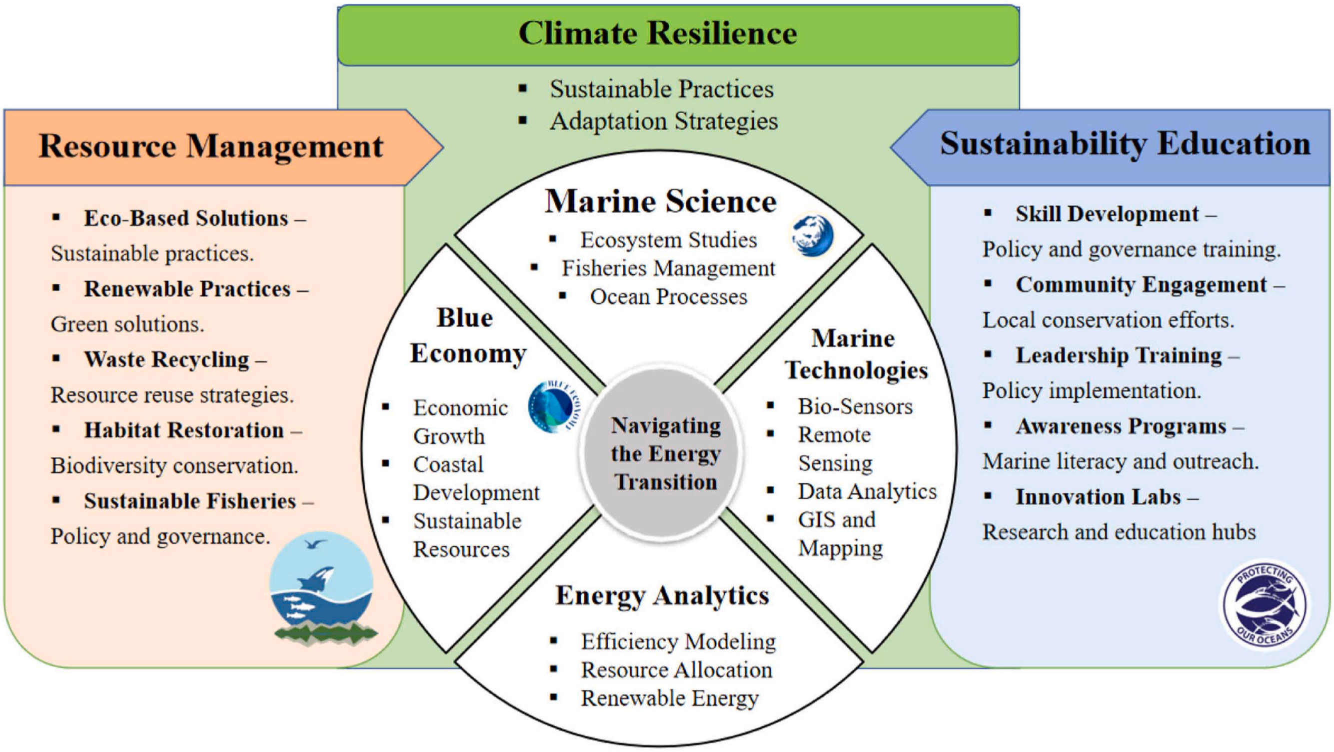

Fig. 1. A diagram illustrating interactions between marine science, blue economy, energy analytics, and sustainability education.

another isolated solution, but in organizing existing knowledge within a coherent decision-oriented logic capable to support more coordinated and sustainable marine renewable deployment pathways.

2. Methodology

This systematic review followed PRISMA guidelines. Relevant studies were identified through database Scopus, covering 2000–2025. Inclusion criteria required peer-reviewed articles, case studies, and reviews addressing the interplay between at least two focal disciplines, such as publications listed in the Norwegian Register Level 1, ERA 2018, ERA 2023, UGC Journal List Group II, or VABB-SHW. A thorough literature search was carried out using the Scopus, concentrating on key terms like *Navigating Energy Transition, Blue Economy, Transdisciplinary Challenges, Energy Analytics, MRE, and Marine Science.* The review aimed to explore the role of energy transition, particularly focusing on renewable energy technologies. Out of an initial pool of 1151 studies, 210 met the inclusion criteria, which is about one-fifth of the total search results (Fig. 2).

A bibliometric analysis was performed to uncover collaboration

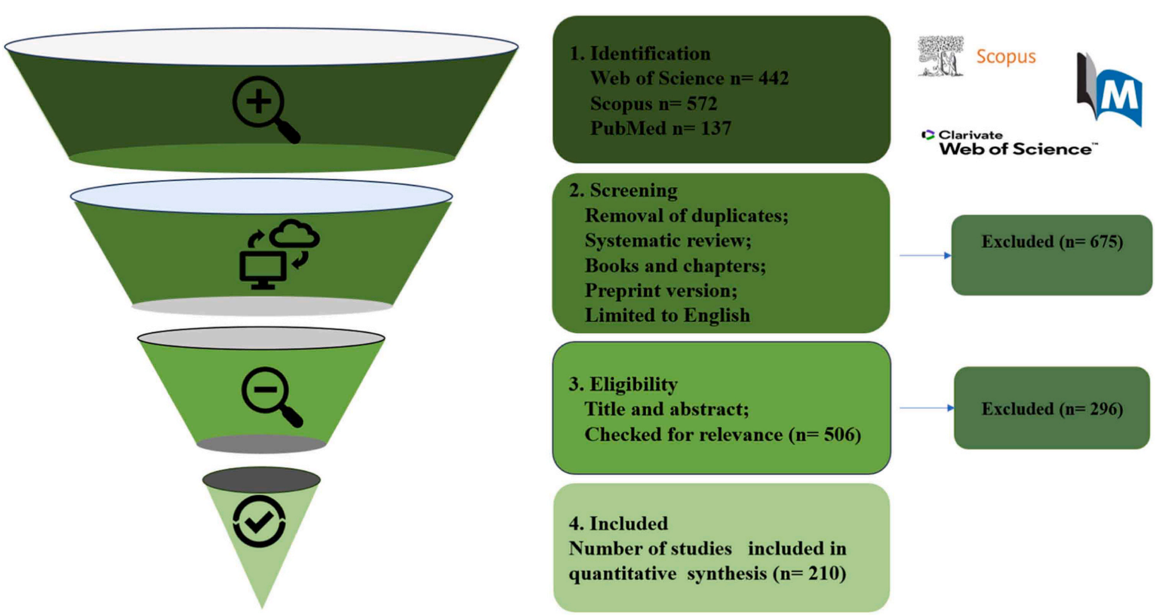

Fig. 2. This PRISMA flow diagram illustrates the identification of studies, screening, and inclusion for systematic review. It illustrates records yielded by database and manual searches and exclusion criteria applied at each point.

trends within the field. This analysis examined co-authorship, citation counts, and research collaborations among various countries and institutions. The findings showed notable co-authorship networks, reflecting strong research partnerships. Papers with higher citation counts were identified as significantly contributing to the progress of renewable energy technologies. Furthermore, international collaborations among leading institutions underscored the global commitment to achieving energy transition objectives. These findings, depicted in Fig. 3, showcase the co-authorship networks and research partnerships at both the country and institutional levels. This review provides an overview of the current landscape of research in energy transition and renewable energy technologies, offering insights into collaborative efforts and potential avenues for future investigation. The bibliometric analysis explores research trends in the energy transition and its transdisciplinary connections with sustainability, renewable energy, and technological development. A comprehensive literature review was conducted using primary academic databases, employing core terms such as "energy transition," "renewable energy," "sustainability," "technology adoption," "offshore," and "policy frameworks." Covering the period from 2000 to 2025, this analysis provides a broad overview of developments in the field.

VOSviewer 1.16.20 was utilized to examine co-authorship, keyword co-occurrence, and citation networks. The co-authorship analysis mapped research collaborations at individual, institutional, and national levels, identifying key contributors. Keyword co-occurrence analysis revealed thematic clusters, highlighting emerging topics and research gaps. Additionally, citation network analysis mapped the intellectual structure of the field, tracking the most cited publications and their interconnections.

Predictive and real-time energy models play a crucial role in optimizing marine energy systems by enhancing efficiency, forecasting energy generation, and ensuring adaptive control strategies; Table 1 shows a comparative analysis of key predictive and real-time models, highlighting their methodologies, advantages, and applications in marine energy optimization.

3. Marine science and renewable energy

The energy transition is a complex and multidimensional process that involves moving away from energy systems that rely on fossil fuels and toward renewable energy sources. MRE—particularly offshore wind farms—emerges as a crucial element in this scenario. The ability of offshore wind farms to produce substantial energy outputs while lowering carbon footprints is examined in this research. It also explores related issues including habitat disturbance and biodiversity preservation, and assesses methods for combining maritime energy infrastructure with aquaculture and conservation initiatives.

Over the last five years, research has focused on advances in technological innovation, economic feasibility, environmental benefits, and the integration of offshore wind energy into existing power networks. These advancements emphasize the importance of offshore wind energy in achieving sustainability goals. Furthermore, the strategic placement of offshore wind farms increases their energy-generating potential, as wind speeds in offshore sites are often higher and more steady than onshore winds, resulting in improved energy production efficiency. Studies have shown that offshore wind farms can achieve capacity factors exceeding 50%, in contrast to the 30–40% typically observed for onshore installations (Fernández-Guillamón et al., 2019). The adoption of larger turbines, often with capacities surpassing 10 MW, has further enhanced this potential by enabling higher energy capture and improved efficiency (Cai et al., 2020; Ding et al., 2022). Notably, the emergence of floating offshore wind farms has expanded the scope of energy generation into deeper waters, where wind resources are more abundant (Li et al., 2019; Ningsu Luo et al., 2024). Advances in technology and economies of scale have greatly improved the affordability of offshore wind energy. The Levelized Cost of Energy (LCOE) for offshore wind has experienced a substantial decline, positioning it as a cost-competitive alternative to fossil fuels (Castro-Santos et al., 2018; Wei et al., 2023). A study showed that the cost of floating offshore wind farms depends on factors like turbine prices, installation costs, and distance from shore, but overall, these costs are trending downward (Castro-Santos et al., 2018).

Offshore wind farms significantly reduce greenhouse gas emissions, which serve as a cleaner alternative to fossil fuel-based energy sources and address the primary causes of climate change. Sustainability assessments have revealed that the environmental impact scores of offshore wind farms are considerably lower than those of coal and biomass power plants, thereby emphasizing their critical role in promoting environmental sustainability (Stougie et al., 2018). In addition, the integration of offshore wind energy facilitates the shift toward carbon-neutral energy grids, and this is supported by various national policies that aim to enhance the penetration of renewable energy in power systems (Choi et al., 2022; Fernández-Guillamón et al., 2019).

Although the outlook for offshore wind farms is promising, several challenges persist in their development. Significant hurdles are posed by the high operational and maintenance costs, which constitute 20–35% of total expenditures (Lubing et al., 2020). The likelihood of equipment failure is heightened by the harsh marine environment, requiring that robust maintenance strategies and advanced technologies be implemented to maintain reliability (Kou et al., 2022; Lubing et al., 2020). Additionally, potential spatial conflicts with other marine activities, such as fishing and shipping, must be addressed through careful planning and effective management strategies to minimize adverse impacts (Mehdi et al., 2020; Wang et al., 2021).

Offshore wind energy is positioned as a key component of future energy systems because of its mix of environmental advantages and economic feasibility. The rapid expansion of offshore wind farms (OWFs) as a renewable energy source has raised significant concerns regarding the conservation of biodiversity and the disruption of habitats in marine environments. As global offshore wind energy capacity continues to increase, it becomes essential for the ecological impacts of such developments to be thoroughly understood to ensure sustainable management and effective conservation strategies. Substantial habitat disruption can result from the construction and operation of offshore wind farms. The physical environment is altered by the installation of wind turbines and related infrastructure, which has the potential to affect benthic communities and disrupt the overall balance of marine ecosystems. For instance, the construction of offshore wind turbines leads to significant impacts on benthic ecosystems in the Mid-Atlantic region of the United States, including alterations in fish communities and changes in the foraging behaviors of marine mammals (Cruz-Marrero et al., 2019). Similarly, wind energy development can, directly and indirectly, affect wildlife and their habitats, highlighting the necessity of adopting an ecological risk-based approach for effective management (Copping et al., 2020). Furthermore, the introduction of artificial structures into marine environments has been found to produce mixed ecological effects. While offshore wind farms can create new habitats for certain species, displacement of other species may also occur. For instance, MRE installations (MREIs) can contribute to the restoration of degraded seabed habitats by preventing destructive fishing practices; however, the ecological succession following construction may require variable timeframes (Sheehan et al., 2020; Hridoy et al., 2025d; Lima et al., 2025). This dual nature underscores the importance of comprehensive planning and continuous monitoring to ensure that the benefits and challenges of habitat modification are carefully balanced.

The conservation of biodiversity is a vital concern in the development of offshore wind energy. Changes in species distribution and abundance, particularly among vulnerable marine species, can be caused by the presence of wind farms. For instance, protected species, including the Red-throated Diver (*Gavia stellata*) and Black-throated Diver (*Gavia arctica*), tend to avoid areas surrounding offshore wind

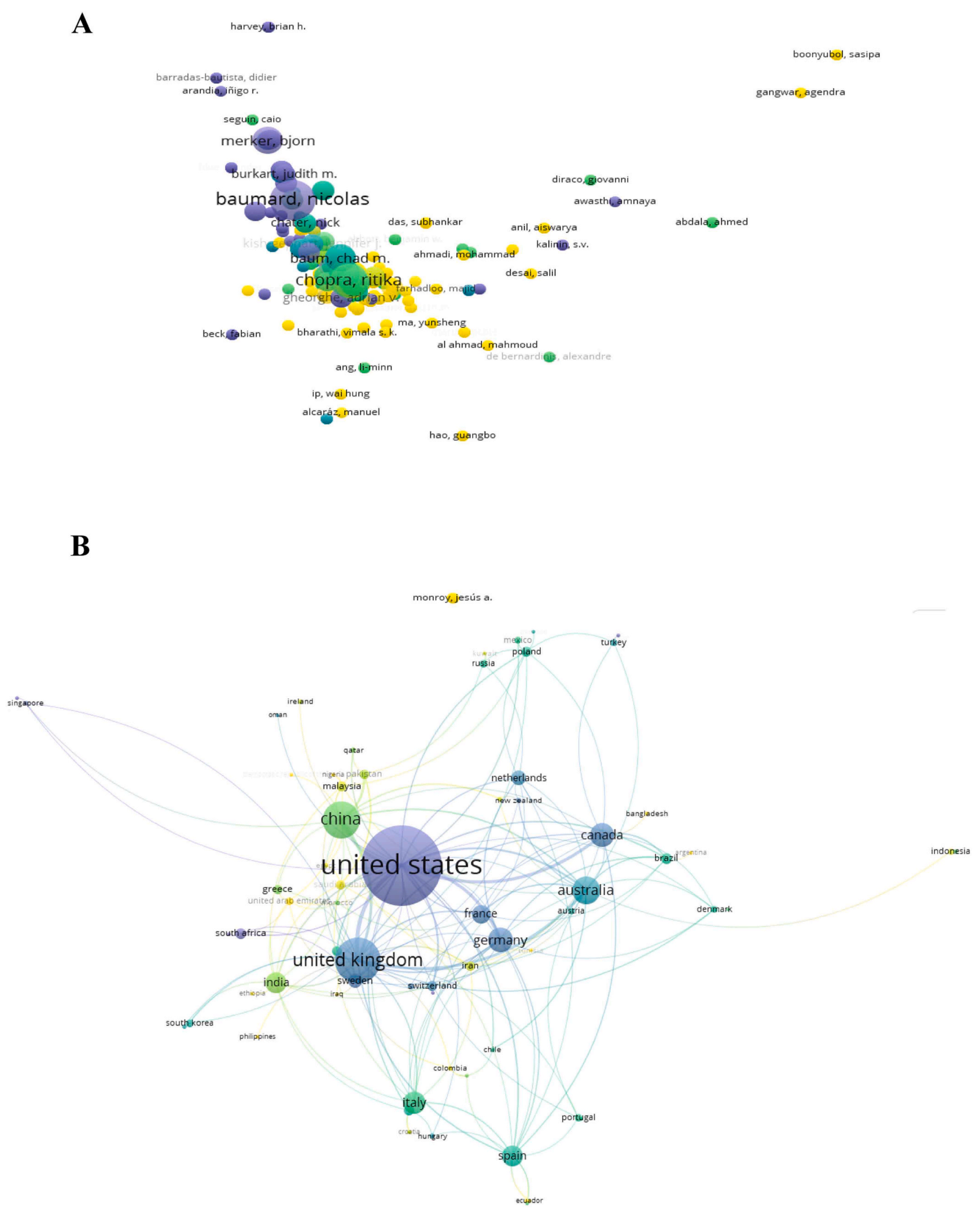

Fig. 3. A bibliometric plot of the interconnectedness of research collaboration at multiple levels: This figure illustrates research collaboration at two levels. (A) The Author Collaboration Network visualizes connections between individual researchers, highlighting key authors and their collaborative relationships. (B) The Country-Level Collaboration Network depicts global research partnerships, emphasizing major contributors such as Australia, the UK, Germany, Spain, the Netherlands, China, and the United States. In this network, larger nodes represent countries with higher collaboration levels, while lines indicate the strength of these connections. Different color groups frequently collaborate with countries, revealing regional or thematic research clusters.

