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OCEAN ENERGY. CURRENT SITUATION, CHALLENGES AND DEVELOPMENT PROSPECTS

Abstract. Human society is facing numerous environmental problems, including climate change, mainly caused by the burning of fossil fuels in power plants to obtain electrical and thermal energy. On the other hand, electricity consumption is increasing due to population growth, urbanization or economic development. In order to reduce greenhouse gas emissions, one of the proposed solutions was the development of renewable energy sources, including oceanic ones. This research aimed to analyze ocean energy, its potential and ways of valorization, its contribution to the global energy system and the challenges to future development. The results show the concerns of many companies and states in identifying the most efficient technological solutions for valorizing ocean energy. It also highlights the growing contribution of the sector to the global energy system, but its share is still very low. Although the great energy potential of the waters of the seas and oceans is recognized, several challenges stand in the way of the large-scale development of these technologies, including environmental and economic challenges.

Keywords: ocean energy, tidal energy, wave energy, salinity gradient, OTEC

1. Introduction

Climate change is one of the greatest threats to the environment and human society and is already affecting many regions of the Earth. It is driven by increasing greenhouse gas emissions, including from the energy sector.

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In addition, global primary energy demand is expected to increase by more than 25% by 2040, reaching around 206,000 TWh/year, driven by the world's growing population, urbanization and economic growth (Taveira-Pinto et al., 2020). As a result, energy systems around the world must increasingly rely on renewable energy sources. The production capacity of renewable energy sources has grown rapidly in recent years, driven by political support and drastic cost reductions for certain sources, such as wind and photovoltaics, which have reached maturity. However, these sources have the disadvantage of being dependent on climatic conditions and the time of day (in the case of solar energy). In 2025, the share of renewable energy in global electricity production was 34.5%, a significant increase from 18.4% in 2000 (IEA, 2026).

Renewable sources also include energy that harnesses the energy potential of seas and oceans (here referred to as ocean energy). This energy resource is abundant, with over 70% of the Earth's surface covered by seas and oceans, and its benefits go beyond the energy sector, potentially driving a global blue economy for multiple end-use applications, including maritime transport (e.g. providing electricity for battery-powered ships, offshore charging stations or other port-based activities), space cooling (seawater air conditioning/SWAC can provide efficient cooling), aquaculture or water desalination. Ocean energy could also contribute to improving the lives of people living in coastal areas and small islands, especially in developing and least developed countries (IRENA, 2021, Herrera et al., 2021).

Ocean energy uses a wide range of technologies that harness the energy potential of tides, waves, currents, or differences in salinity and temperature in the seas and oceans. In a broader sense, marine biomass, offshore wind energy, and offshore solar energy are also included, but they do not use the energy potential of seawater. Many technologies are still under development and testing, some being floating devices, and others submerged or anchored to the seabed (Marinez et al., 2021).

Tides are driven by the gravitational forces of the Sun and Moon and are most significant at the mouths of rivers and in bays. There are two types of tidal energy, tidal barrage and tidal stream. Tidal barrage is the most mature of all ocean energy technologies and works on the same principle as hydropower, requiring a dam to hold back the water. A tidal basin is an inlet into an ocean bay or lagoon that fills with water during high tide and empties during low tide. A bidirectional tidal energy system generates electricity from both incoming and outgoing tides. Because it is not affected by weather conditions, tidal energy is one of the most reliable sources of renewable energy.

The other form of tidal energy operates in deeper waters and generates energy using the currents that occur with the changing tides. Among the technologies that harness tidal streams, the following are distinguished: horizontal-axis turbines, tidal kites, enclosed tips, vertical-axis turbines, undulating membranes or oscillating hydrofoils (table 1). Tidal turbines can be fixed to the seabed or float closer to the surface with anchor points attached to the seabed. The most common type of technology is the horizontal-axis turbine, followed by the tidal kite and the vertical-axis turbine. These can also be used effectively in areas with slower tidal flows (EC, 2025; OEE, 2026).

Table 1

Different tidal energy technologies

Technology	Functional features	Technology readiness level
Barrage	Water that entered an enclosed tidal basin with high tide is released in low tide and generates electricity by passing through turbines.	9
Horizontal-axis turbine	The tidal currents flow past blades that are radially attached to a horizontal shaft and cause rotation, thus generating power, much like a wind turbine underwater. Either the hub or blades need to turn 180 degrees to accommodate a reverse flow direction.	9
Tidal kite	A kite connected to the sea bed or to a floating platform moves through the tidal stream in an eightshaped or linear trajectory. The relative velocity is increased and with it the electricity output.	9
Vertical-axis turbine	The tidal currents flow through a set of blades parallel to a rotating shaft, generating power irrespective of the direction of the flow.	7
Enclosed tips	The tidal stream's velocity is increased by concentrating it in a funnel or duct, in which a turbine is placed to generate energy.	7

Undulating membrane	A wave membrane in tidal energy operates by transforming the hydrodynamic pressure changes of ocean waves or tides into mechanical motion, which is then converted into electricity	7
Oscillating hydrofoil	The tidal flow lifts an oscillating hydrofoil attached to an arm. This up-and-down movement drives a shaft or pistons to generate energy.	6
Archimedes screw/ spiral	A tidal stream passes through the spiral of a helical-shaped impeller. The device starts to turn, and the rotation is converted into energy.	6

Source: IRENA, 2021; European Commission, 2025

Wave energy is mainly influenced by wave characteristics (height, speed, frequency), closely linked to surface winds, and these characteristics are strongest at latitudes between 30 and 60 degrees and in deep waters (over 40 m) (IRENE, 2021; Herrera et al., 2021). Although waves vary seasonally and in the short term, they are considered a reliable source of energy because they can be forecast into the future with a significant degree of accuracy.

