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Research article

Review of the marine energy environment-a combination of traditional, bibliometric and PESTEL analysis

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A R T I C L E I N F O

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A B S T R A C T

Marine renewable energy is regarded as a nascent renewable energy resource that is less utilized due to a number of challenges in the sector. This paper focused on using both traditional and bibliometric analysis approaches to review the marine energy industry. It also assessed the various opportunities and challenges in the sector beyond technological challenges using PESTEL analysis. The results from the study identified the availability of renewable energy targets, international and national greenhouse gas (GHG) emissions reduction targets, job creation, skill transfer from offshore industries, renewable support, and low GHG emissions as the major opportunities for the sector. The challenges in the sector include the lack of commonality in device designs, high initial capital costs, lack of appropriate legal and regulatory frameworks, lack of funding, fragmentations in regulatory institutions, bad macro-economic indicators in some countries, environmental challenges, the survivability of the various technologies in the harsh oceanic environment, and strong competition from other renewable energy sources. The outcome of the bibliometric analysis spanning from 2013 to 2023 shows that tidal power is the focus of research in the field, and most studies are either focused on ways to improve its efficiency in terms of technology or on the identification of resource potentials for the siting of the various marine renewable power systems. Recommendations such as strong cooperation between the government and private sector, increased public education, collaboration with existing players in the marine sector, and increased research and development, among others, were proposed for the development of the sector.

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1. Introduction

The increasing cost of fossil fuels in recent times and the adverse impact linked with their usage on the environment have

Abbreviations

EMF	Electromagnetic Field
GHG	Greenhouse Gases
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelized Cost of Energy
MCA	Multiple Correspondence Analysis
NIMBY	Not In My Backyard
OCE	Ocean Current Energy
O&M	Operation and Maintenance
ORE	Ocean Renewable Energy
OTEC	Ocean Thermal Energy Conversion
PESTEL	Political, Economic, Social, Technological, Environmental, Legal
R&D	Research and Development
RD&D	Research Development and Demonstration
RED	Reverse Electrodialysis
RE	Renewable Energy
RES	Renewable Energy Sources
SDS	Sustainable Development Scenario
SGE	Salinity Gradient Energy
TPP	Tidal Power Plants
UNCLOS	United Nations Convention on the Law of the Sea
WEC	Wave Energy Converters

necessitated the need to discover more sustainable, cheap, and eco-friendly resources for energy production in the world [1,2]. Fossil fuels still command a greater percentage of energy generation globally. Greenhouse gases (GHG) like CO_2, methane, and nitrous oxide are released during fossil fuel combustion, which seriously affects the sustainability of the environment. It is even projected to increase with time as a result of the rapid development of industrialization. The current status of GHG as well as the projected increase in the future will have dire consequences, such as severe health problems, weather changes, changes in the ecosystem, and sea-level rise, if nothing is done to curb it [3–5]. The energy structure transition is increasing in the framework of global carbon neutrality. Due to the growing consensus on global attempts to deal with the issue of climate change, a number of governments across the globe have introduced policies and measures intended to support the development and use of renewable energy (RE) in their countries [6,7].

The world's electricity demand is projected to reach 65% by 2040, with about 85% of that demand estimated to come from

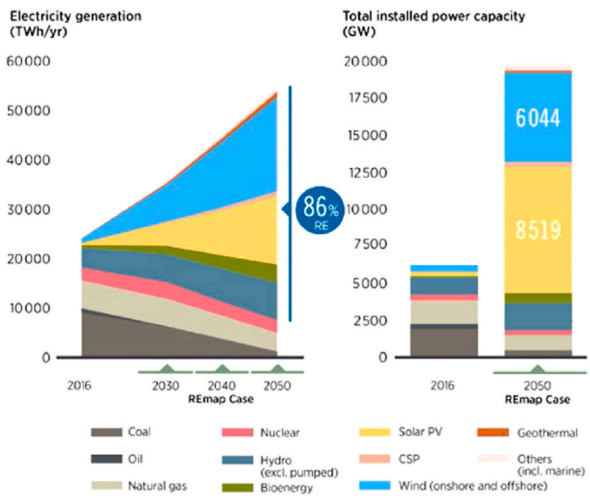


Fig. 1. Forecast the world electricity production from different sources [13] (Republished with permission from Elsevier 5513050859209).

emerging economies; hence, global leaders have projected to increase the composition of RE in the world's energy production mix to about 28% by 2040 [8,9]. Close to 13% of the world's inhabitants, which represent around 940 million people, are estimated to be without a proper energy source. South Asia and Sub-Saharan Africa account for 89% of this population, which is about 840 million people, according to data from the World Bank [10]. The development of RE comes with enormous environmental and economic benefits, job creation, and security of supply [11,12]. The RE sector has witnessed significant research and development (R&D) in recent years; this includes wave, solar, wind, etc. This can be associated with two interconnected factors, i.e., the commitment to reduce CO_2 emissions and the high potential of these resources for electricity generation [12]. Information as presented in Fig. 1 suggests that RE could account for over 86% of the world's electricity generation by 2050, with wind and solar expected to account for over 72% of the installed power capacity globally [13].

Global ocean energy resources are estimated to have a potential of 32,000 GW, greater than that of solar and wind energy. They also have the capacity to generate about 7% of the world's electricity requirement [14]. Among the several types of oceanic energy (i.e., wave, thermal gradient, tidal and marine current, etc.), wave and tidal energy are considered the most developed in terms of technology [15]. The potential for wave energy is projected to be between 16,000 and 18,500 TWh/yr $\pm$ 1200 TWh/yr globally, factoring in coastline alignment and wave direction. This resource is, however, intense on the oceanic coasts; for example, Western Europe's oceanic coast has a projected wave power average of 40 kW/m, whereas the Mediterranean Sea has a mean wave power capacity between 3 and 5 kW/m [16–18]. Although tidal energy is restricted to certain areas, it has a more competitive advantage over other forms of marine energies as a result of its power quality and predictability [19,20].

Bibliometric analysis enables researchers to introduce a reproducible, transparent, and systematic review process based on statistical measurement of science or scientific activity. It provides a more reliable and objective analysis compared to other methods. The large volume of published literature and conceptual developments are the milieu in which bibliometric tools and analysis become important as they provide a structured assessment of large volumes of data. This gives information about the evolution of the research area over time, the researched themes, the prolific institutions and scholars, as well as the extent of research in the research field [21]. A number of studies [22–27] have adopted it in conducting a comprehensive review of various sectors such as finance, energy, waste management among others.

The PESTEL tool has also been used by several researchers to assess the environment of different projects in different fields of study. Segura et al. [14], made use of the PESTEL analysis to provide different strategies and recommendations to help identify the risks in the tidal energy sector in the European Union. Song et al. [28], employed the PESTEL approach to evaluate China's waste-to-energy incineration industry. Their research provided some recommendations for both government and the private sector, relative to the application of Public-Private Partnership (PPP) mode, policy changes as well as efficient project operation in the sector. Igliński et al. [29], performed a PEST analysis on Łódzkie Voivodeship in Poland's RE production. Their analysis concluded that the study area's RE sector has enormous potential. The study identified the country's economic macro-environment as the most promising factor whiles technological factors came as the least favorable factor for the growth of the sector. de Andres et al. [30], also conducted a broad analysis on the growth of ocean energy and deployment using the PESTLE framework. Their study looked at the most relevant factors that could lead to the reduction of cost of energy for tidal and wave energy. Kolios and Read [31], presented an analysis on United Kingdom's tidal energy industry using the PESTLE approach. Findings from their study identified the threats and the various stakeholders engaged in the different phases for the development of tidal energy projects from the conceptualization phase to the decommissioning phase. Widya et al. [32], conducted a stakeholder analysis as well as policy planning for Indonesia's fossil energy industry using PESTLE methodology. The outcome from their analysis showed the relevance of strategically bringing into line the stakeholders' policies to the desires of other important stakeholders. Achinas et al. [33], explored and reviewed Europe's biofuel industry using the PESTLE approach. The study discussed the interrelation between sustainable development and technological facets. Furthermore, Islam and Mamun [34], analyzed the main opportunities in renewable energy generation. They employed two different decision-making tools i.e., PESTLE and SWOT in the analysis.

Furthermore, the authors of [35], assessed Malawi's energy situation using the PESTLE approach, the study was conducted to aid in the growth of the nation's energy sector. Their analysis suggested a paradigm shift in Malawi's energy sector which has the potential to offer long-term supporting mechanisms. Also, Christodoulou and Cullinane [36], used the SWOT/PESTLE tools to identify elements that have negative or positive impact on the acceptance and effective execution of a port management system. Racz et al. [37] conducted an evaluation of the production of biodiesel options with life cycle using multi-criteria decision and PESTLE analyses. Tsangas et al. [38], used a combination of PESTEL-SWOT analysis and Analytical Hierarchy Process to evaluate Cyprus's hydrocarbons sector. Recent study by Do Thi et al. [39] employed the PESTLE and other multi-criteria decision making techniques to investigate the procedure of desalination of seawater using various techniques. Mukelabai et al. [40] utilized the PESTLE method to assess the conditions that could influence the adoption of hydrogen technologies in Africa. According to the outcome of their study, countries within 0.5 and −0.5 government effectiveness index lead in the planning of hydrogen economies. Furthermore, Capobianco et al. [41] followed the PESTLE analysis approach to identify sustainable ways of decommissioning the offshore platforms in the oil and gas sector. Andriuškevičius and Štreimikienė [42] using the PESTLE approach determined the driving factors of mergers and acquisitions in the energy industry. The results reported in their study suggest that whereas the presence and role of mergers and acquisitions in the industry have recorded an increase, the reasons for mergers and acquisitions have changed remarkably.

In this study, the bibliometric analysis package (i.e., Biblioshiny) in the R software and the VOSviewer tool were used to comprehensively assess the marine renewable energy environment from 2013 to 2023 using data from the Scopus database. An assessment of hotspot research areas, the evolution of the study area over time, and the conceptual structure in the research field were assessed using the bibliometric tools. Additionally, despite the enormous potential in the oceanic energy sector, it is yet to see the needed development as compared to other RE resources. Most of these resources are either at their embryonic or immature state, in terms of their development [43]. This can be ascribed to a number of challenges in the sector, these challenges range from political, economic, social, technological, environmental, and legal. However, studies such as [14,31,44–46], concentrated on one of these areas in their study. This study thus employed the PESTEL analysis approach to assess all six factors in the marine energy sector. The objective of the study is to provide developers, researchers, policymakers, and other stakeholders with the needed information in the sector to help shape decision-making to fast-track the growth of marine energy resources globally. To the best of the authors' knowledge, this is the first study that adopts the traditional, bibliometric, and PESTEL approaches to analyze the marine energy environment. This gives a comprehensive bird's-eye view of the sector that can be adopted to shape both decision-making and future research in the study area. The following research questions would be addressed in this study.

- What is the past, current and future research trends in the marine energy industry?
- Why has the marine energy industry not seen the needed development over the years?
- What are the political, economic, social, and technological, environmental, and legal issues confronting the development of the sector?
- What are some policies and programs that can be implemented to address some of the challenges identified in the study?
- What are some of the research gaps in the marine energy sector and possible future areas of study that could help develop the industry?

The paper is structured into 5 sections. A brief overview of the marine energy environment is presented in section 2. The method used for the study is presented in section 3, section 4 presents the results of the bibliometrics analysis, PESTEL analysis, and the way forward for the industry. The conclusion is presented in section 5.

2. Overview of marine energy and its global usage

According to the international energy agency (IEA), electricity production from marine technologies in 2019 is estimated to have increased by some 13%. Even though, this growth is significantly above what was observed in the previous years, the technology is not on track with the Sustainable Development Scenario (SDS), which demands a relatively higher growth per annum at a rate of 24% through to 2030 [47].