Table 1
Overview of Predictive and Real-Time Energy Models for Marine Energy Systems Optimization.

Section	Content Descriptionadded	References
1. Overview of Predictive and Real-Time Energy Models	An overview of the significance of predictive and real-time energy models in enhancing marine energy systems, highlighting their contributions to energy forecasting, management, and optimization.	Pfenninger et al., (2014)
2. Tools for Assessing Energy Potential and Variability	SWAN (Simulation of Waves in the Nearshore): An overview of the SWAN model, highlighting its applications in forecasting wave energy potential and understanding variability in coastal and offshore regions. MIKE 21 (Two-Dimensional Hydrodynamic Model): A summary of MIKE 21's features for evaluating energy variability, with a focus on its application in marine environments, including tides and currents.	Cáceres et al., (2016)
Key Features of SWAN and MIKE 21	SWAN Features: Wave simulation, long-term wave energy forecasting, and analysis of variability. MIKE 21 Features: Two-dimensional flow modeling, real-time forecasting, and the ability to integrate with other environmental data for optimizing energy systems.	sheehan et al., (2020)
4. New analytical derivation of the mean annual water-energy balance equation	Water-Energy Balance: The long-term equilibrium within a catchment area involves the allocation of precipitation (*P*) between evapotranspiration (*E*) and runoff (*R*), shaped by various environmental factors.	Yang et al., (2008)
5. MRE: potential benefits to biodiversity	Shifting from fossil fuels to renewable energy sources is essential for addressing climate change, and the ocean presents significant, underutilized energy opportunities. The growth of offshore wind energy is accelerating, thanks to more favorable wind conditions at sea and reduced land-use conflicts compared to onshore wind farms.	Inger et al., (2009)
6. MRE Seascape	The use of fossil fuels plays a major role in global warming, highlighting the urgent need to shift towards sustainable alternatives like ocean energy. Ocean energy options, including offshore wind, tidal currents, wave energy, and thermal gradients, hold great promise but encounter obstacles related to technology, costs, and regulatory frameworks.	Borthwick, (2016)
7. Hydrodynamic modeling of MRE devices: A state-of-the-art review	It emphasizes progress in model testing, such as ITTC guidelines, the difficulties in simulating Power-Take-Off (PTO) systems and wind loads, as well as the uncertainties surrounding performance predictions.	Day et al., (2015)
8. Tribological design constraints of MRE systems	Governments around the globe are placing a high priority on the expansion of renewable energy, providing financial incentives aimed at lowering emissions, improving energy security, and boosting economic growth.	Wood et al., (2010)
9. Blue economy and competing discourses in international ocean governance	The rise of the "blue economy" in global environmental governance, emphasized at the 2012 Rio+ 20 conference, showcases a variety of interpretations.	Silver et al., (2015)
10. Towards a sustainable and equitable blue economy	The increasing exploitation of oceans for economic benefit, even in light of sustainability objectives such as SDG 14, highlights the pressing necessity for well-rounded policies to tackle challenges posed by industries, climate change, and insufficient protections.	Bennett et al., (2019)
11. Securing a just space for Small-Scale fisheries in the blue economy	Coastal and ocean development, driven by economic and ecological interests, often overlooks social concerns, marginalizing small-scale fisheries crucial for global food security and low-income communities in favor of larger-scale economic and conservation priorities.	Cohen et al., (2019)
12. Challenges of the Blue Economy: evidence and research trends	The Blue Economy (BE) focuses on economic activities reliant on the sea, including sectors like tourism, transport, energy, and fishing. This article conducts a bibliometric analysis to explore the growth and scientific focus on BE, Blue Growth (BG), and related concepts.	Martínez-Vázquez et al., (2021)
13. Transdisciplinary research in sustainability science: practice, principles, and challenges	Sustainability challenges require new approaches to knowledge production and decision-making, involving actors beyond academia to integrate diverse knowledge and values. Transdisciplinary, community-based, and participatory research methods are seen as key to addressing real-world sustainability problems.	Lang et al., (2012)
14. Transient Climate Response in a Two-Layer Energy-Balance Model. Part I: Analytical	It presents an analytical solution to the system and explores two climate change scenarios: step forcing and linear forcing. The article introduces a method to calibrate the EBM parameters using AOGCM experiments and applies it to	Geoffroy et al., (2012)

(continued on next page)

Table 1 (*continued*)

Section	Content Descriptionadded	References
	16 models from the CMIP5 project.	
15. Ocean observing and the blue economy	Ocean observations are crucial for scientific research and offer significant societal and economic benefits, including safety, operational efficiency, and regulation of ocean activities. The ocean economy, currently valued at about US$1.5 trillion, is expected to more than double by 2030, with its growth heavily relying on these observations.	Rayner et al., (2019)
16. Oxygen- and capacity-limitation of thermal tolerance	Rising temperatures challenge aquatic ectotherms by creating a mismatch between oxygen demand and supply, compounded by factors like ocean acidification and hypoxia, which narrow thermal performance windows, reduce fitness, and disrupt ecosystem dynamics.	Pörtner, (2010)
17. Analysis of laminar to the turbulent transition of pulsating flow in ocean environment with energy gradient method	The transition from laminar to turbulent flow in the ocean environment is studied using the energy gradient theory. The ocean environment has a minimal effect on the point of flow breakdown. However, the oscillation period's effect on the transition becomes more significant as the period increases.	Yan, (2011)
18. The blue economy: Identifying geographic concepts and sensitivities	The term "blue economy" has become widely used but lacks a clear, universally accepted definition.	Garland et al., (2019)

farms, suggesting potential population impacts resulting from habitat displacement (Vilela et al., 2021). This avoidance behavior raises concerns regarding the long-term viability of these species in regions experiencing extensive wind farm development. Moreover, the cumulative effects of multiple offshore wind farms within a single area have the potential to amplify these challenges. Data-driven approaches are essential for informing management strategies aimed at mitigating the impacts of offshore wind energy on marine wildlife (Ingram et al., 2024). As the number of offshore wind projects continues to grow, a thorough understanding of their synergistic effects on biodiversity becomes increasingly critical for effective conservation planning. These renewable energy installations can offer advantages like habitat restoration and a decrease in greenhouse gas emissions, but their development also poses threats to marine ecosystems and animals.

To address the challenges posed by offshore wind farms, innovative strategies involving the co-location of marine energy infrastructure with aquaculture and conservation initiatives are being investigated. By optimizing space usage in crowded marine environments, co-location enables multiple activities to occur within the same area (Bujas et al., 2023). For instance, the integration of offshore wind farms with aquaculture operations has been identified as a means to enhance the economic viability of both sectors while simultaneously reducing ecological footprints. A particularly promising approach is the implementation of Integrated Multi-Trophic Aquaculture (IMTA), which facilitates the cultivation of diverse species capable of utilizing each other's waste products. This system, by promoting resource efficiency, contributes to sustainability (Tang et al., 2024). Marine spatial planning (MSP) is recognized as a vital tool in enabling the implementation of co-location strategies. By evaluating the spatial requirements and ecological impacts associated with various marine activities, suitable areas for the joint development of offshore wind farms and aquaculture can be identified (Lin et al., 2022). This approach not only enhances the efficient utilization of marine resources but also reduces the potential for conflicts among competing ocean uses. Moreover, the integration of multi-purpose platforms that combine energy generation, aquaculture, and other marine activities has been shown to provide synergistic advantages, including increased energy efficiency and reduced operational costs (Manolache and Andrei, 2024; Hridoy et al., 2025b). Technological innovations are also essential for the successful integration of marine energy and aquaculture (Acharjee et al., 2026). The development of electrified mariculture systems that utilize renewable energy sources can enhance the sustainability of aquaculture operations by reducing reliance on fossil fuels (Koričan et al., 2022; Das et al., 2024). Fig. 4 presents a conceptual pathway showing how microbial fuel cells can support wastewater treatment while generating renewable energy for coastal community water management (Hridoy et al., 2025f).

Marine research and biodiversity protection face both opportunities and challenges as a result of the shift to renewable energy, especially with the construction of offshore wind farms. The ecological effects of these installations must be carefully considered, although they are essential in lowering carbon emissions. The growth of MRE may be coordinated with aquaculture and conservation efforts by putting into practice efficient marine spatial planning and investigating creative co-location techniques. By integrating multiple industries, this transdisciplinary strategy not only strengthens the blue economy but also promotes the long-term viability of marine ecosystems. It should be noted that the reported energy output estimates reflect different scales and reporting bases (e.g., modelled resource potential, pilot demonstrations, and installed versus planned capacities), and therefore should be interpreted as indicative rather than directly comparable across technologies (Table 2). For instance, tidal systems may show high site-specific potential, whereas salinity-gradient and some hybrid configurations remain limited to pilot-scale deployments. This highlights the importance of aligning technology choice with local resource conditions, ecological sensitivity, and development maturity.

4. The blue economy and sustainable energy

The rapid growth of offshore energy generation in the United States is evident, particularly in the development of offshore wind projects and emerging technologies that harness energy from waves, tides, and ocean currents (Chang et al., 2024). This growth presents opportunities for enhanced data collection on oceanic and coastal resources, which can foster economic development and help address societal and climate-related challenges. Additionally, it points out the obstacles to the large-scale implementation of offshore energy technologies, highlighting the necessity for innovative solutions to fulfill the nation's energy needs and tackle climate change (Chen et al., 2023). In China, the development of the MRE sector plays a vital role in promoting ecological civilization, ensuring energy security, and advancing the "Carbon Peaking and Carbon Neutrality" strategy (Pulselli et al., 2023). Marine energy sources, especially offshore wind and wave energy, hold significant potential for generating renewable electricity in Mediterranean islands. Emerging technologies, including floating wind turbines and wave energy converters, are currently under development (Roesch et al., 2020). Offshore renewable energy sources, such as wind and solar power, have the potential to deliver reliable electricity, facilitate water desalination, enhance aquaculture, and foster a sustainable blue economy that supports global growth and long-term development (Shields et al., 2011). Marine energy, which is generated from waves, tidal currents, ocean currents, and thermal gradients, plays a crucial role in the blue economy. However, its advancement is hindered by various challenges, including technical, social, and market obstacles, as well as the

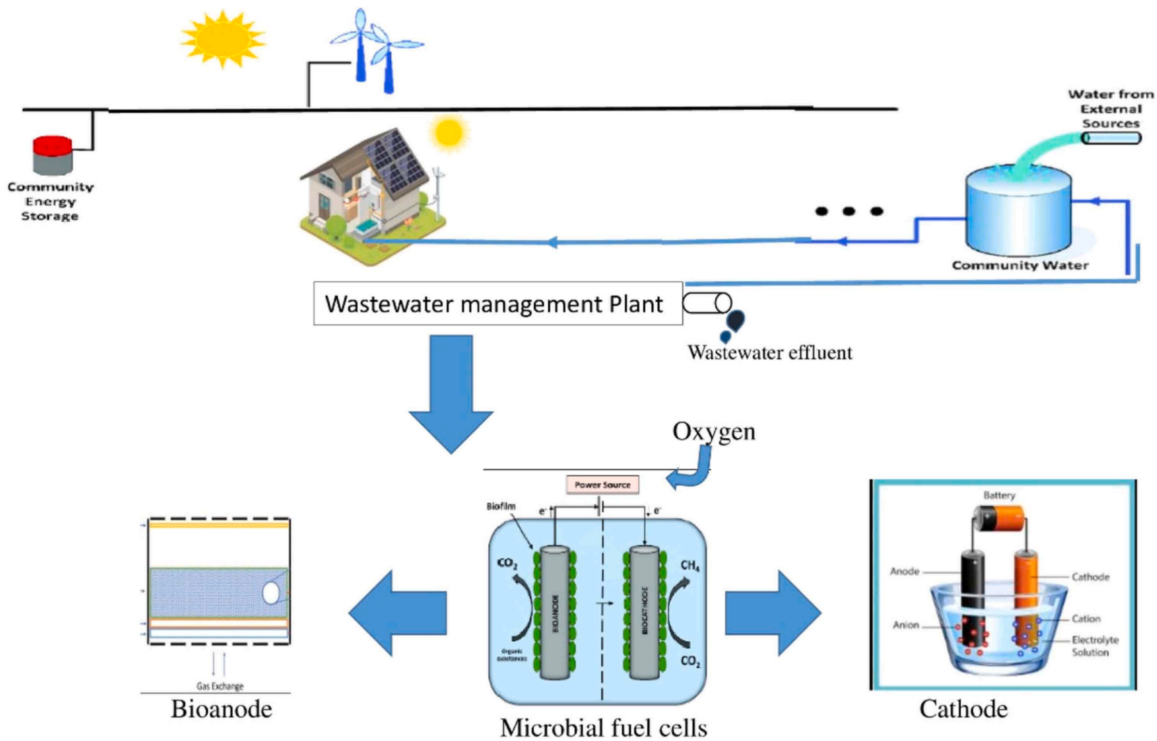

Fig. 4. Integration of Microbial Fuel Cells in Wastewater Treatment for Renewable Energy Generation and Community Water Management.

necessity for improved data accessibility and collaboration between the energy and ocean technology sectors (Shaw, 2021; Geerlofs, 2021). Quick evaluations of MRE resources have been carried out to determine their viability, demonstrating that these resources can greatly improve ocean observation efforts and increase overall ocean observation capabilities (Cavagnaro et al., 2020). Coastal communities in Indonesia, which boasts the second-longest coastline globally, play a crucial role in the nation's economy and society. Approximately 60% of the population resides in these regions, relying on coastal and marine resources for their livelihoods. These communities can be divided into fisheries and non-fishery groups, reflecting their dependence on natural resources and the influence of environmental conditions on their economic activities (Suciptaningsih et al., 2020).

The literature on the blue economy explores the opportunities and challenges faced by coastal communities, with a particular focus on the factors that facilitate or hinder their participation. It also examines the strategies employed by these communities and their supporting organizations to foster a sustainable blue economy. This perspective underscores the importance of prioritizing coastal communities in a comprehensive vision for an inclusive and sustainable blue economy, advocating for the co-development of a common language among stakeholders and the integration of social justice principles, and implementing governance systems that bridge various scales of action to ensure a more equitable ocean economy (Evans et al., 2023). In contrast, Komariah and Aisyah (2020) examined the Family Hope Program, a local initiative that aimed at enhancing the welfare of coastal communities in the Tembilahan District of Indragiri Hilir Regency, Riau Province. This program encompasses various strategies, including cash assistance, food distribution, health insurance, educational services, and support for micro-businesses. However, its effectiveness is largely restricted to fulfilling basic needs and supporting small business growth, indicating a need for further program enhancements, such as expanding its scope to address long-term economic resilience. The study highlights the crucial role of local government oversight in the program's implementation and emphasizes the need for further research to pinpoint and address its shortcomings. Empowering coastal communities both economically and educationally is vital for achieving economic equality and improving their overall quality of life (Table 3).

5. Energy analytics in renewable systems

By 2050, the share of renewable energy in total final energy consumption is projected to increase by per year approximately 0.7 %age points, accounting for nearly half of the total growth in the global renewable energy share. In the REmap Case, electricity consumption in the household and commercial sectors will be more than double relative to 2015 levels, reaching over 42,000 TWh. Simultaneously, carbon emissions from the power sector are projected to decline by approximately 85% (Gielen et al., 2019). This transition implies a substantial expansion of renewable electricity infrastructure. As a result, installed renewable power capacity is projected to increase nearly eightfold, from approximately 2000 GW to 16,000 GW by 2050, driven primarily by rapid electrification of end-use sectors and accelerating deployment rates. Within this expansion, solar energy is expected to contribute approximately 7122 GW at the same time wind energy contributes around 5445 GW, representing roughly a twofold increase in solar capacity and a threefold increase in wind capacity relative to 2017 levels (Cherp et al., 2021). No more coal plants should be built, and 95% of existing coal plants must be decommissioned to meet decarbonization goals. To reach a goal of USD 500 billion per year until 2050, the investment in renewable energy sources needs to be increased. In the context of the fully decarbonized power sector, total investments are projected to average approximately USD 1 trillion annually until 2050 (Gielen et al., 2019). The bar chart shows the distribution of new renewable energy capacity, with China accounting for more than one-third, followed by the United States, India, and the European Union (Fig. 5).