There are several technologies for harnessing wave energy, including: oscillating water columns, point absorbers, oscillating wave surge converters, overtopping, attenuators, pressure differential devices, rotating masses or Archimedes screws (Table 2) (IRENA, 2021; EC, 2025).

Table 2

Prototypes of wave energy technologies

Technology	**Functional features**	**Technology readiness level**
Oscillating water columns	Passing waves raise the water level within a hollow, demi-submerged structure, causing the enclosed air to compress and flow to the atmosphere, driving a turbine.	9
Point absorbers	This floating or submerged buoy generates energy from the buoy's movement caused by waves in all directions relative to the base connection.	9
Oscillating wave surge converters	This structure uses the surge movement of the wave (back-and-forth motion) to capture energy in an oscillating arm.	8

Overtopping device	Water of passing waves is captured in a reservoir and released through a shaft. A turbine is located in the shaft that generates energy when water passes.	8
Attenuators	The attenuator consists of multiple connected segments or a single long and flexible part that extracts energy from waves by following the parallel motion of the waves.	8
Submerged pressure differential devices	The rise and fall of passing waves cause a pressure differential in the structure to trigger pressure pumps and generate electricity	7
Rotating masses	The heaving and swaying in the waves cause a weight to rotate within this device. This rotation drives an electric generator.	7
Archimedes screws	A wave passes through the spiral of a helical-shaped impeller. The device starts to turn, and the rotation is converted into energy.	6

Source: IRENA, 2021; European Commission, 2025

Salinity gradient is a renewable energy source that generates electricity through various technologies, such as pressure-retarded osmosis (PRO) or reverse electrodialysis (RED), which harness the difference in salinity in water. This typically occurs at the mouth of rivers, where fresh water meets seawater, or in stratified water, which does not mix. Pressure-retarded osmosis (PRO) harnesses the difference in chemical potential between fresh water and salt water (osmotic power). Osmotic pressure pushes water through a membrane and drives a turbine to create energy. Reverse electrodialysis is a membrane-based technology that uses electrochemical reaction instead of osmotic pressure. The device uses a series of membranes: half of them are permeable to sodium and the rest are permeable to chloride, with freshwater and seawater flowing interchangeably through each pair of membranes (IRENA, 2021; Azarpour et al., 2022; Watanabe et al., 2025).

Ocean thermal energy conversion (OTEC) plants rely on the difference in temperature (thermal gradients) of ocean waters between the surface and deeper layers (at 800-1000 m depth). This situation is found in tropical regions, such as the Pacific Ocean or the Caribbean Sea. The process involves either an open cycle, in which warm seawater is converted into steam to drive a turbine, or a closed cycle, in which a working fluid is vaporized using the heat of the warm water (Weber, 2025). There are also hybrid-cycle OTEC plants, which combine both closed-cycle and open-cycle characteristics (Herrera at al., 2021). To power an electricity-generating turbine, ocean thermal energy conversion technologies use a temperature difference of at least 20°C between cold and warm water, which indicates that the surface water temperature must be around 25°C, as water temperature tends to stabilize at around 4°C at 1000 m depth (IRENA, 2021; EC, 2025). This temperature difference can be used to produce electricity and to desalinate seawater. Although the efficiency of OTEC systems is still low, they offer the advantage of producing fresh water, making them attractive for regions with limited water resources (Herrera et al., 2021; Weber, 2025).

2. Materials și methods

In the current climate context, the development of the global energy system is oriented towards low-carbon sources. From a spatial point of view, the research aimed to analyze the situation of ocean energy at a global level, and the temporal framework starts from the oldest concerns in the field, up to the present. The data used in this research come exclusively from the specialized literature. Sources belonging to international institutions with concerns in the field were consulted, such as the International Renewable Energy Agency (IRENA), the International Energy Agency, Ocean Energy Europe, the European Commission, as well as specialized scientific articles and other sources that have addressed the issue of ocean energy.

Quantitative and qualitative methods were used in the processing and interpretation of these data. Graphical methods were used to highlight the dynamics of some indicators, and the results were subsequently interpreted.

In the analysis of the current situation regarding the valorization of ocean energy, several aspects were pursued, including the identification of the potential for each type of renewable energy (tides, waves, salinity gradient, OTEC) and areas with high potential for the use of these resources. Also, in highlighting the constraints that influence the large-scale development of ocean energy, aspects such as: the reliability of technological devices, economic efficiency (project costs, production cost) or the impact on the environment (biodiversity, habitats) were pursued. The research also targeted support policies (at national or international level) and the future evolution of ocean energy.

