

Review

Current Status of Development and Application of Ocean Renewable Energy Technology

Xing Su, Jinmao Chen, Liqian Yuan, Wanli Xu, Chunhua Xiong and Xudong Wang *

Systems Engineering Institute, AMS, PLA, Beijing 102300, China; wojiaosuxing123@163.com (X.S.); energycj@163.com (J.C.); 15034678826@163.com (L.Y.); xuwl06@163.com (W.X.); energyxch@163.com (C.X.)

* Correspondence: energywxd@163.com

Abstract: As society continues to develop, the demand for, and dependence on, energy for production and daily life activities are constantly increasing. Driven by environmental awareness and limited land resource, people have begun to reduce their dependence on fossil fuels and turn to the ocean for energy. Oceans contain vast and abundant energy resources, such as waves, tides, temperature differences and salinity gradients, all of which can be used for power generation. These resources are clean, efficient, renewable and inexhaustible, making them reliable “blue energy sources”. In addition, they are also generally not limited by land use areas, meeting the need for sustainable energy development. This article summarizes the technical characteristics of ocean energy, such as wave, tidal current, tidal, temperature difference and salinity gradient energies, and compares through the technological forms of different ocean energies, respectively. It also summarizes the development status of the ocean energy industry, and analyzes the industrial maturity of wave energy, tidal energy, etc, predicts future ocean energy development trends, and highlights the influence of ocean energy on sustainable development. We hope that this article provides a reference for scholars and institutions that dedicated to the research and development of ocean energy.

Keywords: ocean energy; renewable energy; energy development; sustainability



Academic Editors: Jifeng Song and Zuopeng Qu

Received: 4 March 2025

Revised: 8 May 2025

Accepted: 16 May 2025

Published: 19 June 2025

Citation: Su, X.; Chen, J.; Yuan, L.; Xu, W.; Xiong, C.; Wang, X. Current Status of Development and Application of Ocean Renewable Energy Technology. *Sustainability* **2025**, *17*, 5648. <https://doi.org/10.3390/su17125648>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The ocean not only provides humanity with shipping, food and minerals but also contains renewable energy that is inexhaustible and endlessly available. As society evolves rapidly, the demand for energy increases annually. The pollution and non-renewability of traditional fossil fuels no longer meet the sustainable development needs of human society in the new era. Therefore, clean, pollution-free, renewable, widely distributed and land-non-occupying ocean renewable energy has become an important means of alleviating the problems caused by fossil fuels and satisfying the high-quality development needs of society [1,2].

Ocean renewable energy refers to the generation of electricity through the utilization of kinetic energy, temperature differences, salinity gradients and other resources contained within the ocean. They mainly include wave energy, tidal current energy, tidal energy, temperature difference energy and salinity gradient energy (Figure 1) [3,4]. Owing to the renewable nature and environmentally non-polluting advantages of ocean renewable energy, as well as its immense potential for development and utilization, it has garnered worldwide attention and has become a global research focus.

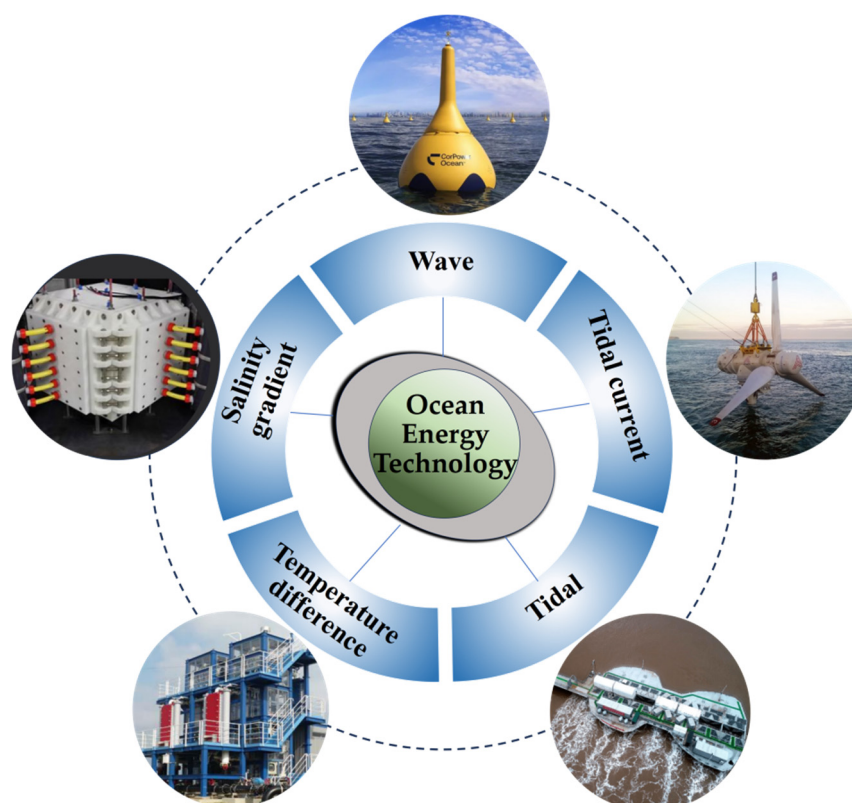


Figure 1. Classification of ocean renewable energy technology.

After long-term exploration and research by enterprises and institutions, ocean renewable energy power generation technology has generally reached the stage of demonstration applications but has not yet completely achieved large-scale commercial application. Moreover, the technological pathways and forms of ocean energy utilization is various and different, and progress in development and application is out of sync. Overall, the ocean renewable energy industry is in an accelerated development stage. This article provides a systematic summary of the development of ocean energy technologies. It summarizes the classification, technical characteristics and current applications of ocean energy technologies. While this article also analyzes the policies, economic viability, markets and operational aspects of the ocean energy industry. Furthermore, it concludes with a discussion of development bottlenecks and trends of ocean renewable energy, highlighting the importance of ocean energy to sustainability and offering suggestions for development. It is hoped that this article will provide support for technological research and industrial development of ocean renewable energy.