Energy analytics is driven by big data and artificial intelligence (Himeur et al., 2023), and it has relevance not only in the broad context of energy systems, but also in the more specialized context of marine energy sources. The world is transitioning to more sustainable energy solutions, therefore, there is an increasing need for data-driven

Table 2
Characteristics and Environmental Impacts of MRE Technologies.

Technology	Energy Output Potential (MW)	Ecological Impacts	Mitigation Strategies	Case Study Location	References
Offshore Wind	2000–8000	Habitat disruption, bird collisions	Co-location with conservation areas	North Sea Wind Farms, Europe	Dhar et al., (2020)
Tidal Energy	(~2000) 1000–3000	Altered tidal flows, fish mortality	Fish-friendly turbines	Bay of Fundy, Canada	Kiranben and Suvin, (2011) Karsten et al. (2011)
Wave energy	0.196–0.422	change oceanic conditions and ecosystems, accelerate coastal erosion, and cause undersea noise pollution.	Environment-friendly equipment and stakeholder collaboration needed	Black Sea, Turkey	Akar and Akdoğan, (2016)
Tidal Stream	6–398 (6 MW installed, 398 MW planned)	destroy marine benthos and habitats, alter the seafloor, and potentially contaminate the surrounding area.	Organism-friendly turbine, eco-friendly power cable	MeyGen project, Pentland Firth, Scotland	Chen et al., (2018)
OTEC	16	Impact on primary production, nutrient pollution.	Environmental awareness is sufficient data for the study.	Martinique island, Caribbean Sea, France	Devault and Péné-Annette, (2017)
Salinity Gradient	0.05	changes in the nutrients and salinity, impact on native species, and natural ecosystems	Considering the effect and proper treatment of effluent	La Carbonera Lagoon, Yucatan, Mexico	Marin-Coria et al., (2021)
Floating solar PV	30	effects on net primary production, concern for coral reefs, and seagrass	need to be assessed comprehensively, public opinion needs to be considered	Swimsol's floating SolarSea™ platforms, Maldives	Hooper et al., (2020)
Hybrid energy system (Solar PV, wind, and wave)	538	Effect on primary production, Biodiversity loss, noise pollution	Considering the effect and sufficient data for the study	Persian Gulf, Iran	Jahangir et al., (2020)
Hybrid energy system (wind and wave)	~3 (pilot-scale)	Collisions with birds and cetaceans, change the oceanic condition	Effective monitoring and assessment needed	Sydney, AU	Gao et al., (2023)
Hybrid energy system (Solar PV and offshore wind)	200–1600	Effect underwater vegetation, habitat destruction	Careful site selection and taking precautionary actions	Asturias, Spain	López et al., (2020)
Offshore Wind	2000–8000	Habitat disruption, bird collisions	Co-location with conservation areas	North Sea Wind Farms, Europe	Dhar et al., (2020)
Tidal Energy	1000–3000	Altered tidal flows, fish mortality	Fish-friendly turbines	Bay of Fundy, Canada	Kiranben and Suvin, (2011)

approaches to manage the inherent variability and intermittency of renewable resources (Bachmann et al., 2022).

Predictive analytics techniques (Rangel-Martinez et al., 2021) are mostly related to forecasting of energy production and demand. This is important for balancing supply and demand in real time and for long-term infrastructure planning (Kaur et al., 2024). In the context of MRE, predictive analytics is particularly valuable for addressing the variability of resources such as tides, waves, thermal gradients, and offshore wind (Nezhad et al., 2024).

Advanced tools in predictive analytics include machine learning algorithms, artificial intelligence, and statistical models (Ahmad et al., 2022; Hridoy et al., 2026d, 2025e). Offshore wind energy, in particular, benefits from predictive tools that forecast wind patterns (Mishra et al., 2020), and ramping events (Mishra et al., 2020). Advanced machine learning models, along with meteorological and oceanographic data, enable accurate predictions of wind speeds and directions. This information is important for adjusting operations to maximize energy generation. Predictive analytics also helps with long-term planning by forecasting maintenance needs and enhancing turbine performance through data-driven insights (Zhou and Yin, 2019). These capabilities allow for smoother integration of offshore wind into energy grids, complementing other marine energy sources like tidal and wave power. These approaches enable accurate forecasts of energy availability and consumption patterns, and when combined with prescriptive analytics, they empower stakeholders to optimize resource utilization (El Morr et al., 2019). Prescriptive analytics (Frazzetto et al.,2019) in the form of optimization methods for hybrid renewable energy systems, those that combine marine energy with other renewable sources like wind and solar—is crucial for maximizing efficiency and minimizing costs.

Prescriptive analytics takes predictive insights a step further by recommending optimal actions based on data-driven forecasts (Stratigakos, 2023; Sa'adi et al., 2025). In the context of offshore wind energy, prescriptive analytics is crucial for enhancing decision-making in areas like turbine operation, maintenance, and energy integration into the grid. By analyzing real-time data on wind speed, turbine performance, and environmental conditions, prescriptive models can suggest adjustments to operational parameters, such as rotor speed or blade pitch, to maximize energy production (Yang et al., 2023; Hridoy and Paul, 2024). Additionally, prescriptive analytics can optimize maintenance schedules by identifying the most cost-effective timing for repairs or replacements, reducing downtime and increasing turbine lifespan (Fox et a., 2022). Ultimately, prescriptive analytics helps offshore wind operators improve efficiency, lower costs, and ensure more reliable energy supply, facilitating the smooth integration of offshore wind into broader energy systems (Santiago et al., 2024). Furthermore, these energy analytics approaches help in improving energy storage strategies,

Table 3
Blue Economy Contributions to Energy Transition and Sustainable Development.

Sector	Renewable Energy Contribution	Environmental Sustainability Practices	Examples	Reference
Offshore Renewable Energy	Significant (Wind, tidal integration)	Eco-friendly infrastructure installation	Wind Farms, North Sea	Afridi et al., (2024)
Marine Transport	Logistic support for energy projects	Shift to low-emission fuels	LNG-based shipping, Europe	Watanabe et al., (2022)
Offshore Aquaculture	Potential for co-located wave (or tidal) energy devices to supply electricity to offshore aquaculture farms, reducing reliance on diesel generators	reduce nearshore environmental effects, reduce greenhouse gas emissions, Provide clean energy and competition for space	Offshore finfish aquaculture, offshore seaweed aquaculture, Europe	Garavelli et al., (2022); LiVecchi et al., (2019); Freeman et al., (2022)
Marine Biotechnology	Product innovation and development (Blue biomass), Growth of fish (Gene transfer technology), disease control (Penaeid shrimp)	Sustainable food supply, genetic variation	Shrimp, fish, seaweed farming, Europe, Asia Pacific	Uddin and Islam, (2019); Aftabuddin et al., (2008); Vaseeharan et al., (2005)
Sustainable Tourism	Ecological tourism, low-carbon tourism, Lohas tourism, wind power installation on sites	Developing a low-carbon coastal tourism economy, improving the quality of resource development, increasing energy utility	Coastal zones, coastal wetlands, Scotland, New Zealand, Costa Rica, Norway, Sri Lanka	Blake, (2007); Fang and Dakui, (2014); Dowling, (2013)
Seabed Mining	Marine mineral exploration and extraction, source for many critical metals and gems (Cobalt, manganese, tellurium)	Protecting vulnerable areas, Preventing, reducing, and controlling coastal pollution, and preventing damage to the flora and fauna from mining activities	Peru Basin nodules, and the Central Indian Ocean Basin, Penrhyn Basin-Cook Islands EEZ	Sakellariadou et al., (2022); Thompson et al., (2018); Hein et al., (2013)
Offshore Oil Industry	Integrated and sustainability-focused ocean economy (oil and gas, fishing and aquaculture, and renewable energy)	Decarbonizing the oil sector and concentrating on locally lowering production emissions can help meet the Paris Climate Agreement	Offshore Oil Industry, Newfoundland and Labrador, Canada	Fusco et al., (2022); World Bank, (2017)
Electrification of The Seas	Charging at wind and fish farms, thermal-powered platforms, by floating solar panels, tidal plants, and offshore container terminals through wave, solar, thermal, wind, and tidal power supplies	Carbon neutrality, carbon emission mitigation strategies	Zero emission ocean economy, sustainable production in maritime and offshore sectors, North Sea Region	Spaniol and Hansen, (2021); Savitz et al., (2020); LiVecchi et al., (2019); Schober et al., (2018); World Energy Council, (2017); Pachakis et al. (2016); Troell et al., (2004)
Green technologies in Maritime Sectors	Cost-effective renewable hydrogen production in short-sea shipping potential incubators for solutions in deep-sea shipping and hydrogen-based fuels for main engine power of vessels through research and innovation	Reduction of pollutants, energy efficiency addition to renewable energy sources, and decarbonization	Zero-emission waterborne transport, European Union	Campana et al., (2021)
Biofuel Production	Implementing microalgae as a renewable feedstock for biofuels (solid, gas, liquid fuels) and crude oil manufacture	Smaller carbon footprint than fossil fuels, renewable and eco-friendly	Efficiency as renewable, and sustainable biomass resource for third-generation biofuel production	Subhash et al., (2022); Choudhary et al., (2021); Debnath et al., (2021)
Offshore Renewable Energy	Significant (Wind, tidal integration)	Eco-friendly infrastructure installation	Wind Farms, North Sea	Afridi et al., (2024)
Marine Transport	Logistic support for energy projects	Shift to low-emission fuels	LNG-based shipping, Europe	Watanabe et al., (2022)

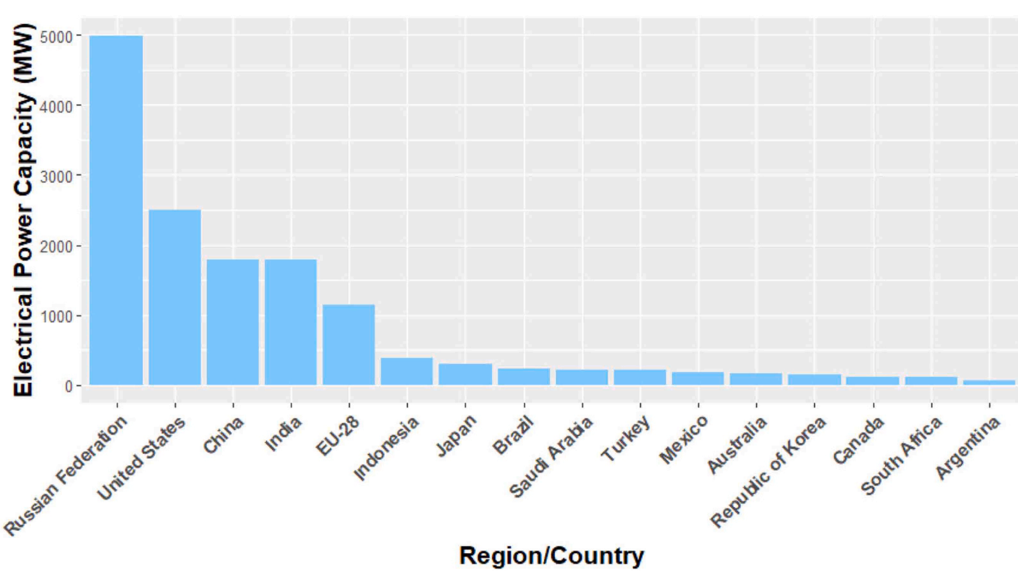

Fig. 5. Projected Renewable Power Generation Capacity Additions (2018–2050): Forecasted Electrical Power Capacity (GW) by Region/Country (Adapted from Gielen et al., 2019).

recommending optimal times for charging batteries or other storage systems based on predicted energy production patterns (Rangel-Martinez et al., 2021). By employing a combination of predictive and prescriptive analytics, marine energy systems can operate more efficiently, reduce operational costs, and better integrate into national grids, ultimately contributing to a more resilient and sustainable energy transition (Jaramillo Jimenez et al., 2025).

Finally, the integration of marine energy sources, such as tidal, wave, and offshore wind—into national grids is a critical challenge that requires careful planning, advanced forecasting, and sophisticated energy management strategies (Weiss et al., 2018; Simbolon et al., 2024). Marine energy, while highly promising as a renewable resource, presents unique challenges due to its variability and location-specific nature. Predictive and prescriptive analytics play a key role in addressing these challenges by providing data-driven insights into the optimal times for energy generation, transmission, and storage. Tidal and wave energy, for example, are often predictable but intermittent, meaning their generation may not always coincide with peak demand. This is where integration strategies come into play, utilizing tools like demand-side management, energy storage systems, and grid flexibility to accommodate fluctuations in marine energy output (Kumar et al., 2022). By leveraging real-time data from marine energy farms and forecasting tools, grid operators can anticipate periods of high or low energy production and adjust the grid's operation accordingly. Furthermore, advanced grid infrastructure, such as smart grids and flexible interconnectors, allows for better transmission of marine energy from remote offshore locations to mainland grids. The combination of marine energy with other renewable sources, like solar and wind, can also enhance overall grid stability by creating a diverse energy mix that balances out intermittent power production (Khurshid et al.,2024). In this context, marine energy can become a reliable and integral part of national grids, contributing to the transition to a low-carbon energy future (Simbolon et al., 2024; Masood et al., 2025). This table provides a comprehensive overview of various applications of energy analytics in MRE systems, offering a snapshot of the key areas, technological methods, recent developments, and references in this field. A key takeaway from the identified literature is the diversity of technological approaches used to address the multifaceted challenges of marine energy systems, such as optimizing energy output, enhancing grid stability, minimizing environmental impacts, and improving cost efficiency.

The literature presented in the table also highlights the advancements in analytics tools (e.g., machine learning, predictive modeling, optimization algorithms) that are being increasingly integrated into marine energy systems to improve operational performance and reliability. As can be noted, there is a clear emphasis on hybrid solutions, like combining marine energy with storage systems (e.g., hydrogen, battery storage) and integrating multiple renewable sources (e.g., wind, solar, and marine energy) to enhance overall system efficiency and resilience. Another important observation that can be done from the existing literature, is the growing role of real-time monitoring and predictive maintenance, which helps in minimizing downtime and ensuring consistent energy production. The integration of marine energy with smart grids and the use of technologies like blockchain and IoT are emerging trends aimed at improving grid management and securing

Table 4
Role of Energy Analytics in Optimizing MRE Systems.

Energy Analytics Application	Key Area of Focus	Technological Methods	Recent Developments/Trends	References
Predictive Modelling for Energy Output	Optimizing energy generation efficiency	Machine Learning, Artificial Neural Networks (ANN), Support Vector Machines (SVM)	Integration of predictive algorithms for energy forecasting in wave and tidal energy systems, enhancing predictive accuracy under variable ocean conditions	Shadmani et al., (2023)
Energy Storage Optimization	Enhancing grid stability and reducing intermittency	Battery Storage, Flywheels, Hydrogen Storage, Dynamic Modeling	Cutting-edge energy storage options combined with marine energy systems, include hybrid storage that combines the production of hydrogen and batteries.	Atawi et al., (2022)
Real-time Monitoring and Control	Enhancing system reliability and efficiency	Internet of Things (IoT), Remote Sensing, SCADA Systems	Monitoring and control in real-time increasing system efficiency and dependability SCADA systems, remote sensing, and the Internet of Things (IoT).	Karad and Thakur, (2021)
Environmental Impact Assessment	Minimizing ecological disruption	Geographic Information Systems (GIS), Data Analytics, Machine Learning	For precise environmental effect prediction and mitigation planning, sophisticated GIS and machine learning methods are utilized.	Anwar and Sakti, (2024)
Cost Optimization and Resource Allocation	Reducing operational costs and maximizing resource use	Economic Modeling, Optimization Algorithms	Allocating resources optimizing cost utilization and cutting operating expense algorithms for economic modeling and optimization multi-objective optimization methods are used in marine energy projects to balance performance and cost.	Yaiprasert and Hidayanto, (2024)
Integration with Smart Grids	Enhancing energy distribution and management	Smart Grid Technology, Blockchain, Advanced Metering Infrastructure (AMI)	Using AMI for real-time data communication between marine systems grids and blockchain for safe energy transactions	Appasani et al., (2022)
Turbine Performance Analytics	Improving energy capture and efficiency	Computational Fluid Dynamics (CFD), Digital Twins	Utilizing digital twin technology to optimize blade design and simulate turbine performance in tidal and wave systems	Erdogan et al., (2025)
Predictive Maintenance	Reducing downtime and maintenance costs	Predictive Analytics, Machine Learning	Predictive maintenance technologies are being used to track and foresee malfunctions in vital marine energy equipment.	Udo et al., (2024)
Hybrid Energy System Integration	Combining multiple renewable energy sources	System optimization algorithms, hybrid modelling	Integrating several renewable energy sources into a hybrid energy System Hybrid modeling and system optimization algorithms create hybrid systems that combine marine, solar, and wind energy to increase output and dependability	Verma et al., (2024)

energy transactions. Overall, the literature indicates that analytics enables forecasting, optimization, predictive maintenance, and smart-grid integration across MRE systems (Table 4).