3. Results

Although many technologies are still in the early stages of development, ocean energy is believed to have a significant theoretical potential that could meet current and future global electricity demand. Many studies state that the potential of ocean energy is considerably higher than the annual global electricity demand (Melikoglu, 2018; Khan et al., 2022; Samsó et al, 2023). Although it varies greatly depending on the technology, the cumulative theoretical potential has been estimated to be between 45,000 and over 150,000 TWh/year (Taveira-Pinto et al., 2020; IRENA, 2021; IEA, 2025). However, a distinction must be made between theoretical and technical potential, as the exploitation of ocean energy depends on the efficiency of available technologies and certain restrictions related to the exploitation of resources, such as those of a legal, economic or environmental nature (Taveira-Pinto et al., 2020).

The cumulative operational capacity for all forms of ocean energy is over 513 MW, with 1.6 MW added in 2024 (REN21, 2025). Of this capacity, 494 MW (i.e. 96%) comes from two large tidal dam projects in South Korea and France (table 4). As for global electricity production from ocean sources, it was 928 GWh in 2023, down from previous years (Fig. 1). Within renewable energy, the share of ocean electricity production remains extremely low. In 2024, solar electricity alone provided over 2000 TWh (Ember, 2025).

According to the PRIMRE Projects Database (2026), 284 projects have been identified, defined as deployments of ocean energy devices in open waters, intended to generate electricity or provide an alternative benefit. This also includes decommissioned, cancelled or planned projects (Fig. 2). Most projects have been implemented by the United Kingdom (55 projects), the United States, China, Japan, Australia, Canada, Italy, France, the Netherlands and Denmark.

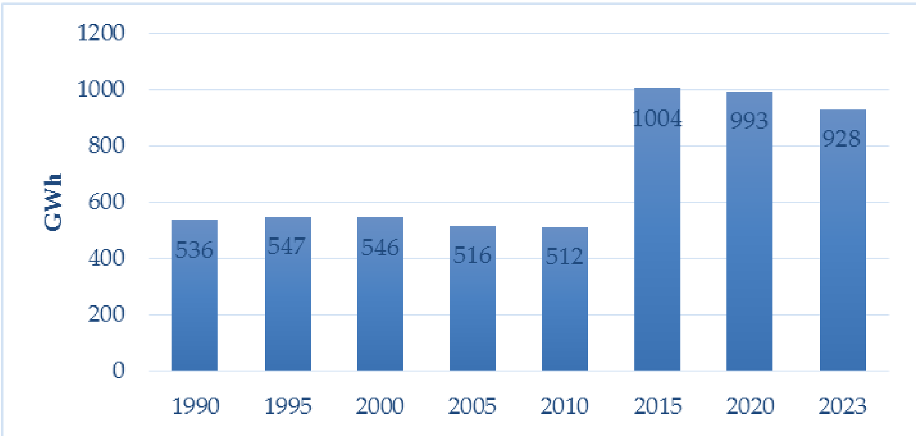

Figure 1. Global electricity generation from ocean sources 1990-2023
(*Source:* IEA, 2025)

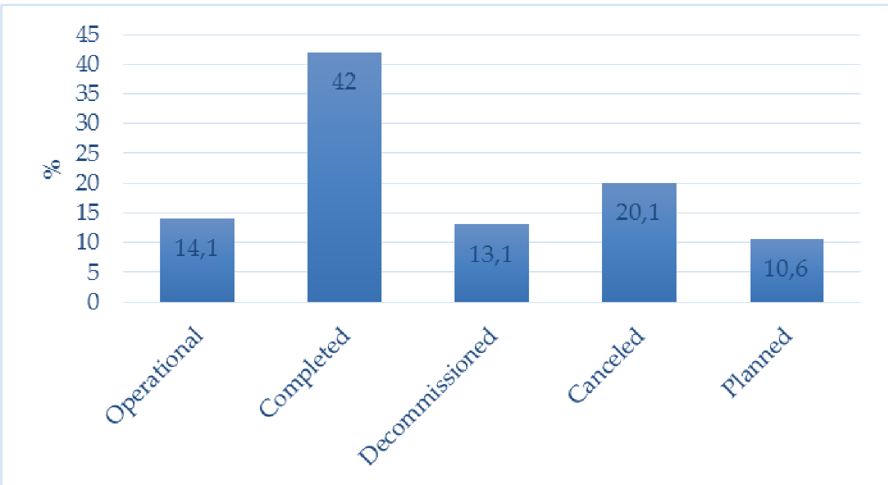

Figure 2. Projects by Life Cycle
(*Source:* OpenEI/PRIMRE, 2026)

The decommissioning of ocean energy projects has been driven either by the completion of demonstration phases or by financial and technical difficulties, as is the case with the Aguçadora Wave Farm project in Portugal. Many demonstration projects were designed with a limited lifespan, for example, 5 years for SeaGen. Between 2022 and 2024, 32 ocean energy projects were implemented globally (table 3).