2. Overview of the Development of Ocean Renewable Energy Technology

Ocean renewable energy is renewable and environmentally friendly. The forms of energy that utilize ocean kinetic energy, such as wave and tidal energy, exhibit certain natural fluctuations. Seawater has a higher mass density than air and therefore contains more kinetic energy. Consequently, the power-generation capacity should be higher than that of wind energy theoretically. Temperature and salinity difference for power generation, have relatively less variability. However, the industry chain is not yet ready at the current stage, and the initial construction costs are high, thus, ocean energy has not been applied on a large scale. With continuous in-depth research and long-term investments by research institutions, ocean energy technology is becoming increasingly mature. After overcoming the challenge in present demonstration application stage and achieving certain technological breakthroughs, it will be applied on a large scale.

Progress in the development of different ocean renewable energy technologies varies significantly. Wave energy, tidal current energy and tidal energy have developed rapidly to be mature. The large-scale applications are expected soon. However, temperature difference energy and salinity gradient energy technologies still require further development before they can meet the standards for industrial applications.

2.1. Wave Energy

Wave energy devices transform the kinetic and potential energies of surface waves into another form of energy [5]. These energies mainly originate from the wind blowing on the sea surface. Wave energy generation devices capture the horizontal, vertical or rotational movement of waves and convert this mechanical energy into electrical energy. Wave energy generation has tremendous application potential, particularly in coastal areas which are rich in wave resources. It can provide electricity to isolated islands, offshore facilities and coastal communities, results in reducing dependence on fossil fuels.

2.1.1. Working Principle and Classification of Wave Energy

The basic principle of wave energy technology (Figure 2) is as follows. The conversion of wave energy from energy capture to electricity generally involves three stages. The first stage is the conversion of the wave energy into the energy forms required by the transmission system, through the motion of the energy-capturing mechanism under the waves. The second stage is the conversion of the energy captured by the energy-capturing mechanism through the transmission system into the energy form required by the generator. The third stage is the output of energy in the form of electrical power through devices such as generators [6,7].

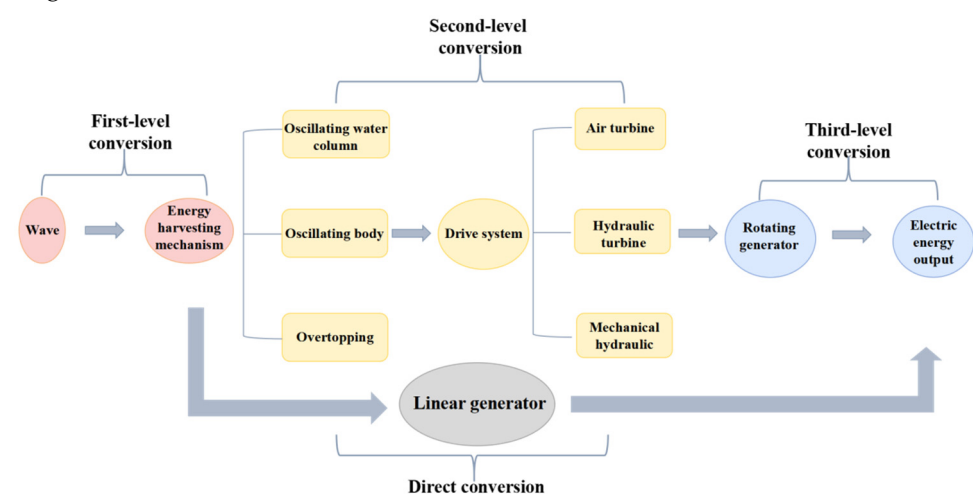


Figure 2. Schematic diagram of the basic principle of wave energy power generation devices.

Wave energy can be classified into fixed and floating types based on the installation form. Installation locations can be categorized as shore-based, nearshore or offshore wave energy [8–10].

Based on different first-level energy conversion systems, wave energy can be divided into oscillating water columns (OWC), oscillating bodies and overtopping types as shown in Table 1. The OWC-type wave energy power generation device utilizes the rise and fall of waves to drive the oscillation of the water column with air compressed and flowed in the air chamber. The airflow causes the turbine to rotate, which, in turn, drives the generator to produce electricity. The OWC-type wave energy power generation device is mainly composed of basic components such as air chamber, turbine and generator, etc. This device is adaptable to waves of different frequencies and amplitudes, and at the same time, the

device does not produce greenhouse gas during operation, which has less impact on the marine ecological environment. Moreover, its structure is partly hidden underwater and has less impact on the marine landscape, and it can be combined with marine infrastructure such as harbors and breakwaters, which improves the utilization rate of marine space. An oscillating body is a device that converts wave energy into mechanical energy using a single or multiple degree-of-freedom motion of the energy-capturing mechanism under waves. Oscillating body type wave power generation device mainly consists of oscillating floats, transmission system and generator and other components. Compared with some other types of wave power generation device, oscillating body type wave power generation device has higher energy conversion efficiency, and can adapt to harsh sea conditions. At the same time, this type of power generation device is relatively easy to maintain, and the corresponding costs are relatively low [11,12]. The overtopping type mainly uses the wave-focusing effect and overtopping action to convert wave energy into electrical energy. The overtopping type wave energy power generation device mainly consists of wave gathering structure, water reservoir, turbine and generator, etc., which has the characteristics of steady power generation and high stability, and the parts of the device, such as wave gathering structure and water reservoir, are relatively sturdy and not easy to be affected by impacts and damages of waves, which reduces the possibilities of failures due to damage of the parts [13–16].

Table 1. Classification of common wave energy generation technologies.

Classification	Technical Form
Working principle	Oscillating water column type, Oscillating body type and Overtopping type
Installation form	Fixed type, Floating type
Installation position	Shore-based type, Nearshore type and Offshore type
Wave energy absorption type	Attenuator type, Point absorption type and Terminator type
Energy transfer mode	Pneumatic type, Hydraulic type, Mechanical type and magnetic type

Second-level energy conversion systems can be divided into pneumatic, hydraulic, mechanical and magnetic types. The pneumatic type uses the pressure difference generated by the motion of wave energy through pneumatic effects to drive gas circulation within a device, thereby pushing turbines or generators to produce electricity. The hydraulic type converts the captured wave energy into high-pressure hydraulic energy to drive hydraulic motors that generate electricity using a generator. The mechanical type directly drives the mechanical gears or linkages to convert the captured wave energy into mechanical energy to drive the generator. A magnetic wave energy power generation device uses a permanent magnet linear generator to directly convert the vertical kinetic energy of the wave energy into electrical energy, bypassing intermediate energy conversion and improving the energy conversion efficiency.