The medium-term RE market report by the IEA indicated that the capacity of the world's energy generation from the oceans was about 530 MW in 2014, it was estimated to reach about 640 MW by 2021. This is virtually insignificant if compared to generations from other RE sources across the globe. For instance, total global installed photovoltaic capacity as of 2014 was 180,000 MW. This confirms the lag in technological and simultaneous capacity expansion of resources of the ocean energy [11]. China and South Korea lead in Asia in the development of Ocean energy since 2011 as a result of the development of tidal barrage facilities, through the support of their government. Their government adopted policies such as reduction in tariffs and tax exemptions, policies on subsidy to promote scientific research and development, prototype demonstrations and the growth of the RE industry among others [48,49]. France has also established the La Rance tidal barrage. The UK leads in terms of capacity of installation, Spain, Sweden, Netherlands, Norway, Portugal, and Italy follows. The development of these technologies is however, at advanced stage in North America specifically in Canada and United States, with the execution of demonstration scale commercial projects. Central America, Africa, South America, Oceania, and the Caribbean are also at the early stages in terms of the development of ocean resources for energy generation [48].

It is theoretically estimated that the yearly capacity of ocean energy ranges from 4 to 18 million tonnes of oil equivalent. Deployment of the world's ocean power potential is projected to be about 337 GW [11,50]. Another study also puts the global ocean energy potential as follows: 2000 TWh/year for osmotic, 800 TWh/year for tidal, between 8000 and 80,000 TWh/year for wave, and

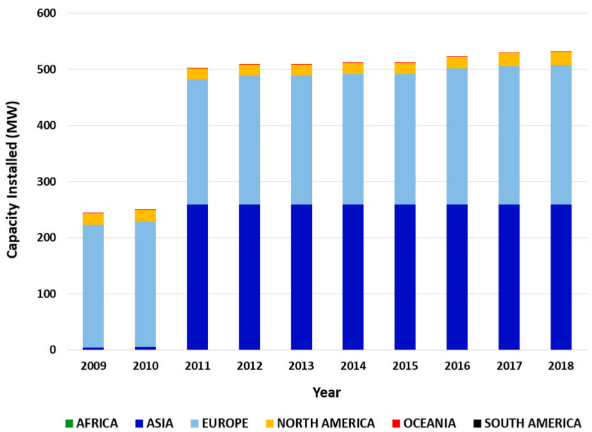


Fig. 2. Marine energy: continental installed capacity according to IRENA (2019) [48] (Published under open access).

between 10,000 and 87,600 TWh/year for thermal sources [51]. It is however important to note that wave energy cannot be implemented everywhere, which is a major setback. The Southern part of Canada, western coasts of Scotland, Australia, Southern Africa as well as the northwestern and northeastern coasts of the United States are endowed with huge wave energy potentials for electricity generation. The Pacific Northwest region alone has a potential to generate about 40–70 kW (kW) per 3.3 ft (1 m) [52]. Fig. 2 shows the capacity of installed oceanic energy by continent.

2.1. Brief overview of ocean renewable energy

This section presents the various renewable energy generating options available in the oceans. Research has shown that the ocean has lots of energy to meet the world's power demand in the form of waves, thermal, salinity gradient, currents, and tides.

2.1.1. Waves power

The passage of wind over the ocean or water generates surface waves. The differential heating of the earth and the passage of air over water bodies produces wind. The wind is converted into waves through specific mechanisms, i.e., the waves are generated in a three-step process. Firstly, the circulation of wind on the surface of the sea exerts a divergent stress on the water surface, this results in the creation of waves. Secondly, the disorderly flow of air close to the surface of a water body creates a speedily unreliable shear stress and pressure fluctuations. In the situation where the generated fluctuations come in phase with the accessible waves, further waves are generated. Lastly, when certain waves reach a definite size, a stronger force can be applied by a wind on the exposed surface of the wave, which is maximized if the speed of wind and that of the wave is equal [52]. The first commercial installation of wave energy generation from the ocean commenced in 2008 in Portugal-Pelamis and UK-SeaGen [53]. Table 1 indicates the resources of waves in some selected countries. Information as presented in Table 1 shows an enormous wave resource potential for countries such as Chile, Argentina, Norway, Ireland, South African and Coast of Southwest Africa, and Australia.

The basic processes in the conversion of wave energy can be represented as: the force of an incident wave originates a relative movement amongst an absorber and a point of reaction; this moves a working fluid through a generator prime mover. The relative motion will be oscillatory due to the ocean wave's periodic nature. Different prime movers and working fluids are used to transform these forces of the slow wave into high-speed, unidirectional rotation of the shaft of a generator [55]. Currently, there are four primary

Table 1
Wave Energy Resource in some selected countries [54] (Republished with permission from Elsevier 5522420901157).

Country	Location	Wave resources (kW/m)
Argentina	Argentine sea	61.3–69
Africa	South African and Coast of South West Africa	40–50
Australia	Southern Australian shelf	25–30
Brazil	North East region	2–14
Belgium	Belgium Continental Shelf	4.64
Canada	North Pacific Ocean (Vancouver Island)	25
	North Atlantic Ocean (Sable Island)	25
China	Bohai Sea	7.73
	East China Sea	6.36
	Yellow Sea	6.29
	South China Sea	5.32
Chile	Los Lagos	71–87
	Magallanes	78
Denmark	North Sea	9.8
Greece	Crete Island	4–11
France	Bay of Biscay	24.3
India	Indian Coast	5–10
Italy	Mediterranean Sea	8.91–10.29
Ireland	West of Malin Head	30–40
Japan	Japan Sea Coast	7.2
	Entire Coast	6.4
	East Coast	6.3
Norway	Norwegian Sea (Runde Island)	40–50
Malaysia	West Peninsular Malaysia	0.5–2.0
	East Peninsular Malaysia	<6.5
	Sabah Ocean	6.5
	Sarawak Ocean	3.1–4.5
Spain	Galician Coast	14.7–50.1
	Death Coast	50
Portugal	Portuguese Near Shore	30–40
United Kingdom	Celtic Sea	15–32
Sweden	Skagerrak Strait	2.8–5.2
United States	California Coast	10–32
	Hawaii	15–25
	Southeast Atlantic Coast	9–15
	Pacific Northwest	36

ways of wave energy conversion, this can be done using the following devices, i.e., point absorbers, wave attenuators or linear absorbers, oscillating water column, and overtopping devices [53,56].

2.1.1.1. Technical challenges of wave energy. Generation of energy from waves is significantly different from other conventional power conversions, the system has inherent features such as low velocities and large wave forces. These inherent features are basically the main challenges in wave energy production which results in very low energy conversion efficiency and reliability. Also, since WECs are designed to extract energy from waves, they must be placed in highly energetic areas to be able to extract the maximum energy. However, the harsh conditions in such areas apply severe challenges to the survivability and reliability of the wave energy converters (WEC) which are expected to survive for more than 20 years in the sea environment to be able to generate power continuously and efficiently [57]. The efficient operation of WEC is dependent on the realization of resonance between the energy converting device and the ocean wave field. The attainment of resonance is however highly susceptible to fluctuations in the excitation force and viscous damping which comes from non-linearities in the field of the surface wave. Wave-breaking is a major cause of non-linear effects. Wave breaking affect the operations of the WEC via energy dissipation and hydrodynamic loading [58].

2.1.2. Tidal power

The generation of tidal energy is dependent on the rise and fall of the ocean or sea waters. Around 4–12 m range and neap tides have a capacity which ranges from 1 to 10 MW/km along the seashores. Power generation capacities from this resource are affected by the variations in terrestrial and celestial gravitations. The spring tides which are also known as the high tides occurs during new and full moon periods whiles neap tides also known as low tides take place during waxing or waning half-moon periods as a consequence of the misalignment of the earth with the sun and moon [51]. The earth revolves around the sun at a velocity of 107,000 km/year and rotates on its axis at a velocity of 16,500 km/h. The earth takes 24 h (one day) to complete one rotation whereas, the moon takes 29.53 days to complete a single revolution around the earth. The solar month has 30 days whiles 29 days and 10 min make up the lunar months, therefore, the lunar month is 50 min shorter than the solar month. The moon and the earth become aligned twice to exert a maximum gravity pull on the ocean to generate spring tides. The range of water springs could reach as high as 11.4 m in Penzhinsk, Russia to 12.4 m in Cobequid in Canada. The highest tide in the world occurs at the Bay of Fundy, Canada at 17 m; Severn River Estuary, UK at 15 m; and the France at the Bay of Monte Saint Michel, at 13.5 m. Countries such as Australia, Argentina, South Korea, China, Russia, and India also have enormous potential for tidal power [48,59].

Oceanic tidal resources can be classified into tidal streams, oceanic currents, and river streams. Ocean currents provide non-zero mean value of velocities for a period of time, for a minimum of one year, the tidal streams have mean velocities of zero for a period of about half a day and an entire night. Generally, the term tidal that is mostly used in literature include the two categories of streams [60,61]. Tidal currents are the periodic movement of water which occurs not essentially via head difference generated via out-of-phase ocean tides [62].

Four technologies can be used to convert tide energy into electricity, these include tidal lagoons, tidal barrages, dynamic tidal power plants, and tidal stream converters [63]. Tidal barrages have dams, barrages and reservoirs, the barrage has many gates in which the turbines are placed. Movement of water can take place between the reservoir and the sea through the gates or the channels in tidal occurrences. Electricity can therefore be generated through the rotation of the turbines caused by the water stream. The operating principle for the tidal lagoons for the generation of electricity is comparable to that of the tidal barrages. The reservoirs in tidal lagoons are however independent enclosures in highly tidal environment. The kinetic energy of tides from water flow is extracted using current type tidal power plant or tidal stream converters. Electricity is obtained from these power plants using the kinetic energy of the tidal currents through the help of the tidal turbines which is similar to that of wind turbines. The difference in the level of water which is created via a perpendicularly constructed open-dam structure to the coast is used to rotate bidirectional turbines to generate electricity in the case of the dynamic tidal power plant. The largest construction among these technologies globally is the barrage type tidal power plant [64].

2.1.2.1. Technical challenges with tidal energy. A key challenge linked with tidal energy conversion is how to improve the efficiency of the turbines. In the case of tidal current technologies, a basic technology exists, however, technical challenges continue to exist as a result of insufficient experience with the devices. The materials of the devices are exposed to rough environmental conditions, therefore in order to make such a technology commercially competitive there is the need to increase attention on the technical risks in designing, constructing, installation and operation of such a facility [65]. Also, the availability of tidal energy is another challenge associated with the development of tidal power plants (TPP). Tides are more strongly connected to lunar than the solar cycle, which makes the ranges vary with annual and semi-annual components, and spring and neap tides. High tides ranges are available at a period of 5–6 h after the high tide cycle. The high tides may not coincide with the periods with peak demand hours of electricity within the day, because the cycles move 50 min each day. The site for the construction of TPP also need to have some specific features such as a large basin area with narrow entrance in order to reduce the barrage size [66].

2.1.3. Salinity gradient power

Salinity gradient energy (SGE) is produced when there is mixing of water with different salt concentrations, for example when the sea and rivers meet. Research shows that, close to 2.5–2.7 MJ (0.70–0.75 kWh) is released when 1 m^3 of sea water mixes with 1 m^3 of a river [67]. The released Gibbs free energy that occurs from the mixing of the two different salinities is captured by the SGE. In the case of an estuarine system, the natural mixture of seawater and freshwater can be redirected to an SGE system to generate electrical power under control mixing. Sewage generated from wastewater treatment plant and industrial brine can be utilized at SGE installations [68–70]. Two SGE technologies are at pilot stage and are being studied for commercial purposes: pressure retarded osmosis (PRO), and reverse electrodialysis (RED). The additional technologies that are presently at early stages are the osmotically induced nanofluidic electric currents, capacitive mixing and hydrogels [70,71]. Freshwater discharge into saltwater from various rivers is spread globally with an estimated volume of 44,500 km^3/year. In a situation whereby only 20% of the yearly discharge is used for SGE generation, then the general capacity of this resource is projected to be approximately 2000 TWh/year (7.2 EJ/year) [48,72].

2.1.3.1. Technical challenges with this SGE. One of the main challenges associated with the SGE technology is the vast surface area membrane needed to produce large scale commercial electricity. For instance, research has shown that a 2 MW power plant will need at least 1×10^6 m^2 of membrane surface area, the used membrane also requires maintenance and replacement with time of around 5 years. Research indicates that the current maximum power of membranes is less than 3 W/m^2, however, some experimental works have attained power densities more than 14 W/m^2. In order to apply this technology to large scale electricity generation, there is the need to improve the membrane efficiency. Other identified challenges are pretreatment of water, bio-fueling, as well as the development of modules to house the membranes [73].