Table 3

Ocean energy devices deployed worldwide in 2022, 2023 and 2024

Country	**Location**	**Device developer**	**Type and year of implementation**	**Capacity device (kW)**
France	Bordeaux	Hydrokinetic	Vertical Axis (2022)	25
France	Brest	EEL Energy	Undulating membrane (2022)	30
UK	Strangford Lough (Northern Ireland)	Gkinetic	Vertical Axis (2022)	12
Slovenia	Adriatic Sea	Sigma Energy	Point absorber (2022)	30
UK	Orkney (Scotland)	AWS	Point absorber (2022)	16
Belgium	Ostend	Exowave	Oscillating Wave Surge Converter (2022)	3.5
China	Xiushan Island, Zhejiang Province	Hangzhou LHD United Energy Corporation	Horizontal axis (2022)	1600
China	Shengsi island	Hann Ocean	Wave Rotor (2022)	15
US	Washington State	C Power	Rotating mass (2022)	1
Israel	Tel Aviv	Eco Wave Power	Attenuator (2022)	100
UK	Shetland (Scotland)	Nova Innovation	Horizontal Axis (2023)	100
UK	Shetland	Nova Innovation	Horizontal Axis (2023)	100
France	Etel Estuary	Nova Innovation	Horizontal Axis (2023)	50
France	Rhône river	EEL Energy	Undulating membrane (2023)	30
Portugal	Aguçadoura	CorPower Ocean	Point absorber (2023)	300
Italy	Mediteranean Sea	Eni	Oscillating WEC (2023)	260
Spain	Valencia	Rotary Wave	Point absorber (2023)	20
France	Nantes (SEM-REV)	GEPS Techno	Attenuator (2023)	10

US	Alaska	ORPC	Horizontal axis (2023)	40
US	Maine (3 devices)	ORPC	Horizontal axis (2023)	50 (cumulative)
China	Guangdong	GIEC, China Southern Power Grid	Point absorber (2023)	1000
US	Maine	Oscilla Power	Point absorber (2023)	-
US	New Jersey	OPT	Point absorber (2023)	-
Denmark	Faroe Islands	Minesto	Kite (2024)	1200
Netherlands	Ameland	SeaQurrent	Kite (2024)	200
UK	Strangford Lough (Northern Ireland)	ORPC Ireland	Horizontal Axis (2024)	18
Spain	Canary Islands	Wavepiston	Oscillating Wave Surge String Attenuator (2024)	30
UK	Aberdeen	ZOEX Power	Attenuator (2024)	100
US	Oahu (Hawaii)	OceanEnergy Group	Oscillating water column (2024)	500
US	Strait of Juan de Fuca (Washington)	Panthalassa	Other (2024)	40
Australia	King Georges Sound	University of Western Australia	Attenuator (2024)	1 to 10
Australia	North Fremantle	Carnegie Clean Energy	Point Absorber (2024)	5.7

Source: OEE, 2023-2025

3.1. Harnessing the energy potential of tidal waves

People have used tidal energy since ancient times to power stone mills. Tide mills, based on small basins or ponds, appeared on the Atlantic coasts of Europe around the 11th century and persisted until the 20th century (Smith, 2023). In 1920, the United Kingdom proposed using tidal energy to generate electricity, and China built small tidal power plants around 1956 (Li et al., 2025).

The theoretical potential of tidal power has been estimated to be between 450 and 1200 TWh/year (El Tawil et al., 2017; Sangiuliano, 2017; IRENA, 2021; Samsó et al., 2023), being the lowest of all ocean energy technologies. Europe has an estimated potential of 24 TWh/year, mainly in the United Kingdom (almost half), France and Ireland (El Tawil et al., 2017).

Of all ocean energy technologies, tidal power is the most mature and the first to be implemented on a large scale, with large plants in South Korea and France (EC, 2025). The La Rance tidal power plant in Brittany (France) was the first commercially operational plant of this type, inaugurated in 1966. This plant generates enough electricity to power a settlement of about 223,000 inhabitants. The Rance estuary has one of the largest tidal amplitudes in the world, 13.5 m (EDF, 2012).

Later, tidal power plants were installed in Russia, China, Canada and South Korea (table 4). The Kislaya Guba Experimental Tidal Power Plant, near Murmansk, is the second oldest. Although it has a limited capacity, the plant represented a pioneering effort in the development of tidal power in cold climates (Smith, 2023). Located in Yueqing Bay (near Wenling), the Jiangxia Experimental Tidal Power Station is the largest tidal power plant in China and generates about 7 million kWh annually. In 2022, this plant was integrated into a hybrid project, which includes 100 MW of floating solar panels (Garanovic, 2022).

The Sihwa Tidal Barrage Power Plant in the Sihwa Lake area (South Korea) is the largest of its kind in the world. The plant was installed in 2011 by the Korea Water Resources Corporation, has 10 submersible generators and provides power for a population of 500,000 (OpenEI, 2026). Since 2011, no new projects using tidal barrage technology have been developed globally (EC, 2025).

With some of the largest tidal energy resources in the world, several tidal barrage projects have been proposed in the UK, but none have been completed to date. It is estimated that these projects (Swansea Bay, Merseyside, the North Somerset Coast and the North Wales Coast), which are currently stalled, could deliver 10 GW of installed capacity by 2030 if they receive the appropriate permission and funding (Ferris, 2022).