According to the types of wave energy absorption, wave energy can be divided into the attenuator, point absorber and terminator types. Attenuator-type wave energy converters typically attenuate energy when waves interact with device, during which the wave's energy is gradually converted or consumed, and the kinetic energy of the wave is transformed into usable energy through an energy conversion mechanism. The point-absorber type utilizes the vertical movement of one or more oscillating buoys under the action of waves to capture wave energy. Terminator-type wave energy converters usually consist of one or more floating bodies parallel to the direction of wave energy propagation,

which perform a longitudinal reciprocating motion with the movement of the wave energy, and capture the energy of the waves [17–19].

2.1.2. Characteristics of Wave Energy Technology

Wave energy, as an important part of ocean energy, has the following advantages. First, the reserves of wave energy are abundant, with an estimated global wave energy potential of approximately 2.5 billion kW. Second, as a clean renewable energy source, it does not produce pollution. Third, wave energy does not occupy land space and is located offshore, which can provide electricity to the islands. Fourth, wave energy has a high energy density and is widely distributed for direct utilization [20,21].

From the formation mechanism of wave energy, it is known that the formation of wave energy and its exploitability depend on external factors which influence the wave motion period and the maximum wave crest height. Hence, wave energy power generation is not stable. Wave energy also has the disadvantages of energy loss during the three-level energy conversion to electrical energy. Seawater is corrosive, and water currents can impact and damage the devices. Thus, there is a high requirement for the corrosion resistance and stability of wave energy devices, and the cost of wave energy power generation is much higher than that of wind, solar and other new energy power generations [22].

2.1.3. Overview of Wave Energy Applications

Currently, many countries have built wave energy devices that have been operated continuously in marine environments. In 2019, the Finnish company AW-Energy deployed the first 350 kW oscillating wave energy generation device, WaveRoller (Figure 3), in the waters off Peniche, Portugal, and successfully connected it to the grid for power generation. The entire device is 43 m long, 18 m wide and 12 m high, with a total weight of 600 tons. The rated power of a single WaveRoller unit (one panel and one power-generation device combination) is between 350 kW and 1000 kW. The estimated power generation can reach 624–813 MWh [23].



Figure 3. Swing wave energy generator WaveRoller. Adapted from ref. [24].

In early 2021, the Institute of Ocean Engineering at Tsinghua University completed the development of China's first 30-kW WaveLoong pneumatic wave energy power generation device prototype (Figure 4). The WaveLoong pneumatic wave energy power generation device is 23.6 m long, 10 m wide, 9 m high with tonnage of 170 tons. In the second half of 2021, the device accomplished sea performance testing at the National Ocean Energy Comprehensive Test Site in the South China Sea. Starting in June 2023, six sets of WaveLoong pneumatic wave energy power generation equipment were successively put into operation. Currently, the technology of the six sets of pneumatic wave energy power

generation devices is being iteratively upgraded with the goal of achieving a technology readiness level of 9.

In June 2023, the world’s first MW-class floating-wave energy generation device, “Nan Kun” had been conducted offshore trials off Wanshan, Zhuhai, and Guangdong (Figure 4). Under full-load conditions, it can generate 24,000 kWh of electricity per day, which is sufficient for providing green power to approximately 3500 households. “Nan Kun” has a planar area of more than 3500 square meters and a total weight of more than 6000 tons. The device includes a power-generation platform, hydraulic system, power-generation system, monitoring system and anchoring system. It utilizes a “triangular” design of the power generation platform to “absorb” waves, and through the electrical energy conversion system which independently developed by China Southern Power Grid, completes the three-level energy conversion from wave energy to hydraulic energy and to electrical energy finally, thereby achieving stable power supply to the grid [25,26].



Figure 4. WaveLoong pneumatic wave energy generation device (left in the figure), “Nan Kun” wave energy generation device (right in the figure). Adapted from ref. [26].

The PowerBuoy wave energy conversion device developed by Ocean Power Technologies (OPT) is a representative point-absorption-type wave energy converter as shown in Table 2. Denmark’s Wavedragon wave energy device is representative of overtopping wave energy technology [27].

Table 2. Wave energy generation devices and parameters. Adapted from refs. [23–27].

Technical Institute	Project Name	Installation Time	Technical Form	Installed Capacity	Length (m)	Width (m)	Height (m)
Denmark	Wave Dragon	2003	Overtopping type	1.5–2 MW	57	27	—
American Ocean Power Company	Power Buoy	2008	Point absorption type	30 kW	—	—	—
AW-Energy	Wave Roller	2019	Hydraulic type	350 kW	43	18	12
Tsinghua University	Wave Loong®	2021	Pneumatic type	30 kW	23.6	10	9
Guangzhou Institute of Energy Conversion	Nan Kun	2022	Hydraulic type	About 1 MW	92	36	27

2.2. Tidal Current Energy

Tidal current energy conversion devices transform the kinetic energy of directed seawater flow into another form of energy (such as electrical energy) (Figure 5). At present, the technology readiness level of tidal current energy technology has reached levels 7–8, where issues of primary energy capture structure technology, unit control technology, machine-electric conversion technology and grid-connected/isolated operation technology

have been essentially resolved. The core critical technologies that tidal current energy needs breakthrough now are high-reliability operation of the energy transmission system and long-term underwater stability and reliability.

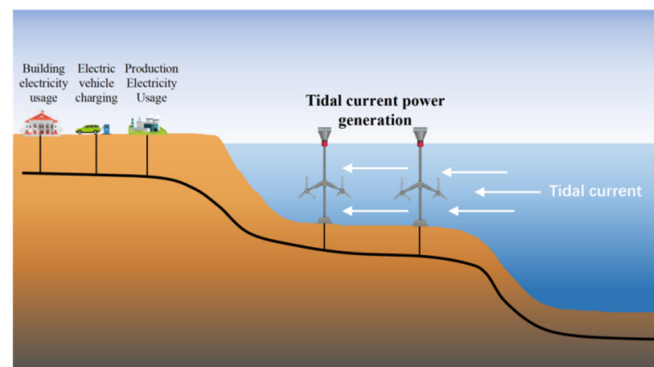


Figure 5. Schematic diagram of tidal energy generation.