2.1.4. Ocean thermal energy

Ocean thermal energy conversion (OTEC) is the process by which electricity is generated through the conversion of sensible heat from stored solar energy in the upper mixed layer of subtropical and tropical oceans through evaporating a suitable working fluid in a Rankine cycle ran among cold deep-water as well as warm surface temperatures. The cold deep water for condensing the working fluid comes from the Polar Regions where it sinks towards the floor of the sea and subsequently moves in the direction of the equator in a cold deep-water layer. There is a sustained thermal stratification as a result of the incident where dense, salty water sinks in the direction of the sea floor whiles the less dense warm water is situated at the surface. OTEC is said to be feasible at areas where the thermal gradient is more than 20 °C between the surface and the deep waters [74,75]. The greatest area on the globe with high potential of this resource are those at the tropical latitudes (0° to 30°) at both hemispheres, this includes the eastern and western coasts of the Americas, the coasts of Africa, some Caribbean and Pacific islands, and India [48]. According to IRENA, OTEC possesses the greatest potential relative to other energy technologies of the ocean, about 98 countries as well as regions are found to have feasible OTEC resources. OTEC alone can meet the world's power generation capacity, and that would not have any impact on the ocean's temperature profiles. OTEC is more financially sustainable in isolated islands in the tropical seas because generation in those areas can be combined with other functions for instance, freshwater production and air-conditioning [76]. Theoretically, a temperature gradient of 20 °C has an efficiency of 6.6%, this increases to 9.6% with a temperature difference of 30 °C, this maybe practically lower compared to other RES [77].

2.1.4.1. Technical challenges of OTEC. The concept of OTEC cycles is same as the thermodynamics of conventional steam power plants. The central dichotomy between the two is the enormous magnitude of cold and warm seawater needed for the process of the heat transfer, which results in the consumption of a percentage of the produced power by the turbine generator in the operation of the pumps. The temperature increase of the seawater as a result of frictional losses is insignificant for practical projects. The perfect energy transformation for 4 °C and 26 °C cold and warm seawaters is 8%. A real OTEC power plant transfers heat irreversibly along the cycle, this produces an energy conversion of 3–4% which are small relative to the efficiencies of traditional power plants [78]. There are other factors that need to be taken into consideration before selecting a particular site for a large-scale development of this technology. Some of these factors are as follows [66]: the distance between the thermal resource and the shore (for the purposes of grid interconnection); the depth of the cold-water location and the sea bottom; the sea bottom conditions (floating power conductors installations, mooring) and the type of OTEC facility (near-shoreline or shoreline, free-floating or platforms).

2.1.5. Ocean Current Energy (OCE)

OCE is a kinetic energy at large-scale, open-ocean, and near-surface currents. Such current is usually persistent, swifter than background ocean currents, sustainable and display the greatest flows close to the ocean's surface [79]. Ocean current (OC) is the constant flow of ocean water in a particular direction, this can differ significantly in terms of leading driving forces, temporal and spatial scales as well as spatial locations. OC at high speed is rich in hydrokinetic energy. Wind stress, gradient of salinity and temperature are the key driving forces for currents at large-scale (i.e., a length-scale of the order of 1000 km). On the other hand, pressure gradients, river discharge and tides can drive the meso-scale (i.e. order of 100 km) [80]. Ocean surface currents are mostly wind driven and it develops its characteristic in clockwise spirals at the northern hemisphere as well as an anti-clockwise rotation at the southern hemisphere as a result of the forced stresses of wind. The Gulf stream system typifies a current moved by wind at the northern hemisphere which intensifies at the western border of the Atlantic Ocean due to the Coriolis effect. Starting from the northern North Atlantic and ending in the Caribbean, the Gulf Stream represents the world's most intensely studied Ocean current system. The Gulf system is averagely 1000 m deep and 90 km wide, with a current speed at the surface exceeding 2 m/s [80–82]. Some potential sites for large scale development of OCE power plant are identified to be around Agulhas/Mozambique off South Africa, the Gulf stream off eastern North America, the East Australian current and the Kuroshio current off East Asia [48].

2.1.5.1. Technical challenges of the OCE. As a result of the ocean depth at appropriate positions for ocean currents, there is the need to hold turbines at locations with typically submerged systems or moored floating systems [83]. Operating this technology during winter is also problematic in winter. In order to optimize power output during all year round, there is the need to factor local variations in water levels, which is a complicated challenge [84].

3. Methodology

This study uses the traditional reviewing and bibliometric analysis approaches to assess the ocean renewable energy environment. The PESTEL analysis approach was also used to identify some opportunities and threats in the sector.

3.1. Bibliometric and PESTEL analysis approach

A brief bibliometric analysis of the renewable marine energy environment is conducted using data spanning from 2013 to 2023 in the Scopus database, the search was conducted on May 27, 2023. Scopus is recognized as the largest database with peered reviewed documents that can be used for such analysis. In order to filter the data, pertinent terms that addressed the research questions were chosen. A total of 4836 documents were retrieved within the study period based on the following search items "Wave Power Plant" OR "Marine renewable energy types" OR "Tidal power" OR "Salinity Gradient Power" OR "Ocean Thermal Energy" OR "Ocean Current Energy" OR "Ocean Renewable Energy". Various strategies were employed to either include or exclude unsuitable documents from the retrieved data. Documents that were included in the studies are peer reviewed papers, conference papers, book, and chapters, however, documents such as erratum, editorials, notes, and non-English documents were excluded from the analysis. Incomplete and documents outside the scope of the study area were also excluded. A total of 343 documents were therefore excluded from the analyzed data using the strategies provided supra, leaving a total of 4493 documents for the analysis. A brief description of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach used to identify the suitable data used for the analysis is presented in Fig. 3. The PRISMA literature review methodology is used in our study because it can systematically, effectively, and dependably compile results pertaining to a particular discourse domain. We used the PRISMA guidelines in our study to help us choose themes that fell within the purview of our research focus [85]. The VOSviewer tool and the Biblioshiny package in the R software were used for the visualization and analysis of bibliometrics. In the VOSviewer, the fractional counting method was used.

PESTEL analysis is a tool or framework used by investors and other stakeholders to assess and monitor macro-environmental (i.e., external marketing environment) issues which could affect the growth of a business or project [86]. The PESTEL framework aids businesses in making sustainable innovation and investment decisions by considering macroenvironmental elements, external drivers of change, and long-term objectives [28,87]. This method of tracking a specific project's environment provides a bird's eye view of the project's environment from different viewpoints, this affords interested stakeholders the opportunity to assess and monitor issues that may be of concern during planning or execution of a project. This approach of analysis is pre-conditional in terms of strategic management, it gives researchers, stakeholders, investors, etc., the needed knowledge on external issues that may impact their operations

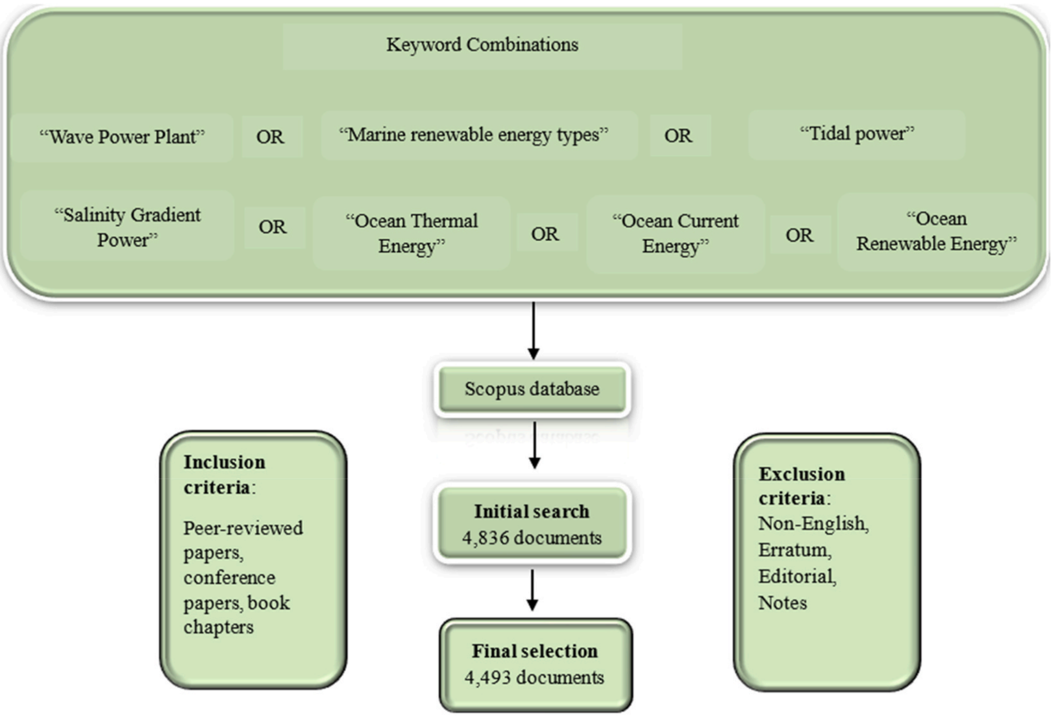


Fig. 3. The PRISMA method used for the study.

either positively or negatively [88]. The various factors under each of the various aspects of the PESTEL were obtained from published literature, i.e., articles, official documents from various institutions and governments, and official websites. The flowchart for the method used for the study is presented in Fig. 4.

4. Results and discussion

4.1. Bibliometric analysis

Based on the analysis, a total of 9556 author keywords were found from 1233 sources. The highest annual scientific research production was recorded in 2021 within the period of analysis, a total of 615 documents were published that year.

4.2. Word cloud and network visualization

A total of 17 clusters with links of 5116 and a total link strength of 3364 were found. As indicated in Fig. 5 the most occurring author keyword is *tidal energy* followed by the phrase *renewable energy*, with link strength of 249 and 228, respectively, OTEC and the salinity gradient power followed. The links mostly associated with tidal energy are in relation to resource assessment, tidal turbines, vertical axis turbines, numerical model, multi-objective optimization and hydrodynamics. Similarly, keywords such as OTEC, resource assessment, tidal current assessment, delf3d, wave power plant, pressure retardation osmosis, and energy policy are some of the