6. Policy implications

Human interactions with oceans have historically shaped civilizations, cultures, and economies. However, advancements in human enterprises have led to increasing ocean exploitation, creating complex governance challenges (Jouffray et al., 2020; Hridoy et al., 2026c). Such complex problems demand multiscale collaboration, communication, and transformational behavior change to reconcile sustainable development with environmental stewardship (Patterson et al., 2017; Bennett et al., 2019). The United Nations Decade of Ocean Science (2021–2030) promotes global cooperation for a sustainable ocean. It aims to develop inclusive, equitable, participatory governance frameworks to articulate an intergovernmental understanding of sustainability goals (Guan et al., 2023). MRE (MRE) technologies in Areas Beyond National Jurisdiction (ABNJ) face challenges related to the lack of clear regulatory frameworks that could guide development and resolve issues regarding sovereignty, jurisdiction, and spatial conflicts (Hutchins, 2021). UNCLOS establishes a framework for regulating the seas, granting the freedom to construct installations and submarine cables. However, it emphasizes that these freedoms are not unlimited and must be governed by principles that balance competing interests and prevent ecosystem damage.

Although the blue economy emphasizes sustainable development through the utilization of ocean resources, its implementation remains limited, with only 10% of UN member states achieving substantial progress in adopting high-level policies (Voyer et al., 2021). To address this gap, policies and practices that integrate economic, social, and environmental sustainability are required. International frameworks, such as the ASEAN Leaders Declaration (ASEAN, 2022), provide critical support for these efforts. However, effective implementation depends on political will, existing institutional capacity, and context-sensitive governance to convert these strategies into implementable policies (Bennett et al., 2019; Keen et al., 2018). The Jamaican example shows how national-level policies can promote sustainable ocean management. However, it also highlights significant weaknesses in policy articulation and implementation, underscoring the need to embed accountability and transparency within governance frameworks (Smith et al., 2022). In parallel to the mechanisms of monitoring, evaluation, and reporting, which are already part of national policies, it is key to support sustainable practices and an equitable economy whilst protecting and restoring ecosystems (Louey, 2022; Voyer et al., 2022).

The importance of integrated frameworks to align local and global approaches is now recognized, given the complexity of governance of MRE technologies and the blue economy. Efforts to balance climate change and biodiversity loss need to be supported by international cooperation, knowledge transfer, and adaptive governance frameworks that promote equitable resource use, protection of ecosystem services, and sustainable development (IPCC, 2018; Allison et al., 2020; Gissi et al., 2022). The regulatory frameworks for MRE (MRE) in Areas Beyond National Jurisdiction (ABNJ) are needed to resolve jurisdictional disputes and spatial conflicts while ensuring environmental protection (United Nations, 1982). Strengthening institutional capacity and adopting adaptive governance frameworks can promote transparency, accountability, and sustainable development (Bennett et al., 2019; IPCC, 2018; Gissi et al., 2022). Policies should also incentivize innovation, facilitate international cooperation, and support knowledge sharing to address climate change and biodiversity loss (ASEAN, 2022; Allison et al., 2020). The Energy Policy Act of 2005 supports MRE (MRE) by providing loan guarantees, tax incentives, and funding, which includes $500 million allocated for Clean Renewable Energy Bonds and $2.7 billion for renewable electricity production credits. This legislation fosters sustainable energy development (U.S. Congress, 2005; Lin et al., 2007; Blazev, 2021). Initiatives like the Ocean Renewable Energy Coalition highlight the significance of engaging stakeholders to expedite the commercialization of MRE and enhance public awareness (Zabihian and Fung, 2011). Future research should investigate the effectiveness of adaptive governance frameworks in addressing jurisdictional conflicts and promoting the global expansion of MRE.

To enhance governance frameworks for MRE and the blue economy, policies should focus on clarifying legal and regulatory frameworks in ABNJ to address jurisdictional disputes, spatial conflicts, and sovereignty issues, thereby promoting sustainable development (United Nations, 1982). Policy Coherence for Sustainable Development (PCSD) harmonizes economic, social, and environmental objectives, providing tools to reconcile energy development with marine conservation in governmental decision-making (Voyer et al., 2020). Integrated scientific approaches are essential for aligning marine conservation with sustainable resource production, particularly in pelagic fisheries, to inform policies that balance energy requirements with conservation initiatives, thereby supporting global sustainability goals (Kittinger et al., 2024). The ecosystem-based natural capital evaluation framework assesses the environmental and socio-economic effects of offshore renewable energy (ORE) projects, facilitating improved marine spatial planning and informed decision-making that reconciles energy sustainability with marine conservation and fisheries management (Trifonova et al., 2022).

7. Transdisciplinary challenges, synergies, and dimensions in research and education

Transdisciplinary approaches foster critical thinking, systems analysis, and collaborative problem-solving by integrating knowledge and methodologies from diverse disciplines. These are essential competencies for navigating the interconnected social, economic, and environmental dimensions of sustainability. Moreover, transdisciplinary education encourages students to engage with real-world problems, working alongside stakeholders from government, industry, and local communities to co-create actionable solutions (Takeuchi et al., 2020).

Navigating the energy transition requires transdisciplinary collaboration to address systemic challenges and leverage synergies across diverse fields such as marine science, the blue economy, energy analytics, and sustainability (Ozsoy and Mengüç, 2023). This section explores the critical dimensions of these collaborations, including their implications for research and education. An integrative framework is presented to illustrate the progression from foundational principles to technological innovation, implementation strategies, and tangible outputs in achieving sustainable energy transitions. While primarily focused on research and practice, the proposed framework offers valuable insights for education by highlighting the competencies and collaborative approaches needed to prepare future leaders. By linking these elements, this section aims to provide a holistic perspective on how transdisciplinary challenges can be addressed in both academic and applied settings.

Fig. 6 presents an integrative framework for advancing marine energy transitions through transdisciplinary collaboration. The framework synthesizes evidence from the reviewed literature and highlights how sustainable MRE deployment requires alignment across four interconnected stages: (i) guiding principles (sustainability, equity, and innovation), (ii) enabling conditions for technological development (infrastructure, financing, policy, and socioecological suitability), (iii) implementation mechanisms (stakeholder engagement, monitoring, and adaptive management), and (iv) outcomes (low-carbon energy supply, ecosystem protection, and blue economy growth). Importantly, the framework emphasizes that successful MRE expansion depends on balancing economic, ecological, and social viability and requires coordinated action among governments, industry, NGOs, research institutions, and coastal communities. This framework therefore provides a structured roadmap for linking research, governance, and deployment pathways in future marine energy transitions. Unlike previous conceptual discussions, this framework explicitly links technology readiness,

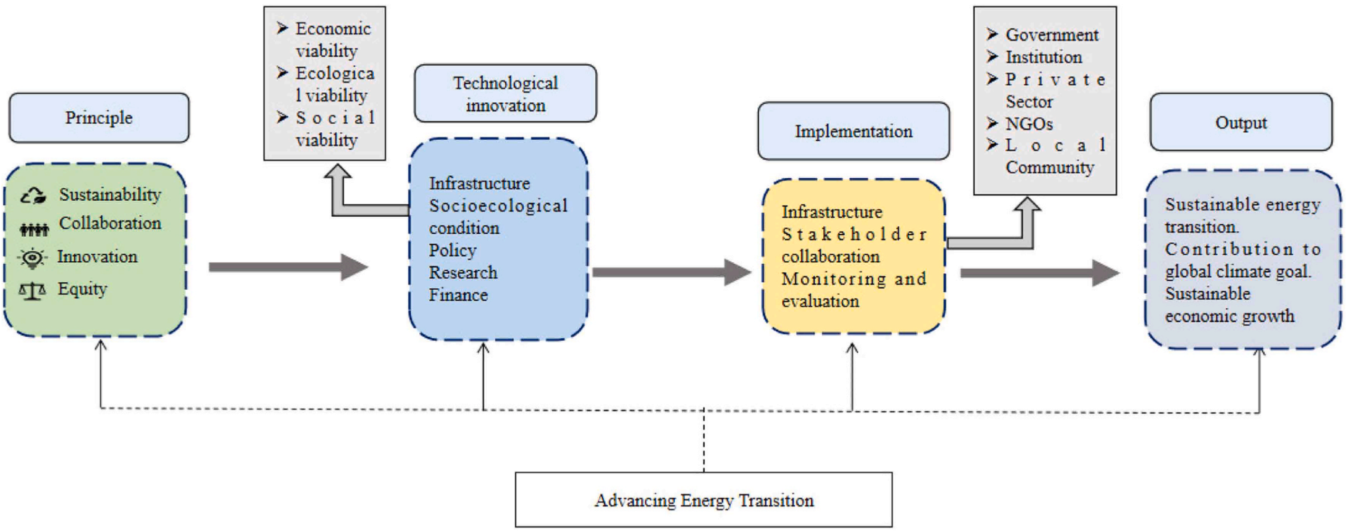

Fig. 6. Integrative Framework for Advancing Energy Transition Through Transdisciplinary Collaboration.

governance, and socio-ecological safeguards in a single pathway for scalable MRE deployment.

8. Integrating economic growth with sustainability

The world's oceans are undergoing rapid industrialization, driven by technological advancements and the increasing global demand for food, energy, and resources. Marine Energy (ME) technologies have reached the stage where they can be deployed on a large scale, moving from experimental phases to commercial operation. While the highest ME potential is found along the Atlantic and Nordic coasts, the Mediterranean Sea also holds valuable resources that can contribute to sustainable energy production and economic growth in Southern Europe (Pisacane et al., 2018). Australia's energy system continues to be largely dependent on fossil fuels, with the transition to renewable sources progressing slowly (Bellon De Chassy, 2020). Similarly, Iran has significant marine energy potential across multiple technologies (Zabihian and Fung, 2011). The coasts of the Persian Gulf demonstrate significant tidal energy potentials, whereas the coasts of the Caspian Sea are appropriate for thermal energy production (Khojasteh et al., 2018). Additionally, wave energy can be efficiently captured along the coasts of the Gulf of Oman and on remote off-grid islands (Rehman et al., 2023). Wave energy potential is highest in western South America, particularly in northern Chile and Peru, characterized by low wave variability (Weiss et al., 2018). Stable wave resources are also observed near the equator in the Pacific, Atlantic, and Indian Oceans, and between latitudes 40° and 60° south, presenting substantial opportunities in Guatemala, Mexico, Gabon, Angola, Indonesia, and New Zealand. While Morocco, Madagascar, and Brazil demonstrate wave energy potential, their unstable wave conditions may diminish the efficiency of Wave Energy Converter (WEC). However, it is important to distinguish resource availability from deployment readiness: despite strong theoretical potential in many regions, wave energy remains at a comparatively low technology readiness level, and large-scale commercial deployment is still constrained by cost, survivability, and operational challenges (Astariz, and Iglesias, 2015). At present, there are no operational offshore wave farms, and commercially viable technology is still inadequately developed (Weiss et al., 2018). Brazil and New Zealand lead in wave power generation, producing 372.1 TWh/month and 285.6 TWh/month, respectively. Simultaneously, South Africa, Argentina, and Australia exhibit superior power efficiency per device (da Cruz Weiss, 2018).

Wind energy potential is mainly found near coastlines, with key high-potential areas in South America, North America, Southeastern Asia, Northwestern Europe, the Mediterranean, the South Pacific, and Morocco (Weiss et al., 2018). Major offshore wind production zones, such as the North Sea, the US, and China align with these high-potential areas. Early-stage developments in Greece, Japan, and South Korea also aligned with these zones. Additionally, unexplored regions like the EEZs of Morocco, Mauritania, Argentina, and Venezuela present significant opportunities for forthcoming offshore wind development. Moreover, according to a global resource assessment the theoretical offshore wind energy potential in the United Kingdom and the United States was estimated at approximately 1470 TWh/month and 1079 TWh/month respectively when evaluated under standardized resource conditions using long-term wind datasets and a representative 10-MW turbine (Weiss et al., 2018). Other countries with significant potential include the Netherlands, Denmark, Brazil, and Germany, with monthly energy outputs of 2.3 GWh per NREL turbine and 4.7 GWh per DTU turbine. Although New Zealand, Argentina, and Uruguay presently do not possess offshore wind farms, they signify promising future markets for wind energy development.

Coastal communities are particularly vulnerable to socio-ecological risks because of their location and dependence on natural resources (Kazimierczuk et al., 2023). Their resilience and ability to adapt to social, economic, and environmental changes are influenced by a variety of factors, including community-specific characteristics and values that affect their development. MRE (MRE) offers a promising solution to enhance coastal resilience, support environmental sustainability, and improve energy security, affordability, and socio-economic benefits (Kazimierczuk et al., 2023; Bhuiyan et al., 2022; Hridoy et al., 2025g, h). The complex nature of energy transitions requires localized, multidisciplinary approaches to thoroughly understand and address the distinct needs of these communities. MRE has strong potential to shape local energy futures, but there is still significant uncertainty about aligning MRE deployment with community goals for resilience and fair development that match the community's values. Studies indicate that MRE deployment is more effective when meticulously coordinated with community priorities (Kazimierczuk et al., 2023). Additionally, addressing conflicts around energy and economic development requires creating opportunities for active engagement between community groups and organizations such as utility providers and local governments. Bottom-up involvement in decision-making tends to build more trust than top-down approaches that focus solely on economic growth or regulatory compliance over community-oriented objectives.

Marine-based renewable energy offers a sustainable solution for building eco-friendly infrastructure by harnessing power from the ocean's waves, tides, and offshore winds. This clean energy can be used to reduce reliance on fossil fuels, lowering carbon emissions and supporting the transition to greener, more resilient infrastructure. Integrating marine energy systems, such as tidal and wave energy converters, into buildings and coastal developments allows communities to harness renewable energy while reducing environmental impacts. This approach improves energy efficiency, strengthens energy security, and promotes sustainability in urban planning and construction. However, shipping is vital for global trade, handling 90% of the world's trade transport commodities (Pournara et al., 2019). Although shipping contributes less to marine pollution compared to other human activities, it remains a considerable source of environmental waste and emissions. Shipping is a significant emitter of air pollutants, with greenhouse gas (GHG) emissions constituting 2.6% of global emissions in 2012. Forecasts indicate this may rise to 3.9–6.5% by 2050 (Barker and Crawford-Brown, 2014). Promoting the adoption of shore power systems and energy-efficient port equipment can significantly lower emissions from ships while they are at the dock. Moreover, adopting alternative fuels, including green hydrogen and biofuels, in port operations and shipping can expedite decarbonization in the maritime sector.

9. An integrated transdisciplinary decision framework for sustainable marine renewable energy deployment

While existing contributions in the literature examine marine renewable energy (MRE), blue economy governance, energy analytics, and sustainability education mostly as separated thematic streams, their operational interdependencies are still not sufficiently structured within a unified and decision-oriented perspective. The current debate remains often compartmentalized, where each dimension is analysed in isolation without fully addressing how these dimensions condition each other in practice.

In order to address this gap, this review proposes an Integrated Transdisciplinary Decision Framework (ITDF) for sustainable MRE deployment.

The bibliometric clustering analysis reveals four dominant but fragmented research streams: ecological impact, governance frameworks, energy analytics, and educational/participatory approaches. The ITDF is derived as a structural integration of these four clusters. Hence, the proposed framework conceptualizes MRE development not as a purely technological pathway, but as a multi-layered decision system where four key pillars (ecological, governance, technical and societal) interact continuously.

9.1. Pillar 1: ecological–marine constraints

The first layer refers to ecological feasibility conditions. It incorporates biodiversity protection, habitat disturbance thresholds, cumulative environmental impact assessment, and marine spatial planning (MSP). This layer defines the ecological boundary conditions within which MRE systems must operate. In other words, technological expansion cannot be considered independent from marine ecosystem resilience. Ecological constraints are therefore not external factors, but intrinsic decision variables influencing system configuration.

9.2. Pillar 2: blue economy governance and socioeconomic viability

The second layer addresses governance coherence and distributive impacts. It integrates coastal livelihoods, fisheries coexistence, equitable resource allocation, policy alignment with SDGs 7 and 14, and conflict mitigation between marine sectors. This pillar evaluates whether MRE deployment generates balanced socioeconomic outcomes or whether it creates spatial and economic asymmetries. Governance mechanisms therefore mediate not only regulatory compliance, but also legitimacy and long-term stability of marine energy projects.