The technical forms of tidal current energy mainly include the primary energy capture structure technology, which refers to the use of turbine technology in tidal current energy units to convert the kinetic energy of tidal currents into the mechanical energy of rotor rotation. Energy transmission technology primarily involves converting low-speed, high-torque rotors into high-speed, low-torque rotors through an energy transmission system, enabling low-speed rotors to drive the generators. For machine-electric conversion technology, the generators for electromechanical conversion technology include permanent magnet synchronous generators, excited synchronous generators and cage asynchronous generators. Grid-connected/isolated operation, unit control, sealing and anti-corrosion, real-sea operation and maintenance technology are also of significance to tidal current energy [28–32].

2.2.1. Classification of Tidal Current Energy

Tidal current power generation devices consist of five subsystems: an offshore supporter, generator, power conversion and control system, energy capture device and load system with a power transmission system. They are primarily classified according to their working principles. Among the turbine types, there are horizontal-axis and vertical-axis turbines, and other types include the oscillating hydrofoil, helical blade, Savonius and Venturi types [33,34].

Horizontal-axis turbines are tidal current turbines in which the direction of the water flow is parallel to the rotation axis of the rotor. These are water turbines with relatively mature modern technology. Horizontal-axis turbines primarily include structures such as blades, hubs, nacelles, brake compartments, brakes, transmission structures, sealing, generators, transmission mechanisms and tower [35,36]. There are many representative types of this kind of turbine, such as the MeyGen project, currently the world's largest tidal energy project developed by the British SIMEC Atlantis Energy (SAE) company.

A vertical-axis water turbine is a tidal-energy water turbine that uses the direction of water flow perpendicular to the rotation axis of the impeller. They primarily rely on the lift and drag forces of the airfoil blades to extract the kinetic energy of the fluid, and there are two main forms: straight blades and helical blades. The projects of this type of device mainly includes the EXIM turbine designed by the Swedish company Sea Power, as well as the first vertical-axis turbine “Wan Xiang II” 40-kW seabed tidal current experimental power station developed by Harbin Engineering University [12,37,38].

2.2.2. Characteristics of Tidal Current Energy Technology

Since the beginning of the 21st century, tidal current energy technology has developed rapidly, achieving significant breakthroughs both in technology and in terms of installed capacity, and it has certain advantages over other sustainable energy sources. First, the tidal current energy has strong regularity and predictability. Second, tidal current energy does not emit pollutants, making it an environmentally friendly energy source. Third, current tidal energy devices are generally installed on the sea floor or floating on the sea surface, eliminating the need for large dams, which have a minimal impact on the marine environment and do not occupy land resources. Fourth, compared with wind and solar energy, tidal current energy has a higher energy density, approximately four times that of wind energy and 30 times that of solar energy [39,40].

The development of tidal current energy also suffers unfavorable factors. For example, the energy density of tidal current energy varies periodically with the speed of ebbing and flowing tides. Hence, the electrical energy output of tidal current energy generators is unstable and requires subsequent improvement before it can be applied to commercial electricity generation. Tidal current energy development devices operate in seawater, where is a harsh environment, imposing strict requirements on the corrosion resistance, wave resistance, and leakage prevention of the devices. Installation at sea requires advanced construction technology and the corresponding marine engineering equipment, leading to high overall development costs [41–43].

2.2.3. Overview of Tidal Current Energy Applications

Countries with advanced tidal current energy technologies, such as the UK and France, have nearly commercialized their horizontal-axis tidal-current energy technology, with several MW-class units already used for construction or long-term marine demonstration operations as shown in Table 3. Taking the development of tidal current energy in the UK as an example, the first phase of the MeyGen tidal current power station had an installed capacity of 6 MW and was grid-connected in 2016 (Figure 6). By the end of 2021, the cumulative power generation will exceed 45 million kWh [44].



Figure 6. MeyGen tidal current power generation device. Adapted from ref. [45].

In recent years, milestone progress has been made in China's tidal current energy technology. By 2021, the total installed capacity of China's tidal current energy demonstration projects would reach 3130 kW, with a cumulative grid-connected power generation of approximately 4.83 million kWh. Currently, approximately 40 units have completed sea trials, with a maximum single unit power of 650 kW. Some units have achieved long-term demonstration operations, making China one of the few countries in the world that have mastered the technology for large-scale development and utilization of tidal current energy.

However, most of China’s tidal current energy projects are still in the experimental stage and have not yet reached a large scale for commerce, and there is no unified standard for calculating tidal current energy electricity prices [46,47].

Table 3. Tidal current power generation device and its parameters [44–50].

Technical Unit	Project Name	Installation Time	Installed Capacity
Atlantis Resources, Edinburgh, UK	MeyGen	2016	6 MW
Zhejiang Zhoushan United Kinetic Energy New Energy Development Co., Ltd., Zhejiang, China	LHD “Fen Jin Hao”	2016	2.7 MW
Harbin Electric Machinery Factory, Harbin, China	Ha Electric Ocean Energy Test Power Station	2019	600 kW

In February 2022, the single-unit 1.6-MW tidal current energy generator “Fen Jin Hao” from Zhejiang Zhoushan United Kinetic New Energy Development Co., Ltd. was loaded into the second phase of the LHD Tidal Current Energy Power Project’s integrated platform. “Fen Jin Hao”, which was launched this time, is the fourth-generation unit of LHD Tidal Current Energy (Figure 7). “Fen Jin Hao” unit weighs 325 tons and is designed to generate an annual power output of 2 million kWh. The annual power generation duration was approximately 1250 h [48].

With the support of “earmarked funds” in 2013, Harbin Electric Machinery Co., Ltd. developed a 600 kW semi-direct drive horizontal-axis tidal current energy unit [50]. In August 2019, the unit underwent sea trials in the waters off the Zhairuo Mountain Island. As of January 2020, it had accumulated more than 3000 h of operation, with a unit conversion efficiency of approximately 37% and cumulative power generation of 12,000 kWh.



Figure 7. LHD “Fen Jin Hao”. Adapted from ref. [49].