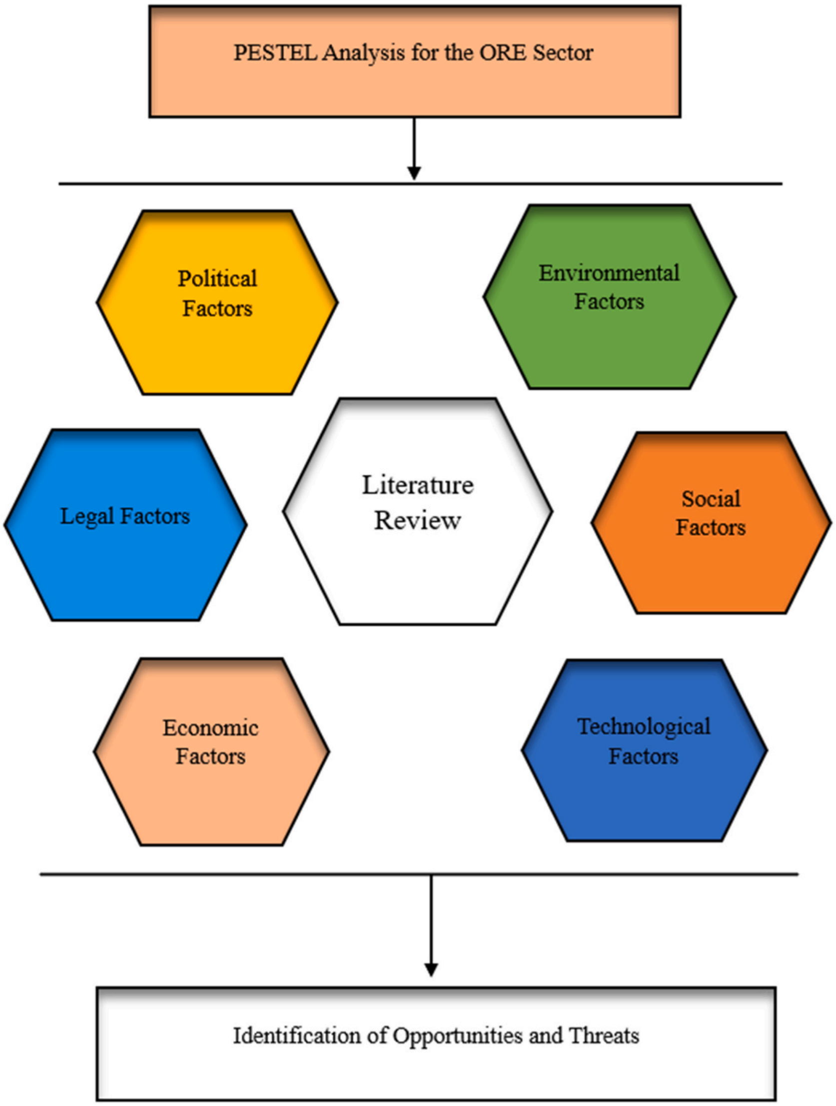
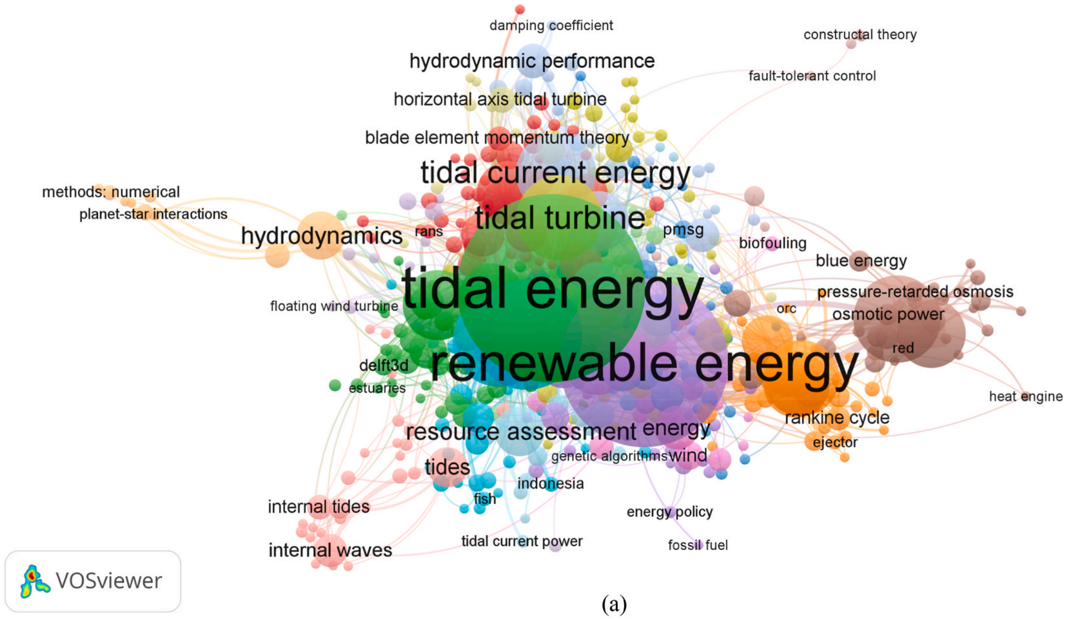
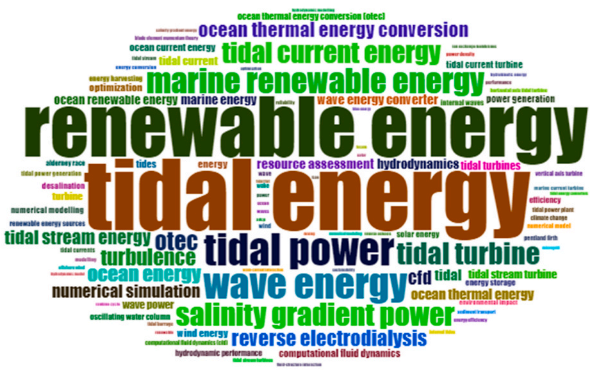


Fig. 4. Flowchart for the method used for the study.



(a)



(b)

Fig. 5. (a) Network visualization of the author keywords (b) Word cloud for the analysis.

keywords linked to the term renewable energy. This trend of research in the ocean renewable energy space within can be attributed to the need to find alternative and sustainable sources of energy generation. The focus on tidal energy could be due to its reliable nature as a result of its availability, since the movement of tides occur twice a day from the gravitational force of the moon [89]. Currently, barrages or tidal dams are the most regarded tools capable of generating electrical power at an economically competitive scale. Therefore, research and development on tidal energy over the years has been mostly focused on tidal turbines and barriers. The coming era is expected to experience profitable sustainable energy from tidal power plants and it is for that reason that much research is required for that technology [11,90,91]. Furthermore, the recent increase in funding for the development of tidal Stream Energy projects is also a contributing factor for the increasing research about the technology. Countries like India, Russia, the UK and Korea are said to be planning to install tidal barrages that amount to some 115 GW [90,91].

Analyzing the technical and economic potential of a renewable resource in an area is key for policy and decision-making and interested stakeholders. It gives governments or investors prior knowledge of the viability of the resource for onward development or investment. As such several studies have been conducted to assess the various resources of renewable marine energies [92–96]. The Delft3D which is tool that is mostly used in investigating the morphology, sediment transport, hydrodynamics and water quality for coastal, estuarine and fluvial environments [97] also appeared to be a key feature in the author keys. Reverse electrodialysis (RED) is also one of the most featured keywords within the period, which suggests it is one of the key areas that researchers are working on. RED is part of the evolving membrane based methods that can be used for the harvesting of energy via mixing of water with different salinities [98]. The RED technology has in the last decade grown significantly, it has gained a rapid increase in its technology readiness level, this has enabled the piloting of some RED systems under varying real environmental conditions [99].

Fig. 6 presents the thematic map of the study based on the number of documents investigated in this study, this is explained by Refs.

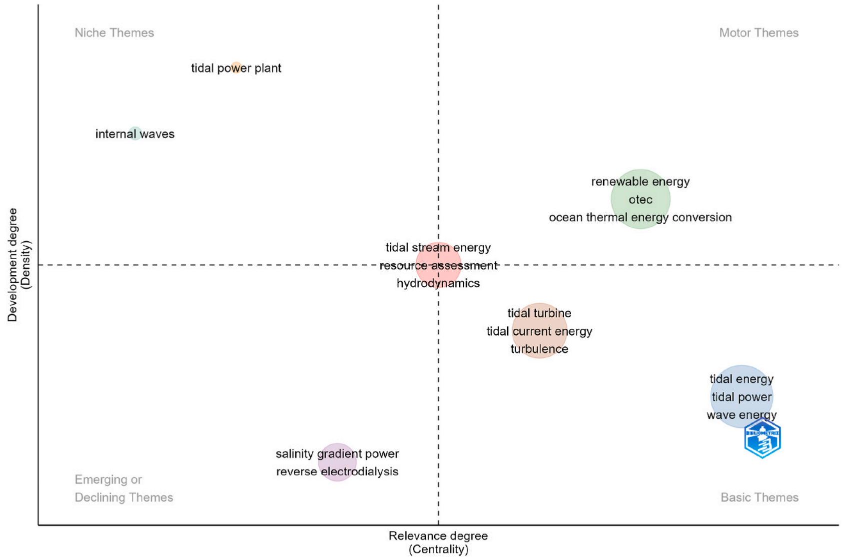


Fig. 6. Thematic map for the author keywords.

[100,101]. The thematic map is key for the identification of core research, declining or emerging themes, and basic themes. It is in the form of a quadrant; every quadrant gives information on the function of a theme in a specific research area. The motor themes quadrant has themes that have high density and centrality. In the motor themes quadrant, renewable energy, OTEC, and ocean thermal energy conversion are found this quadrant. The OTEC technology has several advantages such as the potential to generate microalgae streams, freshwater and the for air conditioning purposes [102]. The first OTEC factory was constructed in 1930 by Georges Claude in Cuba who was a student of d'Arsonval. A number of plats has since been built after that, in the United States for example a closed-cycle unit of an OTEC mini plant was constructed with a capacity of producing an average 18.8 kW of electricity [103,104]. Similarly, an OTEC plant with capacity of 255 kW was built in 1993 at Keahole Point and operated for 6 years continuously, and using the experience gained a new power plant with a capacity of 105 kW was further built in 2013 whose electricity was connected to the grid. Hawaii is therefore expected to construct between 10 and 20 MW by 2045 to help in gaining independence in its energy sector. Furthermore, an OTEC barge with a capacity of 1.5 MW has been tested during the 7th International OTEC Symposium in Busan in South Korea, this was done to assess the large-scale deployment of the technology [104,105]. These are some of the reasons why OTEC featured in the motor themes quadrant as a result of the level of advancement in its technology compared to others. The second quadrant is occupied by the Niche themes, these themes consist of specialized areas of a particular research domain. Such areas are mostly well-developed but have marginal relevance. Their role is mostly supportive or peripheral to the basic or main themes for the research area's development. The two keywords that appeared in the "Niche themes" quadrant are tidal power plant and internal waves. The undersea equivalent of surface waves is said to be an internal wave. Internal waves play a major function in energy, heat and momentum transfer in the ocean [106,107]. The two keywords as shown in the Niche quadrant support the idea for energy generation from the oceans for sustainable development. In the third quadrant i.e., the 'emerging or declining themes', and these are words that are either emerging or declining base on evolution and advancement in the research area. Salinity gradient power is an emerging renewable energy option, it is

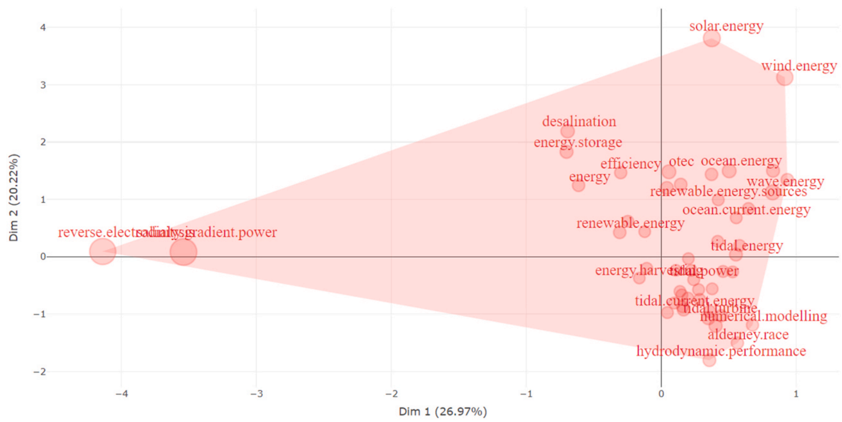


Fig. 7. Conceptual structure: factorial analysis.

obtained through the differences in the concentration of salt between two fluids, which are mostly salt water and freshwater, for instance when a river flows into the sea. A number of tests have been conducted on some demonstration projects that use membranes. Sea and fresh water alternately fill the compartments between the membranes. The driving force for the transportation of ions is the salinity gradient which ends up creating an electric potential that is converted into electricity [108]. The RED as indicated supra is also an emerging and growing research area in the last decade. The final quadrant i.e., the 'basic theme' present themes that are of high relevance towards the field's development, they are however comparatively less developed than the items in the first quadrant, i.e., the motor themes. There still exist research areas that require further development for such themes, and in this case, various studies are focused on improving the efficiency of tidal power, tidal turbines, wave energy among others. There is still the need to work to reduce technological challenges associated with those technologies and also bring the cost associated with them down.