9.3. Pillar 3: energy analytics and system optimization

The third pillar focuses on technical system performance and operational reliability and it includes forecasting models, variability management, grid integration strategies, storage coordination, and optimization of hybrid renewable configurations. The resource potential is translated into operational feasibility in this layer. Energy analytics does not simply estimate production levels, but operationalizes decision making under uncertainty, and optimization techniques allow the coordination of multiple energy vectors within environmental and regulatory constraints.

9.4. Pillar 4: sustainability education and social enabling mechanisms

The fourth layer strengthens adaptive capacity through education, workforce development, public understanding, social acceptance, and participatory governance. This pillar functions as the enabling interface between technological systems and societal implementation. Without adequate educational structures and social engagement processes, even technically mature solutions may fail in real-world deployment.

9.5. From parallel dimensions to interdependent decision layers

Rather than treating the four dimensions as parallel and independent themes, the ITDF structures them as interdependent decision layers:

- Ecological feasibility constrains technical system design.
- Governance frameworks mediate spatial allocation and distributive outcomes.
- Energy analytics operationalizes efficiency within ecological and regulatory limits.
- Education reinforces long-term adaptive capacity and societal legitimacy.

In this perspective, sustainable MRE expansion cannot be reduced to technological readiness alone. Deployment maturity emerges only when coordinated performance across ecological, governance, technical and societal domains is achieved. The framework therefore shifts the analytical perspective from simple resource potential evaluation towards integrated deployment readiness assessment. This conceptual transition is fundamental, because it recognizes that high technical potential does not automatically imply feasible or legitimate large-scale implementation.

Fig. 7 illustrates the graphical representation of the proposed Integrated Transdisciplinary Decision Framework (ITDF) for Sustainable Marine Renewable Energy Deployment. The framework structures MRE development into interacting decision layers, where ecological constraints define feasibility boundaries, governance mediates spatial and socioeconomic allocation, energy analytics operationalizes system performance, and sustainability education strengthens adaptive capacity and social legitimacy. Upward arrows represent enabling progression toward deployment readiness, whereas feedback loops indicate adaptive learning dynamics and constraint interactions between layers.

The side expression *Deployment Readiness = f (Ecology, Governance, Analytics, Education)* summarizes the integrative logic of the framework.

The functional notation does not imply existence of a fixed mathematical formulation. Rather, it signals that deployment readiness emerges as a systemic outcome of dynamic interactions between four pillars. Weakness or misalignment in one dimension may constrain overall readiness, even in presence of strong technical potential. For this reason, deployment readiness is conceptualized not as a purely technological achievement, but as a systems-level equilibrium condition resulting from ecological feasibility, governance coherence, optimization capability, and societal enabling capacity acting together. In conclusion, by explicitly structuring these interdependencies, this review moves beyond descriptive narrative synthesis and proposes a

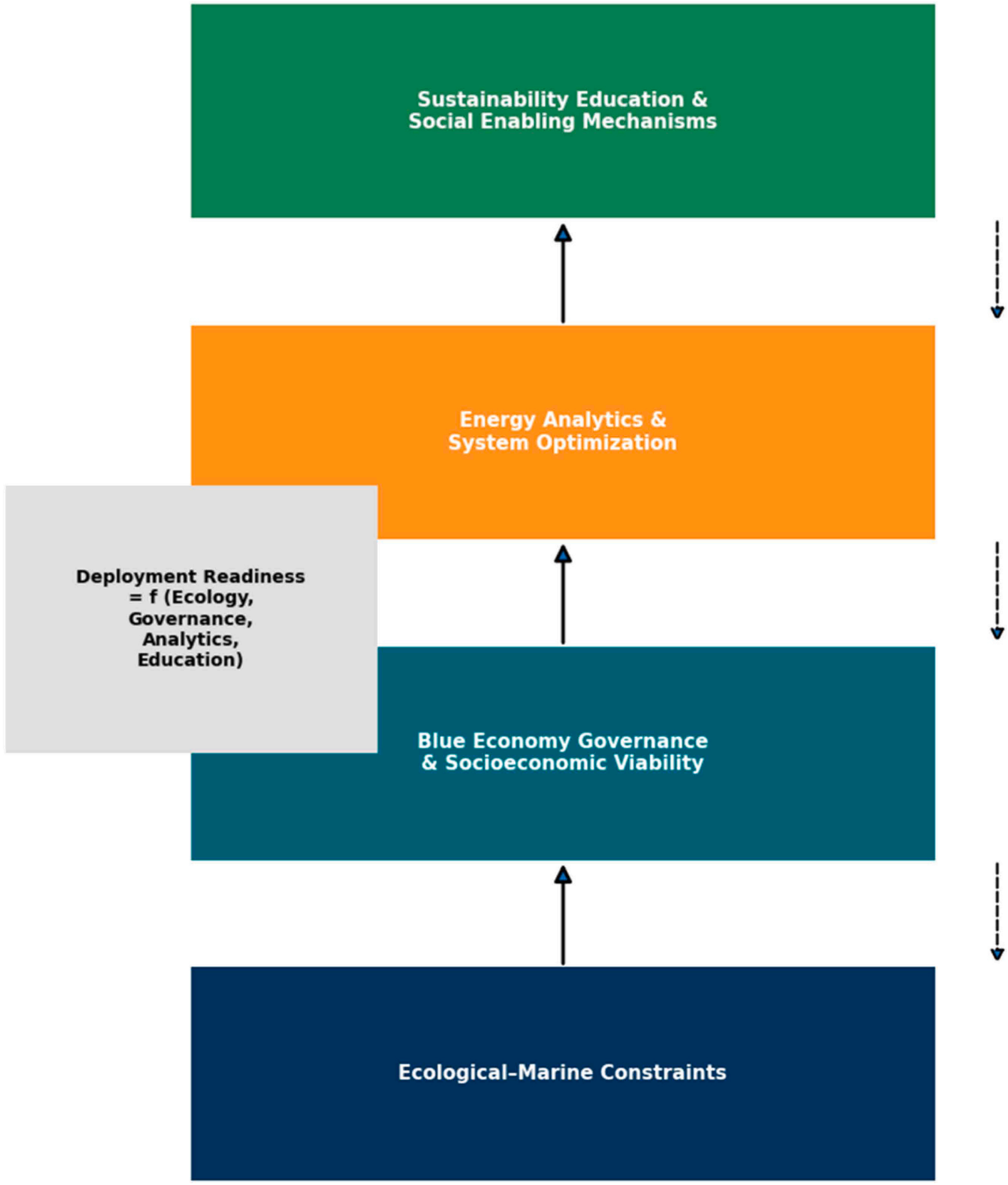

Fig. 7. Integrated Transdisciplinary Decision Framework (ITDF) for Sustainable Marine Renewable Energy Deployment.

decision-oriented architecture capable of supporting more coherent evaluation of MRE pathways within the broader energy transition context.

10. Practical deployment priorities

Despite the existence of substantial theoretical resource potential, large-scale marine renewable energy (MRE) deployment cannot be interpreted as automatic consequence of technical availability. Rather, it depends on coordinated progress across technical, economic, regulatory and ecological domains, which must evolve in parallel. Based on the synthesis presented in this review, several practical deployment priorities can be identified. These priorities highlight that the transition from resource assessment to system integration requires a structured and coordinated decision making process.

10.1. Grid integration and system flexibility

One of the primary constraints to large-scale MRE expansion is related to grid integration. Offshore wind farms and tidal resources are often geographically distant from load centres, which implies necessity of substantial transmission infrastructure, subsea cabling, and grid reinforcement investments. From a system perspective, investment planning cannot consider generation assets in isolation. MRE expansion must be synchronised with the transmission system development and flexibility mechanisms, including storage solutions, demand response schemes, and sector coupling strategies. Without such coordinated grid planning, resource potential remains only theoretical and cannot be translated into reliable contribution to energy system. Therefore, system flexibility is not simply an ancillary component, but a structural prerequisite for scalable marine deployment.

10.2. Technology maturity sequencing

Another important priority concerns the differentiation of technologies. Deployment strategies should explicitly distinguish between commercially mature technologies (e.g., fixed-bottom offshore wind), early commercial solutions (such as floating wind), and pilot-stage systems (e.g., tidal stream and salinity gradient technologies). Policy instruments and financing mechanisms must reflect this maturity gradient. Emerging technologies require risk-sharing frameworks, innovation-oriented support schemes and dedicated pilot programs. Conversely, mature technologies should progressively transition toward market-based competitiveness and reduced dependency from subsidies. Failure to recognize this sequencing may generate inefficient allocation of public resources and distort the long-term innovation trajectories.

10.3. Cost transparency and risk allocation

Economic feasibility of MRE projects is strongly influenced by capital expenditure (CAPEX), operational expenditure (OPEX), financing costs, and decommissioning liabilities. These cost components interact with regulatory stability and with perceived policy risk. Transparent auction mechanisms, long-term contractual arrangements (such as Contracts for Difference), and stable regulatory environments contribute to lowering the investment risk premiums. As a consequence, overall system costs can be reduced thanks to improved predictability. Economic assessment should therefore not rely exclusively on Levelized Cost of Energy (LCOE) indicators. Financing structures, risk allocation mechanisms and policy stability must be also included in comprehensive viability evaluations. A purely technological cost comparison is not sufficient to fully capture the investment realities.

10.4. Ecological safeguards and spatial planning

Marine renewable energy projects operate within complex and sensitive ecosystems. Marine spatial planning (MSP) and cumulative impact assessment play fundamental role in minimizing biodiversity disruption and reducing conflicts with fisheries, shipping routes and other maritime activities. Early integration of ecological constraints into site selection and system design can reduce future mitigation costs and enhance social acceptance. In this sense, ecological considerations should not be interpreted as ex-post regulatory barriers, but rather as boundary conditions which are shaping deployment strategies from the beginning. Ignoring ecological interactions at early stage may lead to delays, increased permitting uncertainty and to erosion of public trust.

10.5. Policy coherence and governance alignment

Large-scale deployment also depends on alignment between energy policy, marine governance frameworks, climate targets and coastal development strategies. Fragmented regulatory environments create delays in permitting procedures and increase uncertainty of projects. Integrated governance mechanisms, capable to coordinate multiple policy domains, represent therefore prerequisite for scalable and efficient implementation. Regulatory clarity reduces transaction costs and facilitates investment planning. Institutional coherence is not secondary to technological performance. It constitutes one of enabling pillars for long-term marine energy expansion.

10.6. From technological potential to system readiness

Taken together, these priorities indicate that sustainable MRE expansion depends not solely on technological efficiency or resource abundance. Instead, it requires coordinated institutional, economic, ecological and system-level readiness. Large-scale deployment emerges as systemic outcome, resulting from the interaction between grid infrastructure adequacy, differentiated technology support, transparent economic frameworks, ecological integration and governance coherence. Therefore, marine renewable energy should be evaluated not only in terms of performance metrics, but also in terms of integrated deployment conditions. Only when these multiple dimensions progress in coordinated manner can the theoretical resource potential evolve into stable and reliable contribution to the energy transition.

11. Economic dimensions and real-world deployment constraints

While the Levelized Cost of Energy (LCOE) for offshore wind has declined significantly over the past decade, economic feasibility cannot be interpreted as direct consequence of headline cost reductions. Reported LCOE decreases often reflect auction-based procurement frameworks, long-term contractual arrangements, learning curve dynamics, and economies of scale achieved in leading markets such as the North Sea. However, LCOE comparisons must be interpreted with caution. They may embed policy support mechanisms, risk allocation structures, and financing assumptions that differ substantially across jurisdictions. As a result, cost-competitiveness in one regulatory context does not necessarily imply replicability in another one. In this perspective, the economic viability of MRE systems is shaped by multiple interacting drivers that go beyond simplified cost indicators:

11.1. Capital Expenditure (CAPEX)

Offshore wind projects require substantial upfront investments. These include turbine procurement, foundation installation, subsea cabling, grid interconnection infrastructure, and port facilities. Floating offshore wind, in particular, is characterised by higher capital intensity due to complex platform structures and anchoring systems. For emerging technologies such as tidal stream and salinity gradient systems, the situation is further complicated by limited supply chains and absence of large-scale manufacturing capabilities. The lack of industrial standardisation increases unit costs and reduces opportunities for scale efficiencies. Therefore, CAPEX profiles vary significantly depending on technology maturity and industrial ecosystem development.

11.2. Operational and Maintenance Costs (OPEX)

Marine renewable installations operate in harsh offshore environments. Corrosion, biofouling, mechanical stress, and weather-related accessibility constraints increase operational complexity and lifecycle expenditures. Operation and maintenance costs can represent significant share of total project costs, especially for deep-water installations and remote locations. In such contexts, maintenance logistics and downtime risks must be carefully considered within economic modelling. Thus, OPEX dynamics are not marginal components but structurally embedded cost drivers over project lifetime.

11.3. Financing Conditions and Risk Premiums

The weighted average cost of capital (WACC) exerts strong influence on project economics. Regulatory uncertainty, permitting delays, and policy volatility increase perceived risk and consequently elevate financing costs. Stable long-term contracts (for instance, Contracts for Difference), clear grid connection rules, and transparent permitting procedures contribute to reduction of risk premiums and improve overall bankability of projects. It is therefore evident that financing conditions can alter competitiveness assessments even when technological parameters remain constant.

11.4. Grid Connection and System Integration Costs

Transmission infrastructure and balancing requirements are often excluded from project-level LCOE calculations. Nevertheless, they represent substantial system-level expenditures. Offshore grid expansion, cross-border interconnectors, and flexibility resources (such as storage systems and demand-side management) are necessary to convert variable marine generation into reliable system capacity. If such integration costs are not internalised in economic evaluations, overall system impact may be underestimated. Economic feasibility should therefore be analysed not only at asset level, but also at system level perspective.

11.5. Decommissioning and Lifecycle Liabilities

End-of-life obligations, including turbine dismantling, material recycling, and seabed restoration, introduce long-term financial responsibilities. These liabilities must be incorporated into comprehensive economic assessment in order to avoid distorted comparisons. Failure to consider lifecycle obligations may create misalignment between short-term profitability and long-term sustainability.

For pilot-stage technologies (e.g., tidal stream and wave energy), economic feasibility is further constrained by limited operational experience, higher technological risks, and absence of standardized deployment frameworks. In such situations, early-stage public support schemes, demonstration funding, and innovation incentives remain essential to bridge the gap between theoretical resource potential and commercial viability. In conclusion, while offshore wind has achieved cost-competitive status in several regions, broader MRE deployment requires differentiated economic strategies. These strategies must reflect technology maturity, regional resource conditions, financing environments, and system integration capacity. A purely resource-based or LCOE-based assessment is not sufficient. Economic feasibility must be evaluated within broader context of institutional stability, grid readiness, financing structures, and lifecycle cost transparency. Only through such integrated evaluation it is possible to move from theoretical competitiveness to sustainable and scalable marine renewable energy deployment.

12. Conclusions

The global energy transition is crucial for alleviating climate change, improving energy security, and building economic resilience. This study emphasizes the important role of marine ecosystems in facilitating renewable energy sources, such as tidal, wave, thermal, and biomass energy. MRE systems have significant potential to cut carbon emissions while preserving ecological balance. Sustainable MRE deployment requires coupling technological maturity (offshore wind), ecological safeguards, enabling governance through the blue economy, and operational optimization via energy analytics, supported by sustainability education to strengthen social acceptance and capacity.

Technically, offshore wind emerges as the most mature and scalable MRE option, while tidal stream and OTEC remain site-specific, and wave and salinity-gradient systems are largely constrained to pilot-scale development due to cost, survivability, and operational limitations. By tackling variability and operational challenges, analytics improves long-term energy planning and helps lower costs. This review achieved its objectives by synthesizing evidence on MRE contributions to a low-carbon transition while identifying key ecological trade-offs. It also evaluated the blue economy's socio-economic and policy dimensions and assessed how energy analytics and sustainability education enable improved integration, public awareness, and innovation. Future analyses should include cost-benefit assessments, life-cycle impacts, and regional economic models to better inform decision-making in MRE deployment. Future research should prioritize (1) policy harmonization and regulatory clarity, especially in transboundary marine zones; (2) feasibility studies on scalable MRE technologies with the greatest near-term impact (e.g., floating offshore wind); and (3) capacity-building in emerging economies to foster inclusive innovation. Ranking future directions by urgency and impact can help allocate resources efficiently and maximize societal benefits.