2.3. Tidal Energy

Tidal power plants are usually built in estuarine areas, where a barrage is constructed at the mouth of a river to form a reservoir behind the dam and low-head turbines are used for power generation.

In principle, tidal power generation is similar to conventional hydroelectric power generation. It utilizes the difference between high and low tide levels to drive the rotation of turbines, which in turn drives generators to produce electricity. The difference lies in the fact that seawater is different from river water. In addition, the stored seawater does not have a large head difference but have a large flow rate and is intermittent. Therefore, the structure of tidal power turbines must have a low head and high flow characteristics [51].

2.3.1. Classification of Tidal Energy

Tidal energy is primarily generated by the periodic rise and fall of seawater owing to gravitational forces from the moon and sun. It includes periodic vertical and horizontal seawater flows. The vertical movement component is the potential energy of the tides, which is known as tidal range energy. Tidal energy is primarily divided into barrage type and open type (Figure 8) [52,53].

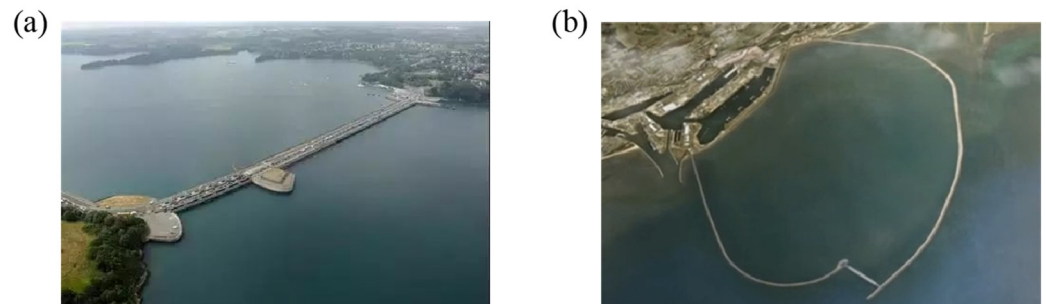


Figure 8. (a) Barrage tidal energy, (b) open tidal energy. Adapted from ref. [54].

1. Tidal barrage power stations

Barrage type tidal energy consists of a barrage, sluice gate and generator set, which utilizes a concrete/earth and rock dam across the bay to create a water level difference to generate electricity, which has the advantages of high efficiency and stability, but suffers from high cost, ecological damage and sediment siltation problems. Barrage tidal power generation technology has matured, and tidal power plants have been in operation for decades. The Francis bulb turbine generator unit is the most widely used tidal energy unit [12,55].

Barrage tidal power stations can be divided into the following three basic types:

Single-reservoir unidirectional power station: there is only one reservoir, and power is generated only during flood or ebb tides, such as at the Shashan Tidal Power Station in Wenling City, Zhejiang Province, China (Figure 9a).

Single-reservoir bidirectional power station: there is one reservoir that can generate power during both the flood and ebb tides, except when the water levels inside and outside the reservoir are the same, such as the Jiangxia Tidal Power Station in Wenling City, Zhejiang Province, China (Figure 9b).

Double-reservoir bidirectional power station: There are two reservoirs, one filled with water during the flood tide as the upper reservoir, and the other releasing water during the ebb tide as the lower reservoir. The turbine generator units are located within the dam, separating the two reservoirs, and the two reservoirs maintain a water level difference, allowing power generation throughout the day (Figure 9c) [56,57].

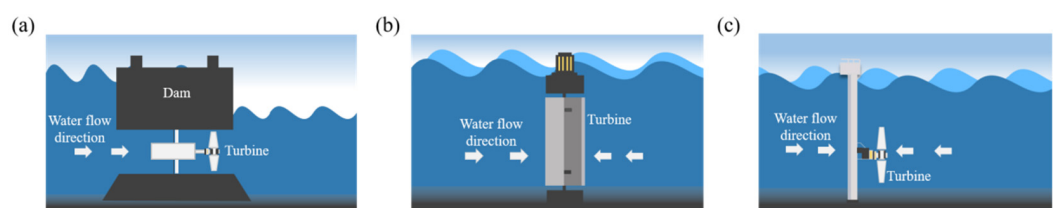


Figure 9. (a) Single-reservoir unidirectional power station, (b) single-reservoir bidirectional power station, (c) double-reservoir bidirectional power station.

2. Open-type tidal power station

To avoid the disadvantages of barrage tidal power stations, such as occupying coast-lines and estuary enclosures, domestic and international research has turned to open-type

tidal energy technologies in recent years, such as tidal lagoons and dynamic tidal energy. Open-type tidal energy adopts underwater or floating turbines with buoys and mooring systems to generate electricity, which is flexible, environmentally friendly and easy to maintain, but is greatly affected by tidal fluctuations, and suffers from shortcomings such as corrosion of equipment, attachment of organisms and low conversion efficiency [58].

Barrage tidal energy generation technology has reached a maturity level 9, and the development and construction of tidal power stations are mainly limited by factors such as the occupation of coastlines and their impact on the marine ecological environment. Open-type environmentally friendly tidal energy technologies have promising application prospect [59–61].

2.3.2. Characteristics of Tidal Energy Technology

Tidal energy is one of the most important renewable energy sources. As a green energy source, it has the following advantages. First, tidal energy is a renewable resource with a large reserve and low operating costs, and it has a minimal environmental impact, with no emissions of exhaust gases, waste, or wastewater during power generation. Second, the reservoirs for tidal power are built using estuaries or bays, and they do not occupy large areas of land, such as river hydropower stations or thermal power stations. Third, tidal power generation is not affected by hydrological factors, such as floods or dry seasons, and the dams of tidal power stations are lower, easier to construct, and require less investment [62,63].

Tidal energy power generation also has disadvantages. For example, tidal energy power generation is unstable, and tidal energy mechanical and electrical equipment often come into contact with seawater, salt mist, and marine organisms, which call for anti-corrosion and anti-fouling technologies. Tidal power plants also have some environmental impact issues: tidal power stations can change the tidal range and tidal currents, as well as the temperature and water quality of the seawater, which may bring adverse effects on groundwater and drainage, and can also cause coastal erosion. Tidal power stations would also affect the growing environment and survival of bird and fish [64].