The Biblioshiny program has a conceptual structure function that allows users to conduct multiple correspondence analysis (MCA) for conceptual structure in the area of study as well as the clustering of the keywords using the K-means approach. This allows for the identification of documents that have concepts that are common. The MCA is used for both numerical and graphical analysis of multivariate categorical data. The interdependences that exist between the set of variables are examined using the MCA, its objective is to find new latent variables. The outcome is explained based on the comparative locations of the various points as well as their allocation along the dimensions. The closer the words are the more similar in distribution they appear [21]. The results as presented in

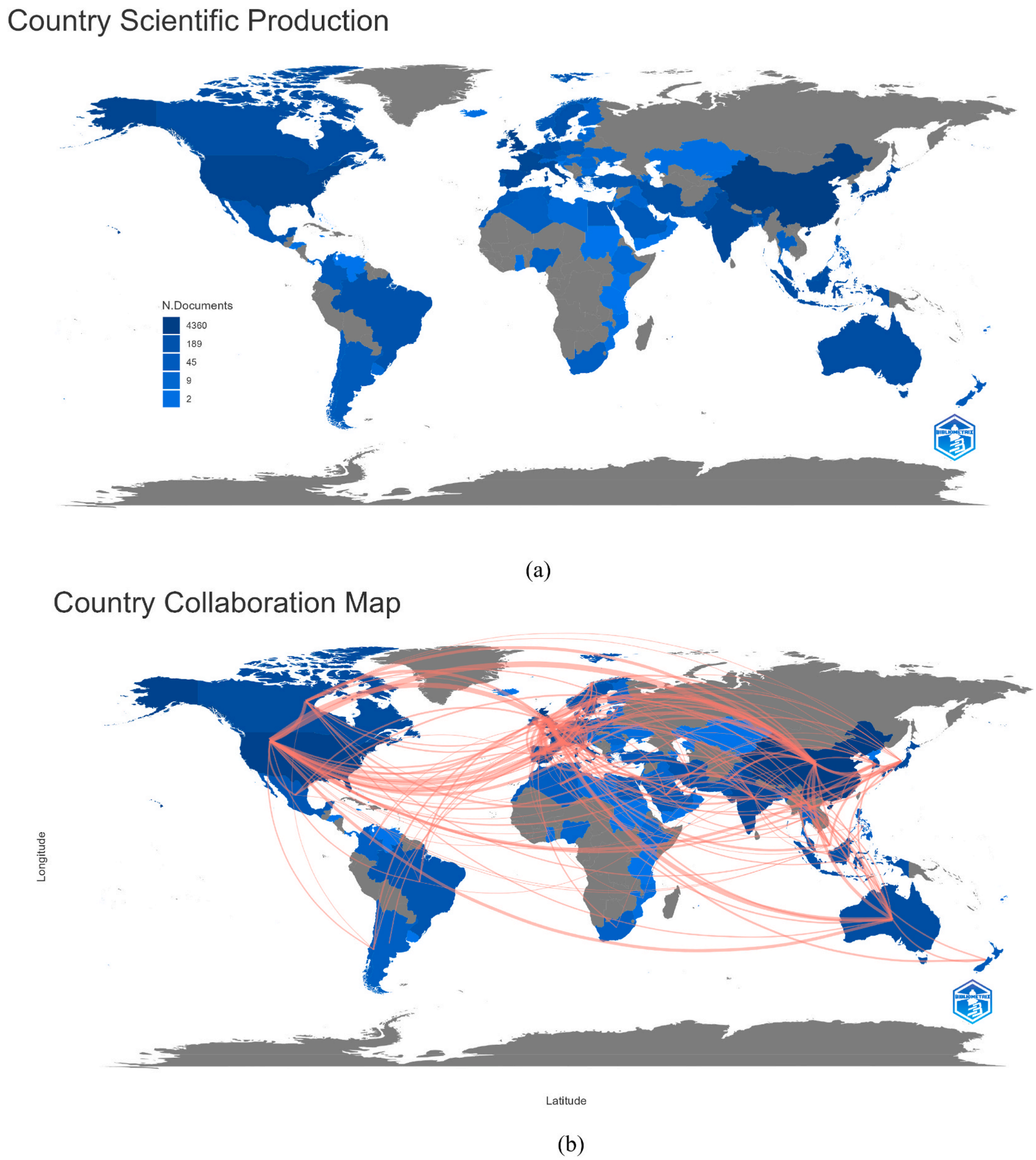


Fig. 8. (a) Countries' specific scientific production (b) collaborations among countries for the study period.

Fig. 7 show that the various author keywords are generally strongly connected. Keywords such as numerical modelling, tidal current energy, wave energy converter, tidal power generation, turbines are found to be more closely connected in studies and seem to be leading in the research space in relation to ocean renewable energy.

4.3. Country scientific research output

The country specific research output is presented in Fig. 8. The top 10 countries are led by China with 4360 documents followed by the UK with 2609. USA (1803), France (937), South Korea (809), India (674), Italy (599), Spain (593), Japan (591), and Canada with 405 documents in that order. It is important to note that the sum of all these documents with respect to the various countries far exceed the total documents studied in this work because some of the documents are a collaboration between two or more countries and hence are multiple-country publications that are counted for the individual countries involve. China has over the last years engaged in rigorous research and investment in the ocean renewable technologies. According to the Made in China 2025 report [109] China has highlighted ocean renewable energy as one of the 10 areas of opportunity for Chinese and UK corporation. The cooperation among other things seeks to integrate RE devices as well as facilities of aqua-culture and to also identify the synergies to share the production, installation, operation and maintenance, and cost of decommissioning. There are 5 projects that has commenced together with the Chinese and UK government-backed experts who seek to manufacture next generation offshore RE technologies. The program is intended to maximize the economic and environmental benefits associated with waves, offshore wind, and tide power. The experts are also to conduct a study to identify the suitable locations for the installation of such facilities in China in order to prevent them from destruction from extreme weather conditions such as earthquakes and typhoons. They are also tasked to identify methods to reduce the uncertainties that are linked to RE technologies. One of the projects is a collaboration between Shanghai Jiao Tong University and Oxford University who are tasked with finding the best structural designs for turbines that can resist typhoons. Another study is also between Harbin Engineering University and Cranfield University who are also looking at finding optimum ways to reduce the cost of installation and operation of offshore facilities. Similarly, Zhejiang University and Imperial College London, through computing and data science are working on a more economically viable offshore wind power plant. The UK supports this project with about £4 m, that of the Chinese government is however not made available online [110]. All these events, among several others, tend to push the two countries above others in terms of research in the area of ocean RE. One of the ways of increasing and improving the quality of research is through collaborations, it also helps in the sharing of knowledge [111]. African countries per the research distribution shown are lagging behind in terms of research output in the area of ORE especially those in Central Africa, possibly due to the fact that they are landlocked and do not see the need for such studies. Those in northern and southern Africa with ocean resources are however engaged in research in the ORE field.

The average citations for each country as presented in Fig. 9 suggest that the United Kingdom comes first ahead of China, even though the reverse is true in terms of number of documents as reported earlier. The UK recorded a total of 15,204 citations compared to 10,513 for China, this places China in the third position in terms of citations. The United States comes second with a total citation of 11,319, whereas France places fourth with 3,971, Italy takes the fifth position with some 3598 citations.

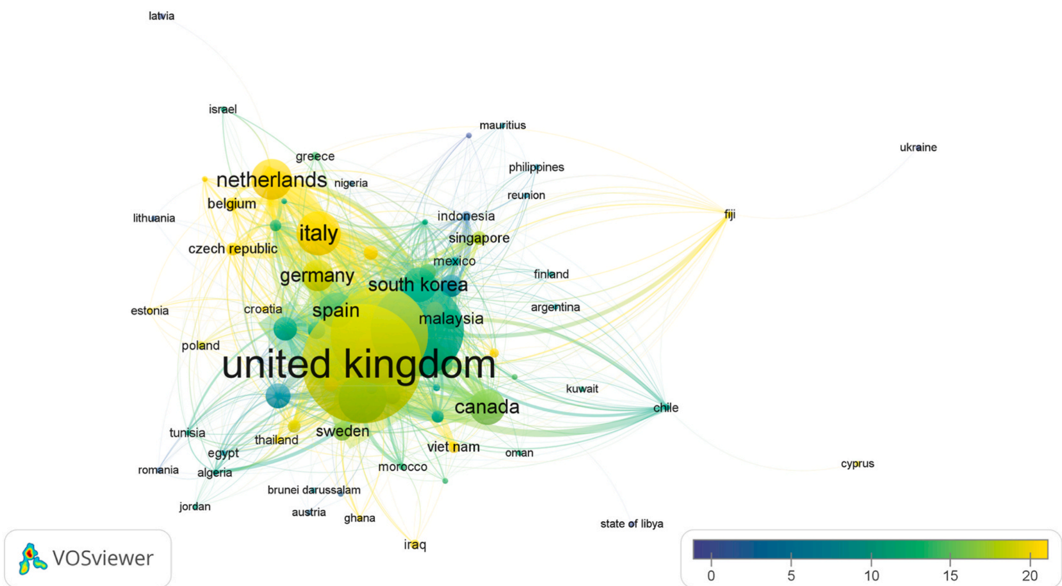


Fig. 9. Average citations for the various countries using the fractionalized method.

4.4. Evolution of the research field overtime

The thematic evolution within the research field as presented in Fig. 10 shows the keywords groups have evolved over time. There has been a considerable change in the areas authors are looking at in the research area. The evolution of author keywords has been mostly focused on tidal power plants, most studies are focused on improving the efficiency of the turbines and resistance against turbulence. As can be seen from Fig. 10b it is clear that researchers are not only focused on building the various technologies but the levelized cost of energy (LCOE) is also central to their decisions. Meaning researchers are also interested in reducing the cost of energy that is associated with the individual ORE technologies being worked on. The outcome also suggests that some of the technologies are moving towards the state of 'development', i.e., there is a gradual shift towards advancement in technology, these include tidal turbines and OTEC. This is an indication that most studies are focused on improving them for commercial scale purposes.

4.5. PESTEL analysis

4.5.1. Political aspects

The political aspect is about how governments around the world intervene in their respective economies to help in the development of projects. This includes policies on trade, tax, and other governmental policies, it also includes trade restrictions and environmental laws. All these policies have the capacity to either negatively or positively affect the smooth operation and growth of businesses and projects. According to the European Ocean Energy Association, the RE (i.e., marine energy) sector requires a formidable and stable political framework in order to guarantee investor confidence. Such a framework has the potential to enable the development and the

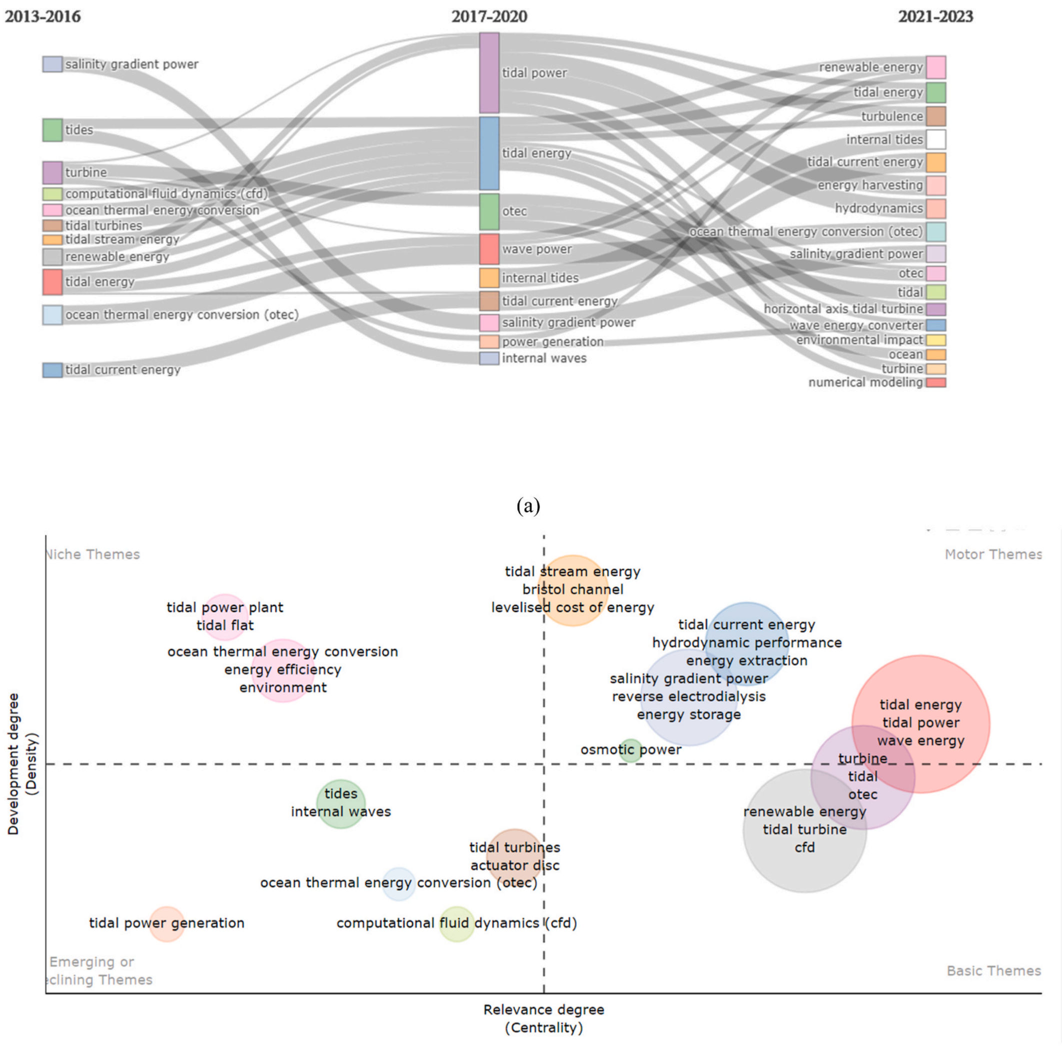


Fig. 10. (a) Thematic evolution (b) thematic map for the research area.

sustainable deployment of marine RE technologies through the provision of stable political environment in which investing bodies can develop long-term investment plans; provision of a framework for the management of human conflicts; and ensuring sustainable deployment of equipment through the balancing of the necessity for RE with possible local environmental impacts [112]. It is for these reasons that governments will have to craft the right policies to create the supporting environment for the growth of the energy sector. The following factors were described under this section.