The proposed Integrated Transdisciplinary Decision Framework, together with the deployment priorities and economic feasibility structuring presented in Sections 9–11, provides a consolidated architecture for translating marine renewable resource potential into implementable and system-ready transition pathways.

CRediT authorship contribution statement

Chiara Bordin: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Funding acquisition, Conceptualization. **Hridoy Md. Abdullah Al Mamun:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **David Gift:** Writing – review & editing, Writing – original draft, Investigation. **Andleeb Masood:** Writing – review & editing, Writing – original draft, Investigation. **Baki Azeez:** Writing – review & editing, Writing – original draft, Investigation. **Acharjee Mahima:** Writing – original draft. **Tanzila Gias:** Writing – original draft, Visualization. **Md. Maynuddin Pathan:** Writing – original draft, Visualization. **Angan Sen:** Writing – original draft, Visualization. **Nath Aporna:** Writing – original draft, Visualization.

Purchase orders for all consumables and/or materials used

As this is a systematic review article, no consumables or materials (such as cells, animals, reagents, etc.) were used in the preparation of this study.

Third-party involvement

No persons or third-party services were involved in the research or manuscript preparation who are not listed as an author or acknowledged in the manuscript.

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Data availability

No data was used for the research described in the article.

References

Acharjee, M.R., Newase, S., Afrin, S., Islam, S., Al Mamun Hridoy, Md A., Ekramul Haque, M., Das, T., et al., 2026. From water and sediment to seafood: Heavy metal contamination and human health risk in wild and cultured oysters from a developing coastal region. Marine Pollution Bulletin 225, 119313.

Afridi, S.K., Koondhar, M.A., Jamali, M.I., Alaas, Z.M., Alsharif, M.H., Kim, M.K., Ahmed, M.M.R., 2024. Winds of progress: an in-depth exploration of offshore, floating, and onshore wind turbines as cornerstones for sustainable energy generation and environmental stewardship. IEEE Access.

Aftabuddin, S., Zafar, M., Noman, A.S.M., Sharmin, A., 2008. Isolation and identification of Vibrio spp. and Aeromonas spp. in wild and hatchery reared Penaeus monodon post larvae from Cox's Bazar. Bangladesh. Pak. J. Mar. Sci. 17, 161–167.

Ahmad, T., Madonski, R., Zhang, D., Huang, C., Mujeeb, A., 2022. Data-driven probabilistic machine learning in sustainable smart energy/smart energy systems: key developments, challenges, and future research opportunities in the context of smart grid paradigm. Renew. Sustain. Energy Rev. 160, 112128.

Akar, S., Akdoğan, D.A., 2016. Environmental and economic impacts of wave energy: Some public policy recommendations for implementation in Turkey. Handbook of

Research on Green Economic Development Initiatives and Strategies. IGI Global, pp. 285–309. https://doi.org/10.4018/978-1-5225-0440-5.ch013.
Akour, M., Alenezi, M., 2022. Higher education future in the era of digital transformation. Educ. Sci. 12 (11), 784.
Al Mamun Hridoy, M.A., Bordin, C., Baki, A.O., Masood, A., David, G.S., Parven, A., Marine, S.S., 2025a. Global perspectives on energy technology assessment and educational pathways for sustainable energy transitions. Discov. Appl. Sci. 7 (11), 1302. https://doi.org/10.1007/s42452-025-07834-0.
Allison, E.H., Arnaud-Haond, S., Bebbington, J., Bennett, N.J., Blasiak, R., Boonstra, W., Choudhury, A., et al., 2020. Towards ocean equity. World Resources Institute.
Altassan, A., 2023. Sustainable integration of solar energy, behavior change, and recycling practices in educational institutions: a holistic framework for environmental conservation and quality education. Sustainability 15 (20), 15157.
Anwar, M.R., Sakti, L.D., 2024. Integrating artificial intelligence and environmental science for sustainable urban planning. IAIC Trans. Sustain. Digit. Innov. (ITSDI) 5 (2), 179–191.
Appasani, B., Mishra, S.K., Jha, A.V., Mishra, S.K., Enescu, F.M., Sorlei, I.S., Bizon, N., 2022. Blockchain-enabled smart grid applications: architecture, challenges, and solutions. Sustainability 14 (14), 8801.
ASEAN, H. (2022). *of state of MS of ASEAN Leaders' Declaration on Antimicrobial Resistance (AMR): Combating AMR through One Health Approach.*
Astariz, S., Iglesias, G., 2015. The economics of wave energy: a review. Renew. Sustain. Energy Rev. 45, 397–408.
Atawi, I.E., Al-Shetwi, A.Q., Magableh, A.M., Albalawi, O.H., 2022. Recent advances in hybrid energy storage system integrated renewable power generation: configuration, control, applications, and future directions. Batteries 9 (1), 29.
Bachmann, N., Tripathi, S., Brunner, M., Jodlbauer, H., 2022. The contribution of data-driven technologies in achieving the sustainable development goals. Sustainability 14 (5), 2497.
Barker, T., Crawford-Brown, D., 2014. Decarbonising the world's economy: assessing the feasibility of policies to reduce greenhouse gas emissions (Eds). World Scientific.
Bellon De Chassy, A.B.J. (2020). *An analysis of the market potential for ocean renewable energy in industrial maritime sectors of Australia's Blue Economy* (Master's thesis).
Bennett, N.J., Cisneros-Montemayor, A.M., Blythe, J., Silver, J.J., Singh, G., Andrews, N., Calò, A., Christie, P., Di Franco, A., Finkbeiner, E.M., Gelcich, S., Guidetti, P., Harper, S., Hotte, N., Kittinger, J.N., Billon, P.L., Lister, J., De La Lama, R.L., McKinley, E., Sumaila, U.R., 2019. Towards a sustainable and equitable blue economy. Nat. Sustain. 2 (11), 991–993.
Bhuiyan, M.A., Hu, P., Khare, V., Hamaguchi, Y., Thakur, B.K., Rahman, M.K., 2022. Economic feasibility of MRE. Front. Mar. Sci. 9, 988513.
Blake, J., 2007. Hotels that blaze a green trail. Cater. Hotelk. 10, 52.
Blazev, A.S., 2021. Global energy market trends. River Publishers.
Bordin, C., Hridoy, M.A.A.M., Pathan, M.M., Islam, S.S., Lima, M.A., Rahim, M.T.N., Sa'adi, Z., 2025. Energy storage in the energy transition and blue economy: challenges, innovations, future perspectives, and educational pathways. Discov. Appl. Sci. 7 (10), 1084. https://doi.org/10.1007/s42452-025-07720-9.
Borthwick, A.G., 2016. MRE Seascape. Engineering 2 (1), 69–78.
Brent, Z.W., Barbesgaard, M., Pedersen, C., 2020. The Blue Fix: What's driving blue growth? Sustain. Sci. 15 (1), 31–43.
Bujas, T., Vladimir, N., Koričan, M., Vukić, M., Ćatipović, I., Fan, A., 2023. Extended bibliometric review of technical challenges in mariculture production and research hotspot analysis. Appl. Sci. 13 (11), 6699. https://doi.org/10.3390/app13116699.
Butt, H.D., Aijaz, M.U., Shamim, M.A., Lodhi, K.S., Hayat, A., Mazhar, M., 2024. Leveraging CPEC for a thriving blue economy and coastal development. Migr. Lett. 21 (S8), 1285–1321.
Cáceres, R.A., Zyserman, J.A., Perillo, G.M., 2016. Analysis of sedimentation problems at the entrance to Mar del Plata Harbor. J. Coast. Res. 32 (2), 301–314.
Cai, X., Wang, Y., Xu, B., Feng, J., 2020. Performance and effect of load mitigation of a trailing-edge flap in a large-scale offshore wind turbine. J. Mar. Sci. Eng. 8 (2), 72. https://doi.org/10.3390/jmse8020072.
Campana, E.F., Ciappi, E., Coro, G., 2021. The role of technology and digital innovation in sustainability and decarbonization of the blue economy. Bull. Geophys. Oceanogr. 123.
Castro-Santos, L., Filgueira-Vizoso, A., Álvarez-Feal, C., Carral, L., 2018. Influence of size on the economic feasibility of floating offshore wind farms. Sustainability 10 (12), 4484. https://doi.org/10.3390/su10124484.
Cavagnaro, R.J., Copping, A.E., Green, R., Greene, D., Jenne, S., Rose, D., Overhus, D., 2020. Powering the blue economy: progress exploring MRE integration with ocean observations. Mar. Technol. Soc. J. 54 (6), 114–125.
Chang, G., Schmaus, C., Kendall, J.J., Kohut, J.T., Kramer, S., Perry, R., 2024. An Evolving Blue Economy: Exploring the Future for MRE. Mar. Technol. Soc. J. 58 (3), 88–93.
Chen, L., Li, X., Ma, W., Wang, H., Ma, C., 2023. Analysis for the development of MRE industry in China. Adv. Eng. Technol. Res. 7 (1), 272-272.
Chen, H., Tang, T., Ait-Ahmed, N., Benbouzid, M.E.H., MacHmoum, M., Zaim, M.E.H., 2018. Attraction, challenge and current status of marine current energy. IEEE Access 6, 12665–12685. https://doi.org/10.1109/ACCESS.2018.2795708.
Cherp, A., Vinichenko, V., Tosun, J., Gordon, J.A., Jewell, J., 2021. National growth dynamics of wind and solar power compared to the growth required for global climate targets. Nat. Energy 6 (7), 742–754.
Choi, N., Kim, B., Kim, D., Park, B., Kim, S., Lee, B., 2022. Grid connection studies for large-scale offshore wind farms considering high penetration of regional renewables. Sustainability 14 (2), 1015. https://doi.org/10.3390/su14021015.
Choudhary, P., Khade, M., Savant, S., Musale, A., Chelliah, M.S., Dasgupta, S., 2021. Empowering blue economy: from underrated ecosystem to sustainable industry. J. Environ. Manag. 291, 112697.
Chu, S., Majumdar, A., 2012. Opportunities and challenges for a sustainable energy future. nature 488 (7411), 294–303.
Cohen, P.J., Allison, E.H., Andrew, N.L., Cinner, J., Evans, L.S., Fabinyi, M., Garces, L.R., Hall, S.J., Hicks, C.C., Hughes, T.P., Jentoft, S., Mills, D.J., Masu, R., Mbaru, E.K., Ratner, B.D., 2019. Securing a just space for Small-Scale fisheries in the blue economy. Front. Mar. Sci. 6.
Copping, A.E., Gorton, A.M., May, R., Bennet, F., DeGeorge, E., Repas Goncalves, M., Rumes, B., 2020. Enabling renewable energy while protecting wildlife: an ecological risk-based approach to wind energy development using ecosystem-based management values. Sustainability 12 (22), 9352. https://doi.org/10.3390/su12229352.
Cruz-Marrero, W., Cullen, D.W., Gay, N.R., Stevens, B.G., 2019. Characterizing the benthic community in Maryland's offshore wind energy areas using a towed camera sled: developing a method to reduce the effort of image analysis and community description. PLOS ONE 14 (5), e0215966. https://doi.org/10.1371/journal.pone.0215966.
da Cruz Weiss, C.V., 2018. Metodologías aplicables a la ordenación del espacio marítimo en el ámbito del desarrollo actual y futuro de las energías renovables y la acuicultura.
Das, P.K., Kawsar, M.A., Paul, P.B., Hridoy, M.A.A.M., Hossain, M.S., Niloy, S., 2024. BD-freshwater-fish: an image dataset from Bangladesh for AI-powered automatic fish species classification and detection toward smart aquaculture. Data Brief. 57, 111132.
Day, A., Babarit, A., Fontaine, A., He, Y., Kraskowski, M., Murai, M., Penesis, I., Salvatore, F., Shin, H., 2015. Hydrodynamic modelling of MRE devices: a state of the art review. Ocean Eng. 108, 46–69.
Debnath, C., Bandyopadhyay, T.K., Bhunia, B., Mishra, U., Narayanasamy, S., Muthuraj, M., 2021. Microalgae: sustainable resource of carbohydrates in third-generation biofuel production. Renew. Sustain. Energy Rev. 150, 111464.
Demirel, N., Ulman, A., Yıldız, T., Ertör-Akyazi, P., 2021. A moving target: achieving good environmental status and social justice in the case of an alien species, Rapa whelk in the Black Sea. Mar. Policy 132, 104687.
Devault, D.A., Péné-Annette, A., 2017. Analysis of the environmental issues concerning the deployment of an OTEC power plant in Martinique. Environ. Sci. Pollut. Res. 24 (33), 25582–25601. https://doi.org/10.1007/s11356-017-8749-3.
Dhar, A., Naeth, M.A., Jennings, P.D., El-Din, M.G., 2020. Perspectives on environmental impacts and a land reclamation strategy for solar and wind energy systems. Sci. Total Environ. 718, 134602.
Ding, H., Zou, G., Ding, N., Wang, C., 2022. Study of the IPOS DC/DC Converter for DC Offshore Wind Farm. J. Phys. Conf. Ser. 2320 (1), 012016. https://doi.org/10.1088/1742-6596/2320/1/012016.
Dowling, R., 2013. The history of ecotourism. International handbook on ecotourism. Edward Elgar Publishing, pp. 15–30.
Edwards, E.C., Holcombe, A., Brown, S., Ransley, E., Hann, M., Greaves, D., 2023. Evolution of floating offshore wind platforms: a review of at-sea devices. Renew. Sustain. Energy Rev. 183, 113416.
El Morr, C., Ali-Hassan, H., El Morr, C., Ali-Hassan, H., 2019. Descriptive, predictive, and prescriptive analytics. Anal. Healthc. a Pract. Introd. 31–55.
Erdogan, N., Bhinder, M., Murphy, J., Cali, U., Aghaei, M., 2025. Digital twin in design and control optimization of MRE and offshore wind energy systems. Digital Twin Technology for the Energy Sector. Elsevier, pp. 143–160.
Evans, L.S., Buchan, P.M., Fortnam, M., Honig, M., Heaps, L., 2023. Putting coastal communities at the center of a sustainable blue economy: A review of risks, opportunities, and strategies. Front. Political Sci. 4, 1032204.
Fan, H., Fan, L., 2024. Role of Education and Awareness Programs in Fostering Energy Conservation Behavior in Cities: Empowering Urban Sustainability Using Deep Learning Approach. Sustainable Cities and Society, 105505.
Fang, W., Dakui, Z., 2014. The study on strategy of sustainable development in coastal tourism resources from the global change perspective. J. Resour. Ecol. 5 (1), 32–41.
Fernández-Guillamón, A., Das, K., Cutululis, N.A., Molina-García, Á., 2019. Offshore Wind Power Integration into Future Power Systems: Overview and Trends. J. Mar. Sci. Eng. 7 (11), 399. https://doi.org/10.3390/jmse7110399.
Fox, H., Pillai, A.C., Friedrich, D., Collu, M., Dawood, T., Johanning, L., 2022. A review of predictive and prescriptive offshore wind farm operation and maintenance. Energies 15 (2), 504.
Frazzetto, D., Nielsen, T.D., Pedersen, T.B., Šikšnys, L., 2019. Prescriptive analytics: a survey of emerging trends and technologies. VLDB J. 28, 575–595.
Freeman, M., Garavelli, L., Wilson, E., Hemer, M., Abundo, M., Travis, L.E., 2022. Offshore aquaculture: a market for ocean renewable energy. Report for Ocean Energy Systems (OES).
Fusco, L.M., Schutter, M.S., Cisneros-Montemayor, A.M., 2022. Oil, transitions, and the Blue Economy in Canada. Sustainability 14 (13), 8132.
Gao, Q., Yuan, R., Ertugrul, N., Ding, B., Hayward, J.A., Li, Y., 2023. Analysis of energy variability and costs for offshore wind and hybrid power unit with equivalent energy storage system. Appl. Energy 342, 121192. https://doi.org/10.1016/j.apenergy.2023.121192.
Garavelli, L., Freeman, M.C., Tugade, L.G., Greene, D., McNally, J., 2022. A feasibility assessment for co-locating and powering offshore aquaculture with wave energy in the United States. Ocean & Coast. Manag. 225, 106242.
Garland, M., Axon, S., Graziano, M., Morrissey, J., Heidkamp, C.P., 2019. The blue economy: Identifying geographic concepts and sensitivities. Geogr. Compass 13 (7).
Geerlofs, S., 2021. Marine energy and the new blue economy. Preparing a Workforce for the New Blue Economy. Elsevier, pp. 171–178.
Geoffroy, O., Saint-Martin, D., Olivié, D.J.L., Voldoire, A., Bellon, G., Tytéca, S., 2012. Transient climate response in a two-layer energy-balance model. Part I: analytical