2.3.3. Current Status of Tidal Energy Applications

The La Rance power station in France, built in 1966 (240 MW) (Figure 10a), and the Sihwa Lake tidal power station in South Korea, built in 2011 (254 MW) (Figure 10c), are the two tidal power stations currently in international operation. Both use single-bulb Francis turbine units that exceed 20 MW as show in Table 4 [65,66].

Table 4. Domestic and international tidal energy power generation devices and parameters. Adapted from refs. [65–69].

Technical Institute	Project Name	Installation Time	Installed Capacity	Operation Mode	Rated Power
France	La Rance power station in France	1966	240 MW	Single-reservoir bidirectional	10 MW
China	Zhejiang Jiangxia tidal test power station	1980	4.1 MW	Single-reservoir bidirectional	0.5 MW
Korea	Sihwa Lake power station in South Korea	2011	254 MW	Single-reservoir unidirectional	—

In addition to traditional barrage tidal energy technology, research institutions in countries such as the UK and Netherlands have conducted research on open-type tidal energy development and utilization technologies, proposing new types of tidal energy technologies with environmentally friendly characteristics such as tidal lagoons and dynamic tidal power (DTP).

The tidal power stations currently in operation in China are the Jiangxia Tidal Experimental Power Station and Haishan Tidal Power Station, both located in Zhejiang Province (Figure 10b). The Jiangxia Tidal Power Station, with a total installed capacity of 4.1 MW, has been operating for over 40 years and currently ranks third in the world in terms of installed capacity [67].



Figure 10. (a) La Rance tidal power station in France, (b) Jiangxia tidal experimental power station in Zhejiang, (c) Sihwa Lake tidal power station in South Korea. Adapted from refs. [68,69].

2.4. Temperature Difference Energy

Temperature difference energy, also known as ocean thermal energy, refers to the heat energy stored in the temperature difference between surface seawater and deep seawater. The utilization of this heat energy can achieve a thermodynamic cycle and generate electricity [70,71].

2.4.1. Classification of Temperature Difference Energy

Ocean thermal energy conversion (OTEC) is a renewable energy technology that utilizes the temperature difference between the ocean's surface warm water and deep cold water to generate electricity. OTEC includes three conversion methods: open, closed and hybrid cycle (Figure 11) [72].

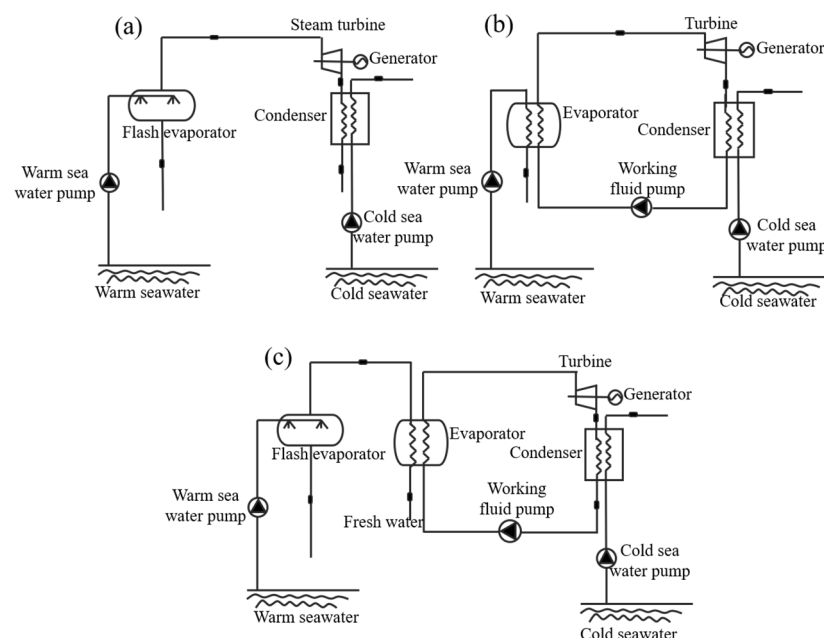


Figure 11. (a) Open cycle, (b) closed cycle, (c) hybrid cycle.

1. Open cycle

In the open-cycle conversion process, warm surface seawater is instantaneously vaporized in a vacuum chamber. Steam acts as the cycle working fluid, which passes through the turbine and is then condensed by cold deep seawater. Through an open cycle, desalinated water can be obtained as a byproduct of OTEC power generation [71].

2. Closed cycle

The thermal efficiency of the closed-cycle was higher than that of the open-cycle. In the closed cycle, warm surface seawater is drawn into a heat exchanger to vaporize the working fluid (such as ammonia, propane, or chlorofluorocarbons), producing high-pressure steam that drives the turbine. The steam is then condensed back into a liquid state by cooling with seawater. Closed-cycle turbines are smaller than open-cycle turbines because they operate at higher working pressures with secondary working fluids [73,74].

3. Hybrid cycle

The hybrid cycle combines the working characteristics of open and closed cycles using instantaneously evaporated seawater vapor as the heat source and ammonia or other media as the working fluid for the closed cycle [75].

Both the Guohai cycles and the Uehara cycle are circulatory systems used for ocean temperature difference power generation. The Guohai cycles mainly utilizes warm water pumps to transport seawater with higher surface temperature to the evaporator, where liquid ammonia absorbs the energy from the warm seawater and then boils into ammonia gas, which pushes the turbine to rotate and work, and then enters the condenser where the gas is condensed by the cold seawater in deep layers into liquid ammonia. Then the liquid is pumped back to the evaporator and circulates in a closed loop. The Uehara cycle is a mixture of ammonia and water as the working medium, by linking the two circulatory systems, with the help of surface seawater heat to make the ammonia boil, and the ammonia steam to drive the turbine to generate electricity. Ammonia vapor is cooled by the deep seawater to become a liquid again, and the difference in seawater temperature will be converted into electricity [76,77]. The problem of power cycle technology for OTEC has already been solved. In terms of cycle efficiency metrics, the Uehara cycle, which is widely applied internationally, has an efficiency of approximately 4%, whereas the Guohai cycle developed by China has superior efficiency compared to the Uehara cycle.