4.5.1.1. International and national GHG emissions reduction targets. The negative effect of GHG emissions on the environment is a global issue that has caught the attention of national leaders in recent times. Its negative impact in the future will likely be immense and is projected to cost more than averting it now. A recent report by the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5 °C has reemphasized the need to adopt decisive steps towards the tackling of climate change, through the transformation of energy use globally. The IPCC calls for an immediate shift to large-scale RE and energy efficiency, mainly because close to two thirds of GHG emissions are released from the energy sector. A number of international fora has been held to negotiate and take actions towards the acceleration of energy transformation which has led to the approval of the Paris Agreement and the 2030 Agenda for Sustainable Development [113].

4.5.1.2. International and national targets on renewable energy. RE targets have now become the defining feature of the world's energy landscape. At least one RE target has been adopted by 164 countries globally as of mid-2015. Emerging and developing economies took the lead role during this period, accounting for 131 out of the 164 countries with targets in place. RE targets usually comes in different forms, it can be embedded into national RE action plans, integrated sector-level resource plans, or broader national development plans [114]. RE target is defined as *"An official commitment, plan, or goal set by a government (at the local, state, national, or regional level) to achieve a certain amount of renewable energy by a future date. Some targets are legislated while others are set by regulatory agencies or ministries"* [114]. The robustness of the target design for countries is dependent on the country's primary policy objective being pursued. Examples from some countries indicates that, instead of being motivated by a single overarching objective, policy makers are increasingly adopting RE targets in order to achieve multiple interrelated objectives such as environmental sustainability, energy security, and socio-economic benefits [114].

4.5.1.3. Institutional fragmentations. One of the issues affecting the smooth implementation of ORE globally is the divisions in the institutions that are tasked to oversee the development of this resource. This situation affects the development of the necessary legal frameworks for ORE, which spans both ocean governance and energy actors. The ORE sector falls under the dictate of dizzying array of both regional and international marine governance institutions, and some other international technical organizations [46]. The numerous institutions that one will need to consult for permits make it difficult for developers to acquire same for the sector's development.

4.5.2. Economic aspect

These are factors that show the performance of an economy which has a direct impact on businesses and projects. The type of economic environment available in a particular country is very important to the success of a business or project in that country. Investors will mostly refrain from investing in countries with bad economic indicators since such areas are considered too risky for their investments. This is even more true for projects that are more capital intensive. It is also more difficult to secure loans in an economy that is unstable [115]. This section therefore takes a look at some of these economic indicators that can either positively or negatively affect the development of the marine energy industry.

4.5.2.1. High initial capital cost and levelized cost of energy (LCOE). RE power plants, unlike those operating on fossil fuel, have a high upfront capital cost, with a relatively low maintenance cost and no fuel cost. However, this high upfront cost makes it unattractive to investors particularly in countries with high risks [116]. Marine or oceanic energy is at an important phase of its development: although it has in recent years attracted the attention of engineering firms, researchers, policymakers and investors, its future prospects, even though attractive, are still uncertain. The cost competitiveness of marine energy with other RE options that are already being used is key to its continuous and sustained growth [117].

Table 2
Comparison of LCOE for other power plants – unsubsidized analysis [119].

Type of technology	LCOE, $/MWh
Alternative energy	
Solar PV – Community	73–145
Solar thermal tower with storage	98–181
Wind	29–56
Geothermal	71–111
Fuel cell	103–152
Conventional energy	
Nuclear	112–189
Coal	60–143
Gas combined cycle	41–74

A research by the International Energy Agency Technology Collaboration Program for Ocean Energy Systems investigated the LCOE for tidal, wave and OTEC technologies which gave industry players the idea about the cost of deploying these systems in their current state [118]. Consideration was given to each technology relative to cost and operational parameters at three developmental stages: 1) involves the initial precommercial array in tidal and wave, 2) the second precommercial array in tidal and wave, and 3) the commercial-scale target. The projected LCOE for the initial commercial-scale project for the tidal energy was in the range of 130–280 $/MWh and that for the wave was 120–470$/MWh [118]. These projections are at the higher side compared to the LCOEs of relatively matured RES such as solar, wind, geothermal etc. and other conventional power plants whose cost are presented in Table 2. The high initial capital cost and LCOE of marine power plants has been one of the major barriers to the sector's development.

4.5.2.2. Lack of interest from large industrial partners to invest in the industry. The marine energy industry is still dominated by university spin-offs and start-up companies, who are doing everything within their means to bring these technologies to pre-commercial status, supporting the development of new demonstration sites at sea or promoting easy access to research facilities. Funds from some governments through their public R&D investments have been instrumental in this process. For instance, the government of the United Kingdom between 2006 and 2011 gave about EUR 20 million annually for this course [120]. In order to scale up the development and use of waves and other forms of marine energies, it will require different sources of funding and investments from all sectors. Policy support, funding, and government grants in addition to research development and demonstration (RD&D) requirements are needed to attract large industrial partners and other private investors into the sector to achieve the large-scale development of these technologies. Some of the policy measures that may be implemented to attract investors in the sector includes but not limited to power purchase agreements, feed-in tariffs, or production tax credits to attract end-users [120].

4.5.2.3. High interest and inflation rates. Several emerging economies are exploring ways to increase their RE portfolios in order to meet increasing energy demand and environmental concerns especially as the cost of generating energy using these technologies keeps falling rapidly. Nevertheless, despite significant land, labor, as well as construction cost advantages, these developing countries usually pay as much for RE as in the case of European countries and US, and even sometimes more than what the US and European countries pay [121]. This discrepancy is attributed partially to the cost of financing such projects; particularly, the cost and terms of the debt. High cost of debt has the potential to create problems for the growth of such capital-intensive projects. Regulatory solutions which have the potential to decrease the cost of financing in other countries – for instance a fixed long-term contract or dependable feed-in-tariffs – are mostly not effective in several emerging economies. This is due to the high cost of debt which limits the potential to fine tune funding in reaction to policy signals. Also, problems in the debt markets have the potential to impact equity investments, since developers or investors may not be interested or able to refinance projects that are completed with debt. These investors may as a result run out of equity to invest in subsequent projects. High cost of debt is a reflection of the high interest rates that are generally associated with developing economies with high inflation, heavy government borrowing, infrastructural deficit and relatively immature financial systems [121]. With the ocean renewable energy sector still being at a nascent stage, it will be difficult for investors to invest in the development of some of those technologies in countries with high interest and inflation rates. This is because the various technologies of ORE are capital intensive, and therefore unstable economic environment could deter investors from the sector especially when most of those technologies have no track record of success at commercial scale [122].

4.5.2.4. Lack of suppliers. One other hurdle in the marine energy industry is the lack of enough suppliers in areas such as turbine supplies and installations, which is one of the main reasons for the high cost in the sector. Expanding the supply base and the marine energy market in its entirety is key for the cost reduction process [123].

4.5.3. Social aspect

This aspect looks at the social environment. The lifestyle and behavior of people at a particular enclave can either negatively or positively affect the smooth implementation of intended projects. This section also presents some of these factors that have a possible impact on the marine energy industry.

4.5.3.1. Public awareness and acceptance. Energy generation from marine renewables has the potential to change a number of things, it can restrict traditional activities such as fishing and shipping activities which can lead to conflict among developers and indigenous sea users [124]. Therefore, the participation of the entire population in the development of such RE cannot be underestimated. It is therefore important to embark on increased education about the potentials in the RE industry [116]. If an agreement of these projects is successful, then there will be the need to conscientize the public on the reasons to adopt them. It is very crucial to factor this aspect during the planning and design stages, otherwise, its implementation may encounter setbacks and even halt if the local stakeholders are not adequately informed [14]. According to Aitken [125], one of the key issues for a successful adoption of wave energy power plants is trust. Trust must flow in both directions, i.e., between project promoters and local stakeholders. The study also highlighted that, beyond the deterministic approaches, it is important for the promoters of these marine infrastructures to trust that the public have valid opinions and legitimate knowledge and as a result should trust the open participation of the local stakeholders.

Due to the visual and noise impacts that are usually associated with WECs, opposition against their development are usually consistent with proximity to nearby stakeholders [126]. The most cited explanation when discussing the lack of community acceptance or support from local stakeholders for the siting of a RE project is the "Not In My Backyard" with acronym NIMBY syndrome [127]. The NIMBY syndrome has the potential to slow the processes for the development and use of MRE projects.

There are various forms that the public may be engaged in relation to the development of such projects, some of these are as follows [128].

- Increasing awareness: this level of engagement is basically about provision of information. The anticipated outcome may likely be a larger public acceptance or legitimacy of the intended project.
- Consultation: this level involves a relatively limited form of feedback from the public in the decision-making process. It is essentially intended to acquire insight into the opinion of the public and to develop a socially appropriate or acceptable policy or project.
- Empowerment: this level involves a more participatory form of public engagement; it assigns more control to the participants. The objective of this kind of engagement is to work more with the public which allows them to play critical roles in the decision-making process, enhancing democracy and building of social capital.

4.5.3.2. Creation of new jobs, and expertise. Just like other RE power plant facilities, the installation of marine energy technologies comes with new job opportunities and the development of expertise [129]. The development of these technologies for electricity generation has the potential to create both direct and indirect jobs for the teeming youths of some of these countries with high graduate unemployment especially in developing countries. According to the 2019 IRENA report [130], the RE sector created about 11 million jobs globally, with more countries into trading, manufacturing and installing of RE technologies every year. The wave, tidal and ocean energy sector alone created 1.057 thousand jobs [130]. Fig. 11 shows the total number of employments created by the RE sector as of 2019.

4.5.3.3. Risks. There are some concerns among the public regarding the development of marine energy such as wave energy. Surfers are of the view that the drawing out energy from the sea has the potential to decrease the size of waves breaking on the shore, which has the propensity to destroy their sports. The fishing community who are made up of both commercial and recreational, are also concerned about the installation of these power plants at prime salmon trolling or crab areas which could affect their business [132].

4.5.3.4. Education. The marine energy sector is a relatively young industry and for that reason, it is very important to develop the expertise that is required for the development of the sector. A number of dependent professions who are involved in such projects are affected by both the services and industrial sectors relative to the creation of human capital in the marine energy sector. Some of these are as follows [14].

- Metallurgical industry is needed for the building of mechanical assemblies.
- Shipbuilding and maintenance.
- Non-metallic materials.
- Operational oceanography and cabinets for environmental study.
- Engineering of marine infrastructures.
- Information and Communication Technologies required for the control command, simulation, and tele-maintenance etc.
- Maritime training division for training of specialized employees.
- New control technologies for the extraction of optimal energy and device maneuvers.
- Aerial and underwater surveillance.
- Manufacturing and setting up of underwater cables and pipelines.