solution and parameter calibration using CMIP5 AOGCM experiments. J. Clim. 26 (6), 1841–1857.
Gielen, D., Boshell, F., Saygin, D., Bazilian, M.D., Wagner, N., Gorini, R., 2019. The role of renewable energy in the global energy transformation. Energy Strategy Rev. 24, 38–50.
Gissi, E., Maes, F., Kyriazi, Z., Ruiz-Frau, A., Santos, C.F., Neumann, B., Quintela, A., Alves, F.L., Borg, S., Chen, W., da Luz Fernandes, M., 2022. Contributions of marine area-based management tools to the UN sustainable development goals. J. Clean. Prod. 330, 129910.
Guan, S., Qu, F., Qiao, F., 2023. United Nations Decade of Ocean Science for Sustainable Development (2021-2030): from innovation of ocean science to science-based ocean governance. Front. Mar. Sci. 9, 1091598.
Hassan, Q., Viktor, P., Al-Musawi, T.J., Ali, B.M., Algburi, S., Alzoubi, H.M., Jaszczur, M., 2024. The renewable energy role in the global energy Transformations. Renew. Energy Focus 48, 100545.
Hein, J.R., Mizell, K., Koschinsky, A., Conrad, T.A., 2013. Deep-ocean mineral deposits as a source of critical metals for high-and green-technology applications: comparison with land-based resources. Ore Geol. Rev. 51, 1–14.
Himeur, Y., Elnour, M., Fadli, F., Meskin, N., Petri, I., Rezgui, Y., Amira, A., 2023. AI-big data analytics for building automation and management systems: a survey, actual challenges and future perspectives. Artif. Intell. Rev. 56 (6), 4929–5021.
Hoerterer, C., Schupp, M.F., Benkens, A., Nickiewicz, D., Krause, G., Buck, B.H., 2020. Stakeholder perspectives on opportunities and challenges in achieving sustainable growth of the blue economy in a changing climate. Front. Mar. Sci. 6, 795.
Hooper, T., Armstrong, A., Vlaswinkel, B., 2020. Environmental impacts and benefits of marine floating solar. Sol. Energy. https://doi.org/10.1016/j.solener.2020.10.010.
Hridoy, M.A.A.M., Akter, P., Bordin, C., Acharjee, M.R., Baki, A.O., Neogi, S., David, G.S., 2025d. Integrated assessment of heavy metal contamination and human health risks in granitic soils of South India: A multi-index approach to pollution and ecological impacts. Results Surf. Interfaces, 100628. https://doi.org/10.1016/j.rsurfi.2025.100628.
Hridoy, M.A.A.M.M., Bordin, C., Masood, A., Khan, K.M., 2025e. Predictive modelling of aquaculture water quality using IoT and advanced machine learning algorithms. Results Chem., 102456 https://doi.org/10.1016/j.rechem.2025.102456.
Hridoy, M.A.A.M., Bordin, C., Pastorino, P., Maulud, K.N.A., Pathan, M.M., Baki, A.O., 2026d. Neural network-based prediction of water contamination dynamics in a rapidly developing tropical region. Case Stud. Chem. Environ. Eng. 9, 101342. https://doi.org/10.1016/j.cscee.2026.101342.
Hridoy, M.A.A.M., Ditthakit, P., & Hosen, A. (2025b). Machine learning–driven prediction of heavy metal pollution for aquatic health surveillance and disease control. *Machine Learning–Driven Prediction of Heavy Metal Pollution for Aquatic Health Surveillance and Disease Control. ISCIENCE-D-25-19889*.
Hridoy, M.A.A.M., Neogi, S., Hossain, M.S., Jamee, M.F., Rasel, M.A., Rahman, S., Amin, J., 2026b. Macroplastic Pollution in the Kalni River Basin: Implications for Sustainable Water Management. J. Hazard. Mater. Plast., 100042
Hridoy, A.A.M., Neogi, S., Ujjaman, R., Hasan, M., 2025f. Water quality interactions and their synergistic effects on aquaculture performance in Bangladesh: A critical review. Results Chem., 102306 https://doi.org/10.1016/j.rechem.2025.102306.
Hridoy, M.A.A.M., Pastorino, P., Bordin, C., Bodini, M., Dhar, N., Schneider, P., Maulud, K.N.A., 2026a. Operational agricultural water management in river-based aquaculture: A machine-learning approach to predict dissolved oxygen in the Halda River, Bangladesh. Aquac. Eng., 102693 https://doi.org/10.1016/j.aquaeng.2026.102693.
Hridoy, M.A.A.M., & Paul, P.B. (2024). Assessing Total Dissolved Oxygen and Electrical Conductivity Using Sentinel-2 Remote Sensing: A Multivariable Approach to Flood Detection in Flood-Prone Urban Area Sylhet. https://doi.org/10.21203/rs.3.rs-5048730/v1.
Hridoy, M.A.A.M., Paul, P.B., Hashar, M.N., Tabaschum, T., Ujjaman, R., Khan, M.S., Shakil, M.A.H., 2025h. Seasonal variations in Water quality and microplastic contamination in the Surma River, Bangladesh: implications for aquatic health and human safety. Environ. Qual. Manag. 34 (3), e70055. https://doi.org/10.1002/tqem.70055.
Hridoy, M.D., Paul, P.B., Rasel, M.A., Rakib Uddin, K., 2025a. Impact of water pollution on physio-chemical properties for fish habitat in the Surma River, Sylhet City, Bangladesh. Water Environ. Sustain. 5 (1), 12–20.
Hridoy, M.A.A.M., Saha, S., Paul, P.B., Chowdhury, T.A., Al Mizan, A., Rahman, M.T., Hasan, M.M., 2025g. Evaluating the socio-economic conditions of fishers and sustainability of small-scale fisheries in the Kalni River, Bangladesh. Ege J. Fish. Aquat. Sci. 42 (1), 41–47. https://doi.org/10.12714/egejfas.42.1.06.
Hridoy, M.A.A.M., Shawkat, A.I., Bordin, C., Acharjee, M.R., Masood, A., Baki, A.O., Al Mamun, M.A., 2025c. Advanced machine learning models for accurate water quality classification and WQI prediction: Implications for aquatic disease risk management. Sci. Total Environ. 1008, 180965. https://doi.org/10.1016/j.scitotenv.2025.180965.
Hridoy, M.A.A.M., Tagri, F.Z., Bordin, C., Islam, M.H., Baki, A.O., Pathan, M.M., Pastorino, P., 2026c. Occurrence and human health risks of microplastics in the Bay of Bengal using Perna viridis as sentinel species. Chem. Eng. J. Adv., 101039 https://doi.org/10.1016/j.ceja.2026.101039.
Hutchins, T.E., 2021. Crafting an international legal framework for renewable energy on the high seas. Environ. Law 51 (2), 485–514.
Inger, R., Attrill, M.J., Bearhop, S., Broderick, A.C., Grecian, W.J., Hodgson, D.J., Mills, C., Sheehan, E., Votier, S.C., Witt, M.J., Godley, B.J., 2009. MRE: potential benefits to biodiversity? An urgent call for research. J. Appl. Ecol. 46 (6), 1145–1153.
Ingram, E.C., Dunton, K.J., Frisk, M.G., Butler, L., 2024. Artificial intelligence and species distribution ensemble models inform resource interactions with offshore wind development, 06 bioRxiv 2024. https://doi.org/10.1101/2024.06.10.598232.
Intergovernmental Panel on Climate Change (IPCC). (2018). *Global warming of 1.5°C*. Retrieved from ⟨https://www.ipcc.ch/sr15/⟩.
Jahangir, M.H., Shahsavari, A., Vaziri Rad, M.A., 2020. Feasibility study of a zero emission PV/Wind turbine/Wave energy converter hybrid system for stand-alone power supply: A case study. J. Clean. Prod. 262, 121250. https://doi.org/10.1016/j.jclepro.2020.121250.
Jaramillo Jimenez, V., Munim, Z.H., Kim, H., Perera, L.P., 2025. Barriers to data analytics for energy efficiency in the maritime industry. J. Offshore Mech. Arct. Eng. 147 (3).
Jattak, Z.U., Wu, W., Gao, J., Zhang, K., Murtaza, S.H., Jan, M., Ahmed, A., 2023. Advancing the initiatives of sustainable coastal and marine areas development in Pakistan through marine spatial planning. Sci. Prog. 106 (4), 00368504231218601.
Jouffray, J.B., Blasiak, R., Norström, A.V., Österblom, H., Nyström, M., 2020. The blue acceleration: the trajectory of human expansion into the ocean. One Earth 2 (1), 43–54.
Jung, C., Schindler, D., 2022. Development of onshore wind turbine fleet counteracts climate change-induced reduction in global capacity factor. Nat. Energy 7 (7), 608–619.
Karad, S., Thakur, R., 2021. Efficient monitoring and control of wind energy conversion systems using Internet of things (IoT): a comprehensive review. Environ. Dev. Sustain. 23 (10), 14197–14214.
Karsten, R.H., Greenberg, D.A., Tarbotten, G., 2011. Technical Report, Acadia University. Assess. Potential Tidal Power Minas Passage Minas Basin.
Kaur, S., Kumar, R., Singh, K., Huang, Y.L., 2024. Leveraging artificial intelligence for enhanced sustainable energy management. J. Sustain. Energy 3 (1), 1–20.
Kazimierczuk, K., Henderson, C., Duffy, K., Hanif, S., Bhattacharya, S., Biswas, S., Jacroux, E., Preziuso, D., Wu, D., Bhatnagar, D., Tarekegne, B., 2023. A socio-technical assessment of MRE potential in coastal communities. Energy Res. & Soc. Sci. 100, 103098. https://doi.org/10.1016/j.erss.2023.103098.
Keen, M.R., Schwarz, A.M., Wini-Simeon, L., 2018. Towards defining the Blue Economy: Practical lessons from pacific ocean governance. Mar. Policy 88, 333–341.
Kellberg, S., Nordine, J., Keller, M., Lewalter, D., 2023. Fostering students' willingness to act pro-environmentally through an identity-oriented socio-scientific exhibition on the energy transition. In: Frontiers in Education, 8. Frontiers Media SA, 1081633.
Khalil, M., Sheikh, S.A., 2024. Advancing Green Energy Integration in Power Systems for Enhanced Sustainability: A Review. IEEE Access.
Khan, N.D., Kalair, A., Abas, N., Haider, A., 2017. Review of ocean tidal, wave and thermal energy technologies. Renew. Sustain. Energy Rev. 72, 590–604.
Khojasteh, D., Khojasteh, D., Kamali, R., Beyene, A., Iglesias, G., 2018. Assessment of renewable energy resources in Iran; with a focus on wave and tidal energy. Renew. Sustain. Energy Rev. 81, 2992–3005.
Khurshid, H., Mohammed, B.S., Al-Yacoubya, A.M., Liew, M.S., Zawawi, N.A.W.A., 2024. Analysis of hybrid offshore renewable energy sources for power generation: a literature review of hybrid solar, wind, and waves energy systems. Dev. Built Environ., 100497
Kiranben, V.P., Suvin, M.P., 2011. Technologies and methods used in marine energy and farm system model. Handb. Renew. Energy Technol. 435–467.
Kittinger, J.N., Rotjan, R.D., Hanich, Q., Pasisi, B., Rambourg, C., 2024. Balancing protection and production in ocean conservation. npj Ocean Sustain. 3 (1), 24.
Komariah, n, Aisyah, s, 2020. Economic empowerment and education strategies in coastal communities. Int. J. multi Sci. 1 (07), 37–43.
Koričan, M., Perčić, M., Vladimir, N., Soldo, V., Jovanović, I., 2022. Environmental and economic assessment of mariculture systems using a high share of renewable energy sources. J. Clean. Prod. 333, 130072. https://doi.org/10.1016/j.jclepro.2021.130072.
Kou, L., Li, Y., Zhang, F., Gong, X., Hu, Y., Yuan, Q., Ke, W., 2022. Review on Monitoring, Operation and Maintenance of Smart Offshore Wind Farms. Sensors 22 (8), 2822. https://doi.org/10.3390/s22082822.
Kumar, K.K.P., Soren, N., Latif, A., Das, D.C., Hussain, S.S., Al-Durra, A., Ustun, T.S., 2022. Day-ahead DSM-integrated hybrid-power-management-incorporated CEED of solar thermal/wind/wave/BESS system using HFPSO. Sustainability 14 (3), 1169.
Lang, D.J., Wiek, A., Bergmann, M., Stauffacher, M., Martens, P., Moll, P., Swilling, M., Thomas, C.J., 2012. Transdisciplinary research in sustainability science: practice, principles, and challenges. Sustain. Sci. 7 (S1), 25–43.
Lee, K.H., Noh, J., Khim, J.S., 2020. The Blue Economy and the United Nations' sustainable development goals: Challenges and opportunities. Environ. Int. 137, 105528.
Li, Y., Le, C., Ding, H., Zhang, P., Zhang, J., 2019. Dynamic Response for a Submerged Floating Offshore Wind Turbine with Different Mooring Configurations. J. Mar. Sci. Eng. 7 (4), 115. https://doi.org/10.3390/jmse7040115.
Lima, M.A., Islam, M.H., Neogi, S., Nasrin, K., Sen, A., Masood, A., Al Mamun Hridoy, M. A., 2025. Recent advances in biochar technology for aquatic pollution control: a critical review of applications, barriers, and future opportunities. Discov. Sustain. 6 (1), 980. https://doi.org/10.1007/s43621-025-01581-3.
Lin, Y., Huang, F., Zhang, Y., Wang, Q., Huang, J., Chen, Q., Xue, X., 2022. An Improved Framework of Marine Major Function-Oriented Zoning in Advancing Ecosystem-Based Management. J. Mar. Sci. Eng. 10 (5), 684. https://doi.org/10.3390/jmse10050684.
Lin, L., Shroff, N.B., Srikant, R., 2007. Asymptotically optimal energy-aware routing for multihop wireless networks with renewable energy sources. IEEE/ACM Trans. Netw. 15 (5), 1021–1034.

Liu, S., Cai, F., He, Y., Qi, H., Rangel-Buitrago, N., Liu, J., Zheng, J., 2024. Integrating marine functional zoning in coastal planning: Lessons from the Xiasha Beach Resort case study. Ocean & Coast. Manag. 249, 107016.

LiVecchi, A., Copping, A., Jenne, D., Gorton, A., Preus, R., Gill, G., Spence, H., 2019. Powering the blue economy; exploring opportunities for MRE in maritime markets. US Department of Energy, Office of Energy Efficiency and Renewable Energy, *Washington, DC*, p. *207*.

López, M., Rodríguez, N., Iglesias, G., 2020. Combined floating offshore wind and solar PV. J. Mar. Sci. Eng. 8 (8), 576. https://doi.org/10.3390/jmse8080576.

Louey, P., 2022. The Pacific blue economy: An instrument of political maneuver. Mar. Policy 135, 104880.

Lubing, X., Xiaoming, R., Shuai, L., Xin, H., 2020. An opportunistic maintenance strategy for offshore wind turbine based on accessibility evaluation. Wind Eng. 44 (5), 455–468. https://doi.org/10.1177/0309524X19852351.

Lüth, A., Keles, D., 2024. Risks, strategies, and benefits of offshore energy hubs: A literature-based survey. Renew. Sustain. Energy Rev. 203, 114761.

Manolache, A.I., Andrei, G., 2024. A Comprehensive Review of Multi-Use Platforms for Renewable Energy and Aquaculture Integration. Energies 17 (19), 4816. https://doi.org/10.3390/en17194816.

Marin-Coria, E., Silva, R., Enriquez, C., Martínez, M.L., Mendoza, E., 2021. Environmental assessment of the impacts and benefits of a salinity gradient energy pilot plant. Energies 14 (11). https://doi.org/10.3390/en14113252.

Martínez-Vázquez, R.M., Milán-García, J., De Pablo Valenciano, J., 2021. Challenges of the Blue Economy: evidence and research trends. *Environmental Sciences*. Europe 33, 1.

Martínez-Vázquez, R.M., Milán-García, J., Pires Manso, J.R., De Pablo Valenciano, J., 2023. Impact of blue economy sectors using causality, correlation and panel data models. Front. Mar. Sci. 10, 1034054.

Masood, A., Zhu, F.R., Sa'adi, Z., Mamun Hridoy, M.A.A., Ullah, I., 2025. Study of meteorological parameters and classification of aerosols using remote sensing over LHAASO. Theor. Appl. Climatol. 156 (7), 375. https://doi.org/10.1007/s00704-025-05610-z.

Masoumi, M., 2023. Machine learning solutions for offshore wind farms: A review of applications and impacts. J. Mar. Sci. Eng. 11 (10), 1855.

Mehdi, R.A., Baldauf, M., Deeb, H., 2020. A dynamic risk assessment method to address safety of navigation concerns around offshore renewable energy installations. Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ. 234 (1), 231–244. https://doi.org/10.1177/1475090219837409.