2.4.2. Characteristics of Temperature Difference Energy Technology

The energy for OTEC power generation primarily comes from the average annual temperature difference of approximately 20 °C between the surface seawater and the undersea water [78]. This method of power generation is clean, environmentally friendly and green, with no emissions of carbon dioxide or other harmful gases throughout the process. The power generation from OTEC has minimal fluctuations, high equipment utilization rates and stable power output. Moreover, the conversion process does not require mechanical moving parts or additional drives and transmission systems, thus avoiding vibrations and noise. Ocean thermal energy power generation also has some beneficial environmental effects. For example, they can pump nutrient-rich deep-sea water into the upper layers, which is advantageous for the growth and reproduction of marine organisms.

The biggest challenges in OTEC power generation are small temperature differences and low energy density. The key to improving OTEC conversion is to enhance the heat and mass transfer technologies. The power generation efficiency is relatively low, generally not exceeding 40%.

2.4.3. Current Status of Temperature Difference Energy Application

High-efficiency aerodynamic turbines are the central equipment in OTEC systems. Mainstream research focuses on optimizing the aerodynamic characteristics of turbines and sealing studies to achieve the optimization of high-efficiency turbines under small temperature differences. The technical bottlenecks for the large-scale application of ocean thermal energy include high power, small temperature differences, high-efficiency tur-

bine technology, cold seawater pipe materials, manufacturing and marine engineering application technology.

OTEC power stations have been constructed worldwide as show in Table 5. For instance, Japan’s 50 kW OTEC integrated utilization power station and the United States’ 100 kW OTEC power station have been in operation for many years (Figure 12). South Korea has conducted offshore test of a 1 MW OTEC power generation system, achieving a power generation capacity of 370 kW under sea trial condition. Concurrently, the United States and Japan have initiated research and demonstration of comprehensive utilization technologies such as OTEC cold seawater aquaculture and refrigeration, whereas India has completed the construction of a demonstration OTEC desalination power station.



Figure 12. 50 kW OTEC demonstration power station in Okinawa, Japan. Adapted from ref. [79].

Table 5. OTEC power generation devices and parameters. Adapted from refs. [79–81].

Technical Unit	Project Name	Installation Time	Installed Capacity
Okinawa, Japan	50-kW OTEC demonstration power station in Okinawa, Japan	2013	50 kW
China Geological Survey Guangzhou Marine Geological Survey, Guangzhou, China	20-kW ocean floating thermoelectric power generation device	2023	20 kW
Zhanjiang Bay Laboratory, Zhanjiang, China	50-kW temperature difference energy generation system onshore joint commissioning	2023	50 kW

On 17 August 2023, the domestic first set of “50-kW OTEC power generation system onshore joint commissioning” undertaken by the Zhanjiang Bay Laboratory was successfully completed at the Longwangwan Park of the laboratory (Figure 13). This marks an important progress in China’s ocean thermal energy research from theoretical studies to practical applications [80].

In September 2023, a 20-kW marine floating OTEC power generation device developed by the Guangzhou Marine Geological Survey of the China Geological Survey successfully completed its first sea trial aboard the “Haiyang Dizhi 2” vessel in the South China Sea (Figure 13). The trial was conducted in an area with a water depth of 1900 m in the South China Sea and a total power generation time of 4 h 47 min, achieving a maximum power output of 16.4 kW. This marks the first time that China has achieved principal verification and engineering operation of OTEC power generation under ocean conditions, signifying a

crucial step for China in the development and utilization of ocean thermal energy, from land-based testing to offshore engineering applications [81].

At present, the thermal efficiency of the ocean temperature difference energy thermal cycle is still at a relatively low level. The efficiency of the traditional Rankine cycle is about 3%, and although it has been raised to more than 5% in the Uehara cycle and the Guohai cycles through ameliorative measures, the overall efficiency still needs to be improved.

The reasons for this are as follows. The first is that the thermodynamic limitation, the temperature difference energy conversion process follows the Carnot cycle principle, and its thermal efficiency is proportional to the temperature difference between the low temperature heat source and the high temperature heat source. And the temperature difference between the surface layer of the ocean and the deep seawater is usually small, usually around 20 °C, which limits the theoretical thermal efficiency. Secondly, in terms of heat exchange loss, in the actual temperature difference energy conversion system, the heat exchanger is the key component, responsible for realizing the transfer of heat energy. However, due to the efficiency problem of the heat exchanger and the various heat losses existing in the system, such as heat dissipation from piping and heat dissipation from the surface of the equipment, the actual conversion efficiency is much lower than the theoretical value. Finally, there are issues of system design and operation, such as the selection of the working fluid, the size of the heat exchange area, and the pressure and temperature control of the system, if which is not properly designed, can lead to an increase in energy loss and a decrease in thermal efficiency [82,83].

Representative OTEC Devices

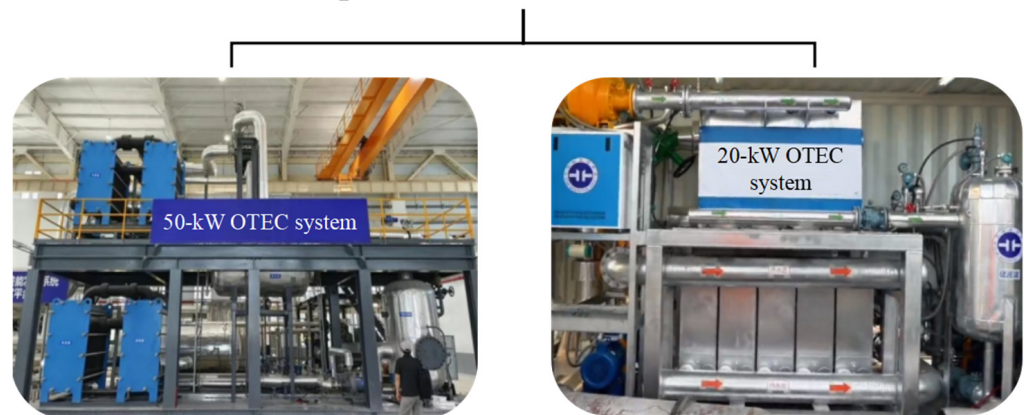


Figure 13. 50-kW OTEC power generation system onshore joint commissioning (left in the figure), 20-kW marine floating OTEC power generation device (right in the figure). Adapted from ref. [83].