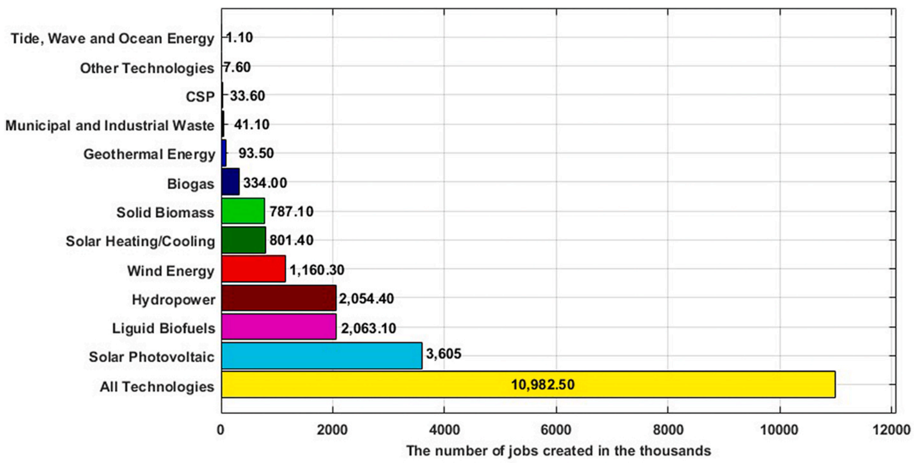


Fig. 11. RE employment by technologies according to IRENA 2019 [131].

4.5.4. Technological aspect

The availability of a specific technology for a particular project or business has the potential to determine its bankability. The prevailing supply chain in a close range has the potential to help a business to expand to new markets. New infrastructure will have to be taken into consideration during planning stages if none exists currently. It is also likely to get other technologies that will emerge to either destroy old ones or open up new markets [115]. This section presents some of these technological issues in the marine energy industry.

4.5.4.1. Lower level of technology readiness and data. The ocean renewable energy (ORE) is still at a difficult point of its maturity, it requires significant levels of investments to develop demonstration devices to be able to obtain the most learnings. The sector requires a comprehensive multi-year dataset measuring and the effects of its deployment, normally more than five years or twenty-five years deployments. Such deployments will give investors and researchers information about the power outputs, environmental impacts, stress fatigue measurements, knowledge in installations and deployments, associated cost and operations and maintenance practice. Conducting such analyses will provide the needed information to stakeholders for them to understand the relative cost for the entire system, it will also help to detect the areas of the system to direct R&D activities in order to reduce LCOE of ORE [133].

4.5.4.2. Technologies under demonstration. Data shows that out of the 209 ocean energy projects that were registered in 2017, 41% belong to tidal energy, wave was 47%, 6% to offshore wave and wind while salinity gradient took 1%. About 16% is currently operational or installed, 10% are cancelled, suspended or put on hold, 31% are completed or decommissioned, and 42% either at planning, development, consented or under construction phases, which are virtually divided into 50:50 wave and tidal resources [134].

4.5.4.3. Competition from other renewables and other conventional plants. Notwithstanding the ongoing technological improvement in the oceanic energy sector, no technology in the marine energy sector has so far reached the level of technological advancement needed to ensure large-scale commercialization or be competitive with other RES. One of the main problems that need to be looked at and addressed by developers of ocean energy is about the performance of the conversion systems as well as their reliability. The lack of maturity in relation to the conversion devices of these energy types (i.e., marine energy) has placed them behind other RES such as solar, wind and hydro energies, since they are relatively mature. Also, these devices for the marine energy sector are meant to function in tough environments and the absence of long-term reliability of these devices impedes their deployment [44].

4.5.4.4. Knowledge transfer from offshore industries. The marine energy industry can benefit significantly in terms of its engineering and hardware competences with knowledge transfer from offshore wind farms and offshore oil and gas operations. Fostering cross-sectorial experience, technical knowledge, expertise and transfer of know-how can lead to a reduction in cost and efforts in the learning process [133].

4.5.4.5. Lack of design commonality. One of the main challenges in the oceanic energy industry is the lack of consensus in relation to the design of devices. It is one of the major technological hurdles that players in the sector will have to overcome, both for the converters and their related components. Technologies in the tidal energy sector are seeing some level of convergence with respect to design of components, especially with respect to the most advanced prototypes; unlike that of the wave energy sector. Attaining an agreement in terms of design is very key to secure the engagement of the supply chain as well as the opening up of cost-reduction processes via economy of scales [44]. Technologies for tidal energy generation are projected to become more commercially feasible ahead of that of wave energy; due to the high consensus that exist in its design, survivability through wide testing and working periods, and more engaged supply chain [135].

4.5.4.6. Inadequate skill in array deployment. The various technologies for converting oceanic energies, i.e., the converters are so far mostly in single forms, the transition from individual devices to integrated form requires significant research. Understanding the behavior of the array relative to its ecological impact, optimal structural configurations, and O&M of arrays etc., will present important information with respect to cost effectiveness of large-scale deployments and the energy captured by the devices [14,136]. A public-private research consortium have quantified the abovementioned aspects using numerical models with the intention of reducing the uncertainty level in the estimations of the captured energy at a particular site [14]. However, this may not give a true picture of such projects, hence the need to investigate using a real-life system deployed on large-scale level.

4.5.5. Environmental aspect

The environmental aspect includes the natural environment, and these are factors that has the ability to affect the marine energy projects, the following factors are presented under this section.

4.5.5.1. Impact on environment. There are still some gaps with respect to the scientific evidence about the environmental effect of energy generation from the various ORE sources due to their relatively immature nature. Current information on this are mostly dispersed among researchers, developers, and nations [15,45]. In order to really assess the effect of these technologies on the environment there will be the need to deploy them on a large-scale (i.e., array level as indicated earlier). Strategic environmental assessments and environmental impact assessments have been conducted in North America and Europe. Some reviews on the conducted study has been published in Ref. [45]. The environmental impact of devices used in extracting energy from the ocean has been summarized by the IEA-OES in three ways: the acoustic impact on marine animals; the physical interactions between the tidal turbines and marine animals; and the impact of energy extraction on physical systems [15].

Wave energy converters have the potential to "*alter water column and seabed habitats locally and bring changes in the wave environment*" [137]. Similarly, tidal energy converters and arrays have the potential to affect benthic habitats as a result of changes in water flows, sediments dynamics and composition of substrate. Other possible effects includes collision risks of marine animals with tidal stream farms and the mortality of fish who pass through the blade-strikes (i.e. turbines) [137]. A study conducted by Ref. [138] indicated that, a change in the sediment dynamics could occur as a result of the installation of tidal arrays, which has an effect on the morphology of the bed as well as the benthic ecosystems.

4.5.5.2. Noise. Wave farms, tidal stream farms and tidal barrages are key civil engineering structures, therefore, their construction as well as decommissioning processes can result in the generation of considerable levels of noise at levels which could have a negative effect on marine life. Noise and vibrations from these apparatus during construction could influence various species in distinct ways. However, the operating noise from any of these systems are not likely to have any substantial effect on the ecology even though there is not much information on the levels of sound generated by their operations [137]. For instance, the operational noise from small number of units in the case of the tidal stream farms may not be more than the threshold levels, however, the aggregate noise from a large number of such units could mask the communication and echolocation sounds from marine animals in that enclave. Determination of the impact of noise on the environment will depend on the acoustic signature of the device for both arrays and individual units, the hearing sensitivity of the marine animals, the ambient noise in the vicinity and the behavioral responses to anthropogenic noise (e.g. attraction, avoidance etc.) [137].

4.5.5.3. Electromagnetic emissions. Research by the European Commission in 2015 [139]**,** indicated that the electromagnetic emissions from parts of the energy generation systems could have a disruptive effect on marine life. It has the potential to affect the migratory routes of sea life within that enclave. Specific marine species that are susceptible to electromagnetic field (EMF) emissions includes rays, sharks, crustaceans, skates, dolphins, fish, whales, bony and marine turtles. Several of these creatures depend on natural magnetic fields to find their way through their surroundings. European Commission's report also shows that EMF caused eels to change their visceral migratory route, they however, did not divert too long before returning to their original trajectory [140].

4.5.5.4. Low GHG emissions. The European commission Joint Research Centre in 2016 [141], conducted a life-cycle assessment on ORE systems to evaluate their potential environmental impact. The study focused on electricity generating tidal current and ocean waves devices to measure the cradle-to-grave environmental effects linked with their installations, sourcing, and utilization materials as well as energy to make the devices, operation, and end-of-life disposal (incineration, recycling, and landfilling), and any transport connected with the devices. The research evaluated the effects of seven forms of tidal-energy and eight types of wave energy devices on thirteen environmental impact categories i.e., acidification, global warming, particulate matter emissions, ozone depletion, human toxicity (cancer), ionizing radiation, freshwater eutrophication, summer smog, terrestrial eutrophication, marine eutrophication, human toxicity (non-cancer), resource depletion, and freshwater ecotoxicity. The quantity of material utilized in the devices, mostly for mooring, foundations, and structural parts contributed to the greatest environmental impact for virtually all the devices. The foundations and mooring alone contributed over 40% of the total, life cycle emission of GHG in total ranged from 15 to 105 g CO2eq/kWh, with an average of about 53 g CO2eq/kWh which is similar to other renewables. Increasing the lifespan and efficiency of these devices could help minimize their life-cycle environmental impact [141].

4.5.6. Legal aspect

This section looks at some of the legal and regulatory frameworks for the development of the oceanic energy sector.

4.5.6.1. Regulatory framework for the oceanic energy sector. Whereas the shipping and fishing, as well as the offshore oil and gas industries have gained much prominence in the marine industry with appropriate regulatory framework, that of the marine energy industry is still an uncharted territory. Whereas a country like Scotland have institutionalized innovative reforms in its marine renewable energy sector to ensure the safe and smooth deployment of ORE devices, regulators in other jurisdictions are relying on existing regulations to issue permits to proposed marine renewable energy projects. Either way, no country has a well-developed regulatory framework for the sector yet, and it is obvious that additional strategic planning as well as strategies for the management of the resource are required to resolve the specific requirements of a commercial marine energy industry [112].

According to a survey by Ref. [142], experts in the marine energy industry highlighted security of tenure as a crucial factor considered before investing in the sector. A developer will have to have confidence in the system, where the developer can utterly exercise its decisions to develop whenever it is prepared to do so. The participants in the survey underscored the necessity to have legally implementable rights in order to be able to occupy that space to develop a consented project. It was the view of the participants in the survey that a number of devices in the sector will function more safely in exclusion zones.

An appropriate regulatory environment benefits the developer by safeguarding equal distribution of the resource, supporting with the development and dissemination of information, managing of conflicts among developers and expansion of the industry, and the provision of designed procedures and periods for project development. The key issues confronting developers in the sector mostly emanates from domestic legal regimes, this is because, marine renewable energy projects are developed relatively near to the shore which is within territorial waters [112].

4.5.6.2. International law. Laws such as the international development law, international civil aviation and international environmental law etc. are all relevant to the development of marine energy, even though the law of the sea is the primary international law that provides the framework that guides that space. International laws play a very important role in marine space, it ensures harmony between the obligations and rights of countries and the interest of various people in that space and the resources they contain. It also guarantees the transport of energy generated, as well the conservation of the marine environment against possible negative effects in the future [43].

The United Nations Convention on the Law of the Sea (UNCLOS), especially affords countries the right to exploit resources under their jurisdiction [46]. According to the UNCLOS, territorial sea or waters includes the coastal waters up to 12 nautical miles from a starting point which is normally taken as the mean low-water mark. Countries along the coast has the right to formulate laws and regulate the utilization of the seas within its territorial waters [15,43]. However, there are some weaknesses with respect to some areas which are beyond national jurisdiction: currently, there exist no form of governance mechanism or coherent institutional framework for such areas, including the development of those areas for ocean energy generation [46]. Legal and regulatory challenges forms a key component of the many hindrance to the development of the ORE aside technical challenges [143].

Even though the UNCLOS empowers individual countries to formulate additional international environmental instruments, there has not been any significant progress in that direction, especially for offshore energy activities at the international level. This can be attributed to the fact that most of these activities occur in areas within specific country's jurisdictions where the state or country is entrusted with exclusive sovereign rights [144]. There is even scarcity with respect to specific global environmental rules when it comes to activities in the nascent marine RE sector. Just like the UNCLOS environmental framework, the international conventions that affects the environmental regulations of activities in the offshore energy industry fits into two general categories [144].