Table 4

Tidal dam power plants

Name	Location	Inauguration	Installed capacity (MW)	Condition
La Rance	France (Rance Estuary, Brittany)	1966	240	In operation
Kislaya Guba	Russia (Kola Peninsula)	1968	0.8	In operation
Haishan	China (East China Sea)	1975	0.25	In operation
Jiangxia	China (East China Sea)	1980	4.1	In operation
Annapolis Royal	Canada (Bay of Fundy)	1984	20	Permanently closed in 2019
Sihwa	South Korea (Gyeonggi Bay)	2011	254	In operation

Source: EDF, 2012; Withers, 2021; Garanovic, 2022; Smith, 2023

Although tidal barrage projects have proven commercially viable, their implementation has been limited by the availability of suitable sites and the impact on the local environment (EC, 2025).

Compared to tidal barrages, tidal stream technologies are expanding. Orbital Marine Power, based in Orkney (Scotland), was the first company in the world to successfully connect a floating tidal turbine to the grid in 2011 (Ferris, 2022), and the first operational pre-commercial tidal farms appeared in Europe in 2016 (the MeyGen and Shetland projects). In 2016, Orbital Marine Power launched the world's most powerful tidal turbine (SR2000), which produced over 3 GWh of electricity in its 12-month continuous testing program (Orbital Marine Power, 2019).

In 2024, the cumulative electricity production from existing demonstration projects and tidal stream farms reached 106 GWh, up from 93 GWh in 2023 and 80 GWh in 2022, with an annual production of 13.4 GWh. The MeyGen and Nova Innovation pilot farms, as well as turbines from Orbital Marine Power, Magallanes Renovables and Inyanga Marine Energy Group, provided the bulk of the electricity. Europe remains the technological leader in tidal stream energy, with a cumulative capacity three times higher than all other countries combined (30.5 MW versus 10.9 MW) (OEE, 2024; OEE, 2025).

The world's largest tidal farm (the MeyGen project), owned by SAE Renewables, is located in northern Scotland, near Stroma Island, in a natural channel that harnesses the tidal flow between the North Sea and the Atlantic Ocean (Edmond, 2020). The tides here are particularly strong, with currents that can move up to five meters per second. The first four turbines of the project, with a cumulative capacity of 6 MW, are already operational, and an additional capacity of 59 MW is planned to be installed by 2029 (Cavcic, 2025). Ultimately, the region is expected to have a capacity of 398 MW, enough to power 175,000 homes (Bithenergy, 2026).

The Zhoushan LHD power plant, off Xiushan Island (Zhoushan Province, China), with a modular capacity of 3.3 MW, holds the world record for continuous operation for a tidal stream project, over 9 years (REN21, 2023).

The United States has no commercially operational tidal power plants, although several locations in the United States have potential, including Cook Inlet in Alaska, which has the second largest tidal range in North America, and several locations in the states of Maine and New York. A number of demonstration projects have been implemented or are in various stages of development, such as: Roosevelt Island in the East River in New York, Western Passage in Maine, and Cobscook Bay in Maine (EIA, 2026).

3.2. Wave energy

The first known concept for harnessing wave energy (a device that would power irrigation pumps) was proposed by Pierre-Simon Girard in 1799. Later, in 1910, Busso Belasek invented an early form of wave-powered power plant, capable of generating 1000 W of electricity. Yoshio Masuda is considered the father of modern wave energy because in the 1940s he developed wave-powered navigation buoys. In the 1980s and 1990s, various projects in this field were tested worldwide (Scotland, Japan, United Kingdom, Portugal). The world's first grid-connected, commercial-scale wave energy device, called LIMPET, was implemented in Scotland (on the island of Islay) in 2000. The 500 kW project was developed by Queen's University Belfast and operated by the Scottish company Wavegen until 2011 (Johanning, 2025).

The first wave farm (Aguçadoura Wave Farm), with a capacity of 2.25 MW, was put into operation near the Portuguese city of Porto in 2008, the result of a pioneering effort by the companies Pelamis (UK), Enersis (Portugal) and Babcock and Brown (Australia). However, after only a few months, due to technical and financial problems, the farm was decommissioned (Marine Insight, 2019).

The energy potential of waves is much higher than that of tides, estimated at around 29,000 TWh per year, which would mean meeting the current global electricity demand (Mørk et al., 2010; IRENA, 2021; OEE, 2026). There are estimates of this potential reaching over 87,000 TWh/year (Samsó et al., 2023). The west coasts of the United States and Europe, as well as the coasts of Japan and New Zealand, have potential sites for the exploitation of wave energy (EIA, 2026). In recent years, wave energy exploitation technologies have been implemented in Spain, Italy, Portugal and Sweden (EC, 2025).

Cumulatively, since 2010, about 27 MW of wave energy capacity has been installed globally, of which 13.5 MW is in Europe. Because many devices were test and prototype devices, only a fraction of the capacity remained continuously active in the water at any given time. For example, in Europe, of the cumulative capacity installed since 2010, 12.6 MW has been decommissioned following the completion of demonstration programs (REN21, 2024; OEE, 2025).