2.5. Salinity Gradient Energy

In estuaries where rivers encounter the sea, there is a difference in salinity between freshwater and seawater. Seawater has osmotic pressure against fresh water as well as concentration gradient energy, such as dilution heat, absorption heat and concentration difference potential energy, which can be utilized for conversion into electrical energy [84].

2.5.1. Classification of Salinity Gradient Energy

Pressure-retarded osmosis (PRO) and reverse electrodialysis (RED) are representative methods currently used to utilize salinity gradient energy (Figure 14) [85,86].

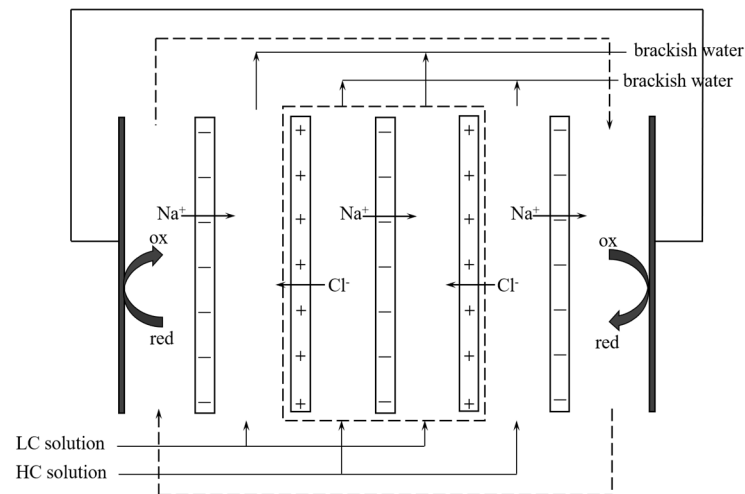


Figure 14. Schematic diagram of the RED principle.

1. Pressure-Retarded Osmosis

Pressure-retarded osmosis, first proposed in the 1970s, utilizes the osmotic pressure generated between two liquids with different salinities to convert chemical potential energy into a pressure difference chemical reaction. Seawater and freshwater have a strong mixing tendency. Before entering the PRO membrane module, seawater is pressurized to approximately half of the osmotic pressure (approximately 1.2 to 1.3 MPa). In the membrane module, freshwater passes through a thin film into pressurized seawater. The resulting brackish water is divided into two parts, with one third used for power generation by a turbine and the remaining portion used to pressurize the newly entering seawater through a pressure exchanger [87].

2. Reverse electrodialysis

Reverse electrodialysis (RED) utilizes the chemical potential difference between seawater and freshwater. Seawater and freshwater come into contact through a series of alternating cation- and anion-exchange membranes. Voltage is generated on each reverse osmosis membrane, and the total voltage of the entire system is the sum of the chemical potential differences across all membranes [88,89].

2.5.2. Characteristics of Salinity Gradient Energy

Salinity gradient energy is a renewable energy source with the highest energy density among ocean energies, and many countries in the world are conducting research on oceanic salinity gradient energy, although this field is generally in its infancy. Overall, salinity gradient energy has the following advantages. First, the power generation potential is enormous due to the salinity differences between freshwater and saltwater in the ocean, which are predictable and stable. Salinity gradient energy is highly efficient, and with proper system design and working principles, high energy conversion efficiency can be achieved. Additionally, the process of salinity-gradient energy generation does not produce greenhouse gases or other pollutant emissions [90,91].

Salinity gradient energy also has certain disadvantages compared with other forms of ocean energy. For instance, it suffers technical challenges, and the technology for harnessing salinity gradient energy from seawater is still in its early stages of development, encountering issues such as high costs, low energy density and material performance. However, as salinity gradient energy relies on the salinity difference between freshwater and saltwater, it can only achieve significant salinity differences in specific geographic locations (such as estuaries and the confluence of lakes and oceans), which also leads to multiple challenges in the scaling up of salinity gradient energy. On the technical level, the

conversion efficiency is low, and the performance of the key materials is unsatisfactory, and the semi-permeable membrane is easy to be contaminated and aging. At the same time, the system integration is complex, and the synergistic control of the components is difficulty. On the economic level, high cost of construction, equipment maintenance lead to a long return on investment cycle, results into the difficulty to attract large-scale investment. On the environmental level, large-scale development of salinity gradient energy will change the salinity of the water body and the water flow, threatening biodiversity, and the improper treatment of concentrated brine will also bring the risk of estuaries and other special areas. Moreover, the equipment is hardly adapted to complex environment, which increases the cost and risk of maintenance [92].

2.5.3. Current Status of Salinity Gradient Energy Application

The world's first salinity gradient power demonstration system was a 10 kW salinity gradient demonstration device built by Norway's Statkraft in 2009 (Table 6), utilizing PRO technology [93]. In October 2013, the Dutch company REDStack and Japan's Fujifilm Corporation collaborated to build a 50 kW salinity gradient demonstration power station based on the RED principle at the Afsluitdijk sea barrier in the Netherlands. Currently, this is the only salinity gradient demonstration power station in operation [94].

At present, due to the limit of mechanical properties, stability performance, ion selectivity and the shortcomings of materials, such as ion-selective membranes used for salt differential energy power generation, the development and utilization of salt differential energy is restricted. Conventional ion-selective membrane materials, such as some polymer membranes, have certain limitations in their molecular structure and properties. For example, they have limited mechanical strength and are susceptible to be damaged by mechanical stress during long-term application. At the same time, the size and shape of their ion-transport channels are less than optimal, resulting in a mutually constraining relationship between ion selectivity and permeability. Salinity gradient energy generation usually needs to be applied in complex environments such as seawater and river water, where factors such as salinity, acidity and alkalinity, and temperature can have an impact on membrane materials, accelerating membrane aging and performance degradation.

Table 6. Salinity gradient energy generation devices and parameters. Adapted from refs. [93,94].

Technical Unit	Project Name	Installation Time	Installed Capacity	Working Principle
Statkraft, Oslo, Norway	10-kW salt difference energy demonstration device	2009	10 kW	PRO
REDStack, Sneek, The Netherlands	50-kW RED device	