- the ones that relate to the conservation of nature and the protection of marine biological diversity.
- the ones that look at the various potential sources of pollution in the marine environment such as shipping related or dumping pollution.

There is therefore the need for stakeholders to specifically fashion out specific laws for the MRE sector to help resolve any ambiguity that may arise during the course of the sector's development in the future.

4.5.6.3. Bureaucratic and uncertain permitting processes. Consenting processes in the marine energy industry has been described as one of the major barriers to its development globally. The sector still has some regulatory uncertainties in several countries and information about the processes is most at times difficult to access [46,145]. Some of the problems in the consenting processes comprises of the large number of authorities involved and the poor structure of communication between them; the integration of ancillary onshore and offshore structures; the absence of an agreeable process which is tailored towards the needs of ocean energy; and the period taken to reach an agreement [46]. The processes that leads to the permitting is very vital since it has an effect on cost and efficiency [146]. Therefore, the processes for permitting and leasing of seabed must be both practical and principled. Firstly, it must guarantee [147].

- Economic efficiency – since the rights that are going to be allocated are for the purposes of exploitation of a valuable resource, it must be allocated in a way that guarantees that, the resource will be efficiently utilized to the benefit of the entire public.
- Sustainability – the regulatory processes must promote sustainable deployment of ORE devices.
- Equity – it should ensure an equitable allocation of the resources among proponents.
- Financial return – governments own and control the seabed; it therefore has the duty to acquire the best financial return in exchange for the private use of public land.

Moreover, the processes must be simple and user-friendly which does not add regulatory burden, and thus, cost and time, to an ORE project.

A clearly identifiable licensing authority is non-available in many jurisdictions around the world and as a result even small-scale test projects are run in full gamut using existing regulatory processes. Also, there is no statutory defined timelines (i.e. specific time)

Table 3
Summary of opportunities and threats in the ORE sector.

Opportunities (+)	Threats (−)
Renewable energy targets (O1)	Lack of commonality in device designs (i.e., technical challenges (T1)
International and National GHG emissions reduction targets (O2)	High initial capital cost (T2)
Job creation (O3)	Lack of appropriate legal and regulatory framework for the sector (T3)
Skill transfer from offshore industries (O4)	Lack of funding (T4)
Renewable support (O5)	Fragmentations in regulatory institutions (T5)
Low GHG emissions (O6)	Bad macro-economic indicators in some countries (T6)
	Environmental challenges (T7)
	Survivability of the various technologies in the harsh oceanic environment (T8)
	Strong competition from other RES (T9)

within which a body charged with regulatory authority must communicate its decision to a developer in most jurisdictions, even though in some instances, timelines are well-defined by legal requirements such as that of the EIA, especially in the European Union [46].

4.6. Opportunities, threats, and the way forward

The various marine energy technologies are at a difficult stage of maturity and therefore require significant attention from all sectors, be it political, economic, technical, social, legal, or environmental planning. From the discussions provided supra; it is clear that the challenges confronting the ORE industry goes beyond just the development of efficient conversion devices. There is therefore the need to conduct a comprehensive study along the entire value chain. Based on the issues raised in this study, the various factors were summarized into opportunities and threats as illustrated in Table 3.

4.6.1. The way forward for the ORE industry

The findings from the review presented supra confirm a number of issues that are either positive or negative for the sectors development. These issues require some level of attention from all sectors in order to see the MRE sector grow as in the case of other RE options. Usually, the main drivers behind the development of RE is the existence of a policy framework for RE at the national level, research and development and targeted budgets for the development of new technologies. Investment incentives, guaranteed prices, a competitive market framework which effectively lessens any externalities, and a proper regulatory and administrative structure also play a supporting role in the development of the RE industry. The availability of an enabling policy framework in any country improves investor confidence. Countries such as Germany, France, UK, New Zealand, Ireland, and Japan have all developed different forms of RE policies, some of which are specifically crafted for the offshore RE sector [145].

In order to resolve the end-to-end challenges identified in this study, there will be the need for a strong collaboration between industry, academia, as well as policy and decision makers to develop a comprehensive development plan for the sector. Whereas researchers in the sector are working around the clock to increase the performance and efficiency of the various devices which has the potential to reduce the LCOE of ORE power plants, the shake-out includes more than just technological barriers as indicated in this study. One of such cases is the failure of the Pelamis and Aquamarine, where a combination of non-technological and technological issues impeded the advancement of the projects [148]. This calls for an integrated and inclusive approach to resolve the barriers, which includes embracing good practices and learnings from previous experiences. The following specific recommendations are suggested.

- Development of specific regulatory framework for the sector – as indicated earlier in this study, most countries rely on existing regulatory frameworks which are not specifically crafted for the sector to issue permits to proposed ORE projects, this has been identified as one of the main challenges in the sector. It is therefore recommended to develop a comprehensive roadmap with resource management strategies to address specific issues confronting the commercial development of the ORE industry.
- Strong cooperation between government and private sector – this is very important because one of the identified challenges aside technological difficulties is the lack of appropriate legal framework and bureaucratic structures one need to go through to secure permits for projects. A synergy between government and developers could reduce these difficulties since governments will be made aware of the challenges developers encounter and possibly find solutions to them. Such synergy should be able to synchronize technological development; align framework conditions as well as support activities, promote certification, standardization, performance guarantees and accreditation [148].
- Increase of technical performance of devices – one of the factors which can drive down the LCOE of MRE power plants is the enhancement of the output performance of the various conversion power plants. It is therefore very important for both governments and researchers to collaborate to find ways to increase the efficiencies of the various proposed devices. Governments can provide the funding whiles researchers and engineers work on enhancing efficiencies.
- Increasing public education – increasing the awareness of people with respect to the potential in the marine energy sector is key to its development. It is therefore recommended to increase public education on the various forms of energies in the marine environment and the possible ways of harnessing them without compromising the safety of the environment.
- Increase research and development – one of the factors this study identified is the lack of enough information on the possible environmental impact associated with the development of marine energies. It is therefore recommended to conduct comprehensive studies in this area to assess its impact, this can however, be achieved if most of the trial projects are moved to a commercial scale level where enough data can be gathered.
- Sound economic situation – the economic situation in a particular country has a significant impact on investment decisions, countries with unstable economic environment maybe too risky to invest in, no matter the enormous nature of a particular resource in the country. A nascent industry such as the marine energy industry which is at its early developmental phase requires a stable economic environment to flourish. Economic indicators such as inflation, interest and discount rates affects the LCOE of energy power plants [149], hence, governments with interest in this energy type must create the enabling economic environment.
- Collaboration with existing players in the marine sector – the existing users of the sea have gained lots of experience overtime and collaborating with them could help reduce possible conflicts and rather highlight the collaborations and opportunities provided by marine energy [132].
- Implementation of practical approaches – it is important for stakeholders to focus on detecting and implementing cost-effective and practical approaches, and also create appropriate incentives for investors in the sector [145].

The output from the bibliometrics analysis suggests that research in ORE technologies is evolving with time and it is gaining more interest among scientists and governments around the world. The outcome shows that tidal power is the main focus of research in the field, and most studies are either focused on ways to improve its efficiency in terms of technology and also the identification of resource potentials for the siting of the various marine renewable power systems. It is also important to state that some studies have also focused on developing the appropriate energy policies for the marine energy technologies as indicated in the visualizations presented supra. This is an indication of how relevant the availability of the right policies is for the sector, other studies also looked at the possible environmental implications from the use of such power plants. It is also clear from the bibliometrics that the most immature technology in the ORE industry is the salinity gradient power and the reverse electrodialysis, these two technologies are now emerging and are at their embryonic stage, it is therefore important for researchers to focus much attention and resources in their development since they are identified to be promising. Furthermore, since marine life stands a chance of been endangered through the installation of ORE technologies, it is recommended to put in place policies and technologies that will minimize their impact on aquatic lives.

4.6.2. Limitations of the study

Although this study has comprehensively reviewed and assessed the opportunities and threats in the marine energy industry, there are some limitations that are worthy of highlighting. The authors agree that there are several other factors that might affect the smooth implementation of ORE which may not have been discussed in this paper, such factors can be studied in future research. It is also important to note that, PESTEL analysis is exposed to subjectivity, therefore it is not a one-off study, some of the factors discussed under the various sections may change with time hence it is recommended to periodically assess such factors to know the extent of any future development in the sector. It is also recommended to combine the PESTEL approach with some multi-criteria decision-making tools such as the Best-Worst Method or the Analytical Hierarchical Process to help assign weights to the individual factors identified in order to help in target decision making for the sector.

5. Conclusions

The dynamics of energy generation around the world have been changing in recent times as a result of increasing demand and the need to protect the environment from destruction, etc. The marine energy industry is a nascent industry that is yet to be fully utilized for energy generation due to a number of challenges the sector faces. As a result, this paper presented a highlight of the different forms of ORE potentials, their conversion mechanisms, and technical challenges. The challenges in the marine energy sector, however, go beyond technical challenges. This study thus conducted a comprehensive analysis of the ORE sector using the bibliometric and PESTEL analysis approach to give a holistic bird's-eye view to stakeholders in the sector.

The bibliometric analysis identified that China leads the world in this field of study with 4360 documents, followed by the UK with 2609. The USA follows with 1803 documents, France (937), South Korea (809), India (674), Italy (599), Spain (593), Japan (591), and Canada (405) also follows in that order. The outcome also suggests that some of the technologies are moving towards a state of 'development', i.e., there is a gradual shift towards advancement in some technologies, especially tidal turbines and OTEC.

Furthermore, the results from the PESTEL analysis identified the availability of renewable energy targets, international and national GHG emissions reduction targets, job creation, skill transfer from offshore industries, renewable support, and low GHG emissions as the major opportunities for the sector. The challenges in the sector include the lack of commonality in device designs, high initial capital costs, lack of appropriate legal and regulatory frameworks, lack of funding, fragmentations in regulatory institutions, bad macro-economic indicators in some countries, environmental challenges, the survivability of the various technologies in the harsh oceanic environment, and strong competition from other RES.

The development of the sector will require a holistic approach, which means that individual investors and multinational companies will have a major role to play in the development of the sector. The private sector, especially the offshore oil and gas companies that require energy for their operations, could invest in the development of ORE technologies to reduce their cost of importing fuel for their operations. This could also lead to a reduction in their GHG emissions. Companies involved in water desalination can also develop various ORE technologies to meet their energy needs. Another sector that can make use of ORE technologies to meet their energy needs is the marine datacenters, which will require energy for their operations. Also, the unmanned underwater vehicles that are used for surveillance and subsea inspections could use ORE for their energy demands. This is because most of those vehicles use batteries, which limit their range and capacity. Pairing the batteries with power from the ORE could extend their capabilities and range. A market for the ORE sector could be formed from these alternative applications, and the private sector could be the lead financing agent for the sector rather than governments. It is, however, important to note that the various governments will have to provide an enabling environment through economic policies and legal and regulatory frameworks to help the private sector. The output from the bibliometrics analysis suggests that research in ORE technologies is evolving with time and is gaining more interest among scientists and governments around the world. The outcome shows that tidal power is the main focus of research in the field, and most studies are either focused on ways to improve its efficiency in terms of technology or on the identification of resource potentials for the siting of the various marine renewable power systems.

The study, therefore, proposed a number of recommendations for consideration by governments, technical experts, private sector players, and other stakeholders in the energy sector. Some future research areas were also proposed, including conducting a comprehensive study on the environmental impact of ORE energy in order to plan for its safe use; intensifying studies on marine spatial planning around the globe, which will give developers and other stakeholders a definitive view of the marine environment to help in decision-making; and finally, legal issues featured strongly as one of the major barriers to the sector's development. It is therefore important to research the various roles both national and regional blocks can play in formulating an appropriate legal framework for the sector. An additional study should also be conducted to evaluate the total market size for the sector.

Data availability

Data will be made available on request.

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CRediT authorship contribution statement

Ephraim Bonah Agyekum: Writing – original draft, Conceptualization. **Tahir Khan:** Software, Data curation. **Jeffrey Dankwa Ampah:** Supervision, Data curation. **Nimay Chandra Giri:** Writing – original draft, Formal analysis. **Wulfran Fendzi Mbasso:** Writing – review & editing, Methodology. **Salah Kamel:** Writing – review & editing, Project administration.

Declaration of competing interest

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

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