In Europe, 4 wave energy installations were deployed in 2023, with a capacity of 595 kW, and two full-scale devices were deployed in 2024, with a total capacity of 130 kW. All new devices in 2024 were deployed in the Atlantic, which has been the focus of wave energy activities in recent years. 2024 marks the third consecutive year in which the majority of deployed devices were full-scale, a clear indication that wave technologies have reached a higher stage of technological readiness (OEE, 2024; OEE, 2025).

The year 2023 marks the largest deployment volume outside Europe since 2019, with a total of 1 MW. In 2024, for the first time since 2015, cumulative deployments outside Europe exceeded those in Europe. This is the result of several deployments in the USA and Australia. However, European companies are still the global technology leaders. The Irish company OceanEnergy Group has deployed the only large-scale wave device (over 1 MW) in Hawaii (OEE, 2024; OEE, 2025).

3.3. Salinity gradient

The concept of salinity gradient energy (osmotic power or blue energy) was first introduced in 1954 by the British Richard Pattle, who discovered that electricity could be produced by mixing fresh and salt water. Later, technological innovations aimed at improving the efficiency of membranes, with various companies being involved in this process (Hsu et al., 2021).

The first pressure-retarded osmosis (PRO) plant was opened in Tofte (Norway) in 2009 by Statkraft, with a generating capacity of 4 kW. Although the process worked, the devices did not produce enough energy to offset the construction, operation and maintenance costs. The plant was therefore closed in 2013 (Ball, 2015).

The Mega-ton Water System Project was carried out in Japan between 2009 and 2013, and on 5 August 2025, Kyowakiden Industry put a PRO system into operation at a seawater desalination plant in Fukuoka City, the first of its kind in the country. The plant is expected to generate approximately 880,000 kWh of electricity annually, which will support the nearby water desalination plant (Asian Water, 2025). Also in Japan, Toyobo is the sole developer of commercial PRO membranes, and the Blue Energy Center for SGE Technology (BEST), a research center established at Yamaguchi University in 2018, has successfully developed a RED stack with the largest membrane area in the world (Watanabe et al., 2025). Denmark introduced a similar installation in 2023 at the Nouryon salt plant in Mariager, developed by the company SaltPower, together with Danfoss and DTU Chemical and Biochemical Engineering (Andersen, 2023). Although they do not use seawater directly, these projects confirm the viability of the technology.

Currently, the most advanced salinity gradient technology is reverse electrodialysis (RED), due to its higher energy efficiency and lower susceptibility to membrane fouling than pressure-delayed osmosis (Hsu et al., 2021). The RED technology was proposed by the Dutch company REDstack, spun off from the Wetsus Institute in Leeuwarden, a European center of excellence for sustainable water technology. In 2015, this company inaugurated the world's first RED power plant on the Afsluitdijk. Powered by the natural mixture of freshwater from the IJsselmeer and saltwater from the North Sea, this pilot plant started producing 50 kW of blue energy and demonstrated the real-world feasibility of continuous clean energy generation (REDstack, 2026).

Further developments to improve membrane performance and cost-effectiveness are ongoing (OEE, 2025). This technology has been tested mainly in the EU, and electricity production began in 2024 in a new demonstration plant built in France by Sweetch Energy (EC, 2025). Although estuaries are numerous globally and salinity can theoretically provide continuous baseload power, geographical requirements impose significant limitations on the potential, which is relatively small compared to other emerging ocean technologies, at around 1650 TWh annually (IRENA, 2021). Salinity gradient is the least mature ocean energy technology.

3.4. Ocean Thermal Energy Conversion (OTEC) plants

The concept of OTEC was proposed as early as 1882 by the French physicist Jacques Arsèe d'Arsonval, and in 1926 it was tested by Georges Claude in Matanzas Bay, Cuba. However, significant progress in the field was only reported in the 1960s. In the 1970s, the US and Japanese governments supported research and development of the technology, followed by France, the Netherlands, the UK and Sweden (Weber, 2025).

The United States has been involved in OTEC research since 1974, with the establishment of the Natural Energy Laboratory of Hawaii Authority, which operated a 250 kW demonstration plant for six years in the 1990s. Another 105 kW demonstration plant, developed by the Makai company in Kailua-Kona, became operational in 2015 and supplies electricity to the local grid (EIA, 2026).

In 1994, the Ocean Energy Institute at Saga University in Japan, a leader in OTEC research, built a 4.5 kW plant. In 2013, a 100 kW OTEC plant was installed on Kume Island to verify the real-world functionality of this technology. Later, in 2015, the plant was also adapted for water desalination (Herrera et al., 2021).

There is currently no operational capacity in Europe for ocean thermal energy conversion technologies (EC, 2025). OTEC prototypes are often land-based, but floating prototypes are also being developed (OEE, 2026). Almost 100 nations have been identified with access to OTEC resources in their exclusive economic zone (Herrera et al., 2021).

A theoretical potential of approximately 44,000 TWh/year is estimated globally (IRENA, 2021; EC, 2025), which could meet current global electricity needs. Thus, OTEC could provide continuous and non-intermittent baseload electricity. However, this energy source is still in the research and development phase, with current deployment limited to 100 kW demonstration plants in Hawaii (USA) and Japan (IRENA, 2021).