Mishra, S., Bordin, C., Taharaguchi, K., Palu, I., 2020. Comparison of deep learning models for multivariate prediction of time series wind power generation and temperature. Energy Rep. 6, 273–286.

Musial, W., Spitsen, P., Duffy, P., Beiter, P., Shields, M., Mulas Hernando, D., … & Sathish, S. (2023). *Offshore wind market report: 2023 edition* (No. NREL/TP-5000-87232). National Renewable Energy Laboratory (NREL), Golden, CO (United States).

Nezhad, M.M., Neshat, M., Sylaios, G., Garcia, D.A., 2024. Marine energy digitalization digital twin's approaches. Renew. Sustain. Energy Rev. 191, 114065.

Ningsu, Luo, Ningsu, Luo, Lluís, Pacheco, Yolanda, Vidal, Hui, Li, 2024. Smart Structural Control Strategies for Offshore Wind Power Generation with Floating Wind Turbines. RE&PQJ 10 (9). https://doi.org/10.24084/repqj10.637.

Ohunakin, O.S., Matthew, O.J., Adaramola, M.S., Atiba, O.E., Adelekan, D.S., Aluko, O. O., Ezekiel, V.U., 2023. Techno-economic assessment of offshore wind energy potential at selected sites in the Gulf of Guinea. Energy Convers. Manag. 288, 117110.

Owusu, P.A., Asumadu-Sarkodie, S., 2016. A review of renewable energy sources, sustainability issues and climate change mitigation. Cogent Eng. 3 (1), 1167990.

Ozsoy, C.M., Mengüç, M.P., 2023. A transdisciplinary approach and design-thinking methodology for energy transition. p. V001T04A003. In: Energy Sustainability, 87189. American Society of Mechanical Engineers.

Pachakis, D., Beamish, P., Menegazzo, P., 2016. Planning of offshore container terminals. Ports 2016, 589–598.

Panda, D.K., Das, S., 2021. Smart grid architecture model for control, optimization and data analytics of future power networks with more renewable energy. J. Clean. Prod. 301, 126877.

Patterson, M., McDonald, G., Hardy, D., 2017. Is there more in common than we think? Convergence of ecological footprinting, emergy analysis, life cycle assessment and other methods of environmental accounting. Ecol. Model. 362, 19–36.

Pavlova, M., 2008. Technology and vocational education for sustainable development: Empowering individuals for the future, 10. Springer Science & Business Media.

Pfenninger, S., Hawkes, A., Keirstead, J., 2014. Energy systems modeling for twenty-first century energy challenges. Renew. Sustain. Energy Rev. 33, 74–86.

Pires Manso, J.R., Martínez Vázquez, R.M., Milán García, J., de Pablo Valenciano, J., 2023. Renewable Energies and Blue Economy: New Trends in Global Research. Energies 16 (10), 4210.

Pisacane, G., Sannino, G., Carillo, A., Struglia, M.V., Bastianoni, S., 2018. Marine energy exploitation in the Mediterranean Region: steps forward and challenges. Front. Energy Res. 6. https://doi.org/10.3389/fenrg.2018.00109.

Pörtner, H., 2010. Oxygen- and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ecosystems. J. Exp. Biol. 213 (6), 881–893.

Pournara, A., Emmanouil, C., Kungolos, A., 2019. The challenges of Blue Economy: Marine pollution, port, and shipping sustainability. Proceedings of the 7th International Conference on Environmental Management, Engineering, Planning and Economics (CEMEPE).

Pulselli, R.M., Mecca, S., Bastianoni, S., 2023. Marine Energy Sources for Decarbonization of Mediterranean Regions Through Maritime Spatial Planning. Mediterranean Architecture and the Green-Digital Transition: Selected Papers from the World Renewable Energy Congress Med Green Forum 2022. Springer International Publishing, Cham, pp. 365–371.

Rangel-Martinez, D., Nigam, K.D.P., Ricardez-Sandoval, L.A., 2021. Machine learning on sustainable energy: A review and outlook on renewable energy systems, catalysis, smart grid and energy storage. Chem. Eng. Res. Des. 174, 414–441.

Rayner, R., Jolly, C., Gouldman, C., 2019. Ocean observing and the blue economy. Front. Mar. Sci. 6.

Rehman, S., Alhems, L.M., Alam, M.M., Wang, L., Toor, Z., 2023. A review of energy extraction from wind and ocean: Technologies, merits, efficiencies, and cost. Ocean Eng. 267, 113192.

Rieckmann, M., 2018. Learning to transform the world: Key competencies in Education for Sustainable Development. Issues Trends Educ. Sustain. Dev. 39 (1), 39–59.

Roesch, R., Boshell, F., Ocenic, E., Salgado, A., Hecke, J., Castellanos, G., … & Abdel-Latif, A. (2020). Fostering a blue economy: Offshore renewable energy.

Sa'adi, Z., Yusop, Z., Alias, N.E., Noor, Z.Z., Kemarau, R.A., Ramli, M.W.A., Masood, A., 2025. Assessing future drought extremes and their impact on hydropower vulnerability in Sarawak. Chem. Eng. Trans. 122, 175–180. https://doi.org/10.3303/CET25122030.

Sakellariadou, F., Gonzalez, F.J., Hein, J.R., Rincón-Tomás, B., Arvanitidis, N., Kuhn, T., 2022. Seabed mining and blue growth: exploring the potential of marine mineral deposits as a sustainable source of rare earth elements (MaREEs)(IUPAC Technical Report). Pure Appl. Chem. 94 (3), 329–351.

Santiago, R.A.D.F., Barbosa, N.B., Mergulhão, H.G., Carvalho, T.F.D., Santos, A.A.B., Medrado, R.C., Nascimento, E.G.S., 2024. Data-Driven Models Applied to Predictive and Prescriptive Maintenance of Wind Turbine: A Systematic Review of Approaches Based on Failure Detection, Diagnosis, and Prognosis. Energies 17 (5), 1010.

Savitz, S., Davenport, A.C., Ziegler, M.D., 2020. The Marine Transportation System, Autonomous Technology, and Implications for the US Coast Guard. Rand Corporation.

Schober, A., Kittel, C., Baumgartner, R.J., Füllsack, M., 2018. Identifying dominant topics appearing in the Journal of Cleaner Production. *Journal of Cleaner Production*, 190, 160–168.

Shadmani, A., Nikoo, M.R., Gandomi, A.H., Wang, R.Q., Golparvar, B., 2023. A review of machine learning and deep learning applications in wave energy forecasting and WEC optimization. Energy Strategy Rev. 49, 101180.

Shaw, S., 2021. Ocean-A vast reserve of renewable energy. In: Journal of Physics: Conference Series, 1834. IOP Publishing, 012017.

Sheehan, E.V., Cartwright, A.Y., Witt, M.J., Attrill, M.J., Vural, M., Holmes, L.A., 2020. Development of epibenthic assemblages on artificial habitat associated with marine renewable infrastructure. ICES J. Mar. Sci. 77 (3), 1178–1189. https://doi.org/10.1093/icesjms/fsy151.

Shields, M.A., Woolf, D.K., Grist, E.P., Kerr, S.A., Jackson, A.C., Harris, R.E., Side, J., 2011. MRE: The ecological implications of altering the hydrodynamics of the marine environment. Ocean & Coast. Manag. 54 (1), 2–9.

Silver, J.J., Gray, N.J., Campbell, L.M., Fairbanks, L.W., Gruby, R.L., 2015. Blue economy and competing discourses in international oceans governance. J. Environ. & Dev. 24 (2), 135–160.

Simbolon, R., Sihotang, W., Sihotang, J., 2024. Tapping Ocean Potential: Strategies for integrating tidal and wave energy into national power grids. GEMOY Green. Energy Manag. Optim. Yields 1 (1), 49–65.

Smith, L.M., Cimoli, L., LaScala-Gruenewald, D., Pachiadaki, M., Phillips, B., Pillar, H., Wright, D.J., 2022. The deep ocean observing strategy: addressing global challenges in the deep sea through collaboration. Mar. Technol. Soc. J. 56 (3), 50–66.

Spaniol, M.J., Hansen, H., 2021. Electrification of the seas: Foresight for a sustainable blue economy. J. Clean. Prod. 322, 128988.

Stougie, L., Giustozzi, N., Van Der Kooi, H., Stoppato, A., 2018. Environmental, economic and exergetic sustainability assessment of power generation from fossil and renewable energy sources. Int. J. Energy Res. 42 (9), 2916–2926. https://doi.org/10.1002/er.4037.

Stratigakos, A. (2023). *Towards the Prescriptive Analytics Paradigm for Energy Forecasting and Power System Optimization* (Doctoral dissertation, Université Paris sciences et lettres).

Subhash, G.V., Rajvanshi, M., Kumar, G.R.K., Sagaram, U.S., Prasad, V., Govindachary, S., Dasgupta, S., 2022. Challenges in microalgal biofuel production: A perspective on techno economic feasibility under biorefinery stratagem. Bioresour. Technol. 343, 126155.

Suciptaningsih, O., Prajanti, S., Setyowati, D., Priyanto, A., 2020. Community Based Entrepreneurship in Coastal Communities: The Impact on the Environment and Economic Empowerment. Proceedings of the 5th International Conference on Science, Education and Technology, ISET 2019, 29th June 2019, Semarang, Central Java, Indonesia.

Takeuchi, M.A., Sengupta, P., Shanahan, M.C., Adams, J.D., Hachem, M., 2020. Transdisciplinarity in STEM education: A critical review. Stud. Sci. Educ. 56 (2), 213–253.

Tang, Y., Ju, C., Mei, R., Zhao, L., Liu, J., Yang, Y., Guo, X., Su, C., Cheng, Y., Liu, Q., 2024. Exploring the optimal integrated multi-trophic aquaculture (IMTA) patterns benefiting culture animals and natural water environment. Aquaculture 589, 741011. https://doi.org/10.1016/j.aquaculture.2024.741011.

Thompson, K.F., Miller, K.A., Currie, D., Johnston, P., Santillo, D., 2018. Seabed mining and approaches to governance of the deep seabed. Front. Mar. Sci. 5, 480.

Tran, M.T., 2024. Fostering sustainable mindsets: A critical exploration of educational psychology in business education. Int. J. Manag. Educ. 22 (3), 101054.

Trifonova, N., Scott, B., Griffin, R., Pennock, S., Jeffrey, H., 2022. An ecosystem-based natural capital evaluation framework that combines environmental and socio-economic implications of offshore renewable energy developments. Prog. Energy 4 (3), 032005.

Troell, M., Tyedmers, P., Kautsky, N., Rönnbäck, P., 2004. Aquaculture and energy use. Encycl. Energy 1, 97–108.
U.S. Congress. (2005). *Energy Policy Act of 2005, Public Law 109-58.* U.S. Government Printing Office. 〈https://www.congress.gov/bill/109th-congress/house-bill/6〉.
Uddin, S.A., Islam, M.M., 2019. Blue biotechnology, renewable energy, unconventional resources and products as emerging frontiers at Sea. J. Ocean Coast. Econ. 6 (2), 8.
Udo, W.S., Kwakye, J.M., Ekechukwu, D.E., Ogundipe, O.B., 2024. Optimizing wind energy systems using machine learning for predictive maintenance and efficiency enhancement. J. Renew. Energy Technol. 28 (3), 312–330.
United Nations. (1982). *United Nations Convention on the Law of the Sea.* Retrieved from 〈https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf〉.
Vaseeharan, B., Ramasamy, P., Murugan, T., Chen, J.C., 2005. vitro susceptibility of antibiotics against Vibrio spp. and Aeromonas spp. isolated from Penaeus monodon hatcheries and ponds. Int. J. Antimicrob. Agents 26 (4), 285–291.
Verma, V., Sorathiya, V., Sonowal, G., Reddy, M.S., 2024. Hybrid optimization for integration of renewable energy systems into smart grids. Meas. Sens. 33, 101170.
Vilela, R., Burger, C., Diederichs, A., Bachl, F.E., Szostek, L., Freund, A., Braasch, A., Bellebaum, J., Beckers, B., Piper, W., Nehls, G., 2021. Use of an INLA latent gaussian modeling approach to assess bird population changes due to the development of offshore wind farms. Front. Mar. Sci. 8, 701332. https://doi.org/10.3389/fmars.2021.701332.
Voyer, M., Allison, E.H., Farmery, A., Fabinyi, M., Steenbergen, D.J., van Putten, I., Song, A.M., Ogier, E., Benzaken, D., Andrew, N., 2021. The role of voluntary commitments in realizing the promise of the Blue Economy. Glob. Environ. Change 71, 102372.
Voyer, M., Benzaken, D., Rambourg, C., 2022. Institutionalizing the blue economy: an examination of variations and consistencies among commonwealth countries. Philos. Trans. R. Soc. B 377 (1854), 20210125.
Voyer, M., Farmery, A.K., Kajlich, L., Vachette, A., Quirk, G., 2020. Assessing policy coherence and coordination in the sustainable development of a Blue Economy. A case study from Timor Leste. Ocean & Coast. Manag. 192, 105187.
Wang, H.-Y., Fang, H.-M., Chiang, Y.-C., 2021. Study on the coexistence of offshore wind farms and cage culture. Water 13 (14), 1960. https://doi.org/10.3390/w13141960.
Watanabe, M.D., Cherubini, F., Tisserant, A., Cavalett, O., 2022. Drop-in and hydrogen-based biofuels for maritime transport: country-based assessment of climate change impacts in Europe up to 2050. Energy Convers. Manag. 273, 116403.
Wei, S., Wang, H., Fu, Y., Li, F., Huang, L., 2023. Electrical system planning of large-scale offshore wind farm based on n+ design considering optimization of upper power limits of wind turbines. J. Mod. Power Syst. Clean. Energy 11 (4), 1784–1794. https://doi.org/10.35833/MPCE.2022.000656.
Weiss, C.V., Guanche, R., Ondiviela, B., Castellanos, O.F., Juanes, J., 2018. MRE potential: A global perspective for offshore wind and wave exploitation. Energy Convers. Manag. 177, 43–54. https://doi.org/10.1016/j.enconman.2018.09.059.
Wibisono, R.B., 2024. Youth-government collaboration in maritime development: a pathway to a sustainable jakarta. J. Kebijak. Pemerintah. 61–85.
Wood, R.J.K., Bahaj, A.S., Turnock, S.R., Wang, L., Evans, M., 2010. Tribological design constraints of MRE systems. Philos. Trans. R. Soc. a Math. Phys. Eng. Sci. 368 (1929), 4807–4827.
World Bank. (2017). *The potential of the blue economy: increasing long-term benefits of the sustainable use of marine resources for small island developing states and coastal least developed countries.* World Bank.
World Energy Council, 2017. The North Sea Opportunity. THE NETHERLANDS The North Sea Opportunity. (2017). 〈https://www.weltenergierat.de/wp-content/uploads/2018/03/North-Sea-Opportunity.pdf〉.
Wu, C.F., Wang, H.H., Chen, S.H., Trac, L.V.T., 2024. Assessing the efficiency of bird habitat conservation strategies in farmland ecosystems. Ecol. Model. 492, 110732.
Yaiprasert, C., Hidayanto, A.N., 2024. AI-powered ensemble machine learning to optimize cost strategies in logistics business. Int. J. Inf. Manag. Data Insights 4 (1), 100209.
Yan, B., 2011. Analysis of laminar to turbulent transition of pulsating flow in ocean environment with energy gradient method. Ann. Nucl. Energy 38 (12), 2779–2786.
Yang, C., Jia, J., He, K., Xue, L., Jiang, C., Liu, S., Cui, H., 2023. Comprehensive analysis and evaluation of the operation and maintenance of offshore wind power systems: a survey. Energies 16 (14), 5562.
Yang, H., Yang, D., Lei, Z., Sun, F., 2008. New analytical derivation of the mean annual water-energy balance equation. Water Resour. Res. 44 (3).
Yoro, K.O., Daramola, M.O., 2020. CO2 emission sources, greenhouse gases, and the global warming effect. Advances in carbon capture. Woodhead Publishing, pp. 3–28.
Yousef, L.A., Yousef, H., Rocha-Meneses, L., 2023. Artificial intelligence for management of variable renewable energy systems: a review of current status and future directions. Energies 16 (24), 8057.
Zabihian, F., Fung, A.S., 2011. Review of marine renewable energies: case study of Iran. Renew. Sustain. Energy Rev. 15 (5), 2461–2474. https://doi.org/10.1016/j.rser.2011.02.006.
Zhou, P., Yin, P.T., 2019. An opportunistic condition-based maintenance strategy for offshore wind farm based on predictive analytics. Renew. Sustain. Energy Rev. 109, 1–9.