4. Discussion

Ocean energy development faces a number of challenges related to hostile environmental conditions, capital costs and high electricity prices, and environmental impacts. Such challenges affect public and investor confidence in these technologies. Projects also involve obtaining permits from local agencies, negotiating power purchase agreements, communicating with local stakeholders, and coordinating with the supply chain for manufacturing and installation (Open EI/PRIMRE, 2026).

4.1. Environmental constraints

The economic exploitation of ocean energy faces challenges related to the exposure of technologies to the hostile maritime environment, marked by strong winds and waves, which make it difficult to install, operate and maintain the facilities. Also negatively impacting are the high humidity and high salt concentration in the atmosphere, which can trigger early corrosion of metal components. These conditions can have a significant impact on equipment, reducing their lifespan, maximum production power and efficiency. Thus, technologies must be designed to withstand extreme environmental conditions, but also to operate efficiently and with low maintenance requirements under frequent conditions. Regarding tidal dams, the development of this technology has been influenced by the small number of locations with high tides, and the favorable ones are located quite far from consuming centers. For example, in North America the only major locations for tidal dams are in Alaska and along the coast of Maine (Ferris, 2022). Regarding tidal streams, the use of tidal energy is generally only feasible in locations where flow velocities are greater than 1 or 2 m/s, a limited number of locations meeting this condition (Taveiro-Pinto et al., 2020). Turbines cannot also be installed in shallow waters due to turbulence caused by waves, nor in very deep waters due to the decrease in tidal current speed with depth (El Tawil et al., 2017).

4.2. Environmental impact

Although ocean energy is seen as an alternative to fossil fuel sources, there are uncertainties about the potential environmental impact, as the technologies used are relatively new and poorly tested, and methods for assessing and monitoring environmental impacts are scarce. Coastal areas are generally fragile ecological balances, and changes to estuaries, coastal areas or currents can significantly affect the local environment. Negative impacts could occur through habitat loss, the risk of collision of animals with turbines (fish, marine mammals), noise or electromagnetic fields produced by submarine cables, which can have effects on aquatic species (IRENA, 2021; Martinez et al., 2021). Tidal dams can alter turbidity (the amount of suspended matter in the water) and affect navigation and recreation.

For example, the La Rance tidal dam (France) led to the siltation of the Rance River estuary, which significantly affected the fish population behind the dam. Similarly, the Annapolis Royal tidal dam (Nova Scotia, Canada) was permanently closed in 2019 due to a combination of technical issues (failure of a critical generator component) and environmental pressures. Studies conducted by Fisheries and Oceans Canada confirmed that the plant's turbines were causing significant fish kills: up to 23% of the American mackerel population passing through them. In addition, the dam caused increased erosion of the Annapolis River banks, affecting upstream farmland (DFO, 2019; Withers, 2021). Thus, environmental impact assessment studies and the implementation of best practices in the field are needed to avoid potential risks.

4.3. The cost issue

Despite investments in ocean energy, the commercial viability of this sector still remains uncertain, also due to the considerable initial costs. It has been found that the long operation of some installations can amortize the cost of the project. For example, the La Rance plant is operating well after almost 60 years, and has produced approximately 28,000 GWh of electricity, amortizing its cost many times over (Ferris, 2022).

In recent years, ocean renewables have seen reductions in the Levelized Cost of Electricity (LCOE), even though ocean energy technologies are still in a relatively early stage of development. LCOEs range from €110 to €480/MWh for tidal power and from €160 to €750/MWh for wave power. The UK government has granted reference prices for several tidal projects in 2023 and 2024. In 2024, the common price for all projects was €204/MWh, 33% lower than in 2023 (€303/MWh), which is a significant decrease (EC, 2025).

Due to high costs, some projects have not been implemented. For example, in the UK, a tidal power project failed. This was a £1.3 billion tidal lagoon proposed in Swansea Bay, off the south coast of Wales. Although the project received planning permission in June 2015, which the developers said could provide electricity for 155,000 homes, the plans collapsed in 2018 when the UK government refused to provide financial support to guarantee the price of electricity (Ferris, 2022).

And in the case of OTEC plants, almost all proposals have not made the leap from experimental prototype to commercial plants due to high infrastructure costs, especially for submarine cables and the hostile and corrosive environment of seawater (Herrera et al., 2021).

4.4. Technological development

Over the past two decades, ocean technologies have experienced varying levels of technological readiness, accompanied by an increase in innovation. Thus, tidal and wave energy holds the majority of patents filed internationally among ocean energy technologies. Since the early 2000s, over 24,000 patents have been filed. Other energy technologies, such as OTEC and salinity gradient, have also made progress (IRENA, 2021).

Ocean energy technologies are being developed and used in several countries, but only a few are more active: the United Kingdom, France, Finland, Ireland, Italy, Portugal, Spain, Sweden, Australia, Canada, China or the United States. These countries have the most tested, implemented and planned projects, as well as the most developers and manufacturers of devices. Although most ocean energy technologies are in the research and development phases, a growing number of companies, research institutes, universities and investors are showing interest in ocean energy technologies (IRENA, 2021).

Because these technologies are immature, they will face a number of challenges that could hinder commercialization. In the case of OTEC plants, there are still some technological difficulties, including the considerable amounts of dissolved gases in seawater (especially nitrogen and oxygen), which must be removed if flash evaporation is used (Weber, 2025).

4.5. Ocean energy support policies and growth projections

Ocean energy projects have benefited from significant investment, both from public and private sources. Government support schemes, such as the UK's Contracts for Difference (CfD), launched in 2021, and the French feed-in-tariff, are also important. Power purchase agreements (PPAs) can complement or provide an alternative to financing farms. For example, the Minesto farm in the Faroe Islands is being developed under a PPA with utility company SEV. However, PPAs can only provide a sufficiently high return for innovative projects in areas where competing alternatives are costly (OEE, 2025).

In Europe, dozens of ocean energy projects have been funded with over EUR 180 million. The EU supports the most advanced projects in particular through the EU Innovation Fund (EUR 31.3 million for Normandies Hydroliennes) and the European Innovation Council Accelerator (EUR 17.5 million for CorPower) (EC, 2025). Also in 2024, the ONDEP wave energy project received EUR 19 million in funding through the Horizon Europe programme (OEE, 2025). The EU Offshore Renewable Energy Strategy, initially published in 2020, sets a target of at least 1 GW of installed capacity for ocean energy by 2030 and 40 GW by 2050 (EC, 2026).

US funding reached $141 million in 2024 and a cumulative total of $591 million over five years, focused primarily on wave energy. California and Oregon have passed dedicated ocean energy legislation. China is also an active player in ocean energy, with major deployments and ambitious plans. Several energy bills were published in 2024 that support the continued exploitation of ocean energy. China's public support is channeled through a combination of generous grants and revenue support (OEE, 2024, OEE, 2025).

In the UK, in November 2021, the fourth round of allocations for the UK's contracts for difference scheme announced that £20 million per year would be set aside for tidal stream projects, a signal that this is a viable technology. However, some large projects, including the £7 billion Tidal Lagoon in North Wales, have yet to be implemented (Ferris, 2022).

Future developments are encouraged by technological advances in recent years. An increase in installed capacity is expected, with the implementation of publicly funded projects. As a result of market expansion, IRENA estimated in 2021 that ocean energy technologies could reach an installed capacity of around 70 GW by 2030 and 350 GW by 2050 globally (Fig. 3). Also, according to the International Energy Agency's Ocean Energy Systems (IEA-OES), ocean energy has the potential to contribute 300 GW of renewable energy generation capacity to the global transition to Net Zero emissions by 2050 (OES, 2023).

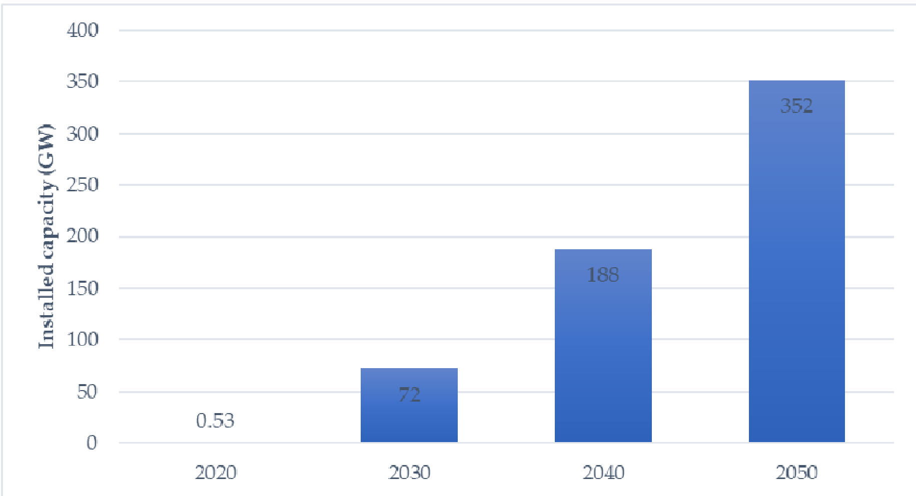

Figure 3. Projected ocean energy capacity by 2050
(IRENA, 2021)

Conclusions

It is widely accepted that the burning of fossil fuels is the major cause of climate change, and the development of renewable energy sources is necessary to reduce greenhouse gas emissions. Renewable sources also include ocean energy.

It is estimated that the potential of ocean energy sources is significant and could cover the global demand for electricity. However, most ocean energy technologies are still under development and face various problems, including high implementation costs, durability of equipment in the marine environment and some forms of environmental impact.

Although increases in installed capacities have been reported in recent years, electricity production is still very low. An increase in installed capacity is expected, with the implementation of pre-commercial parks financed from public funds.

Despite investments, the commercial viability of this sector still remains uncertain, also due to the high implementation costs. Under these conditions, public institutions and the private sector should support research and development in the field more consistently to identify the best solutions and technologies to capitalize on these renewable energy sources and to satisfy global energy demand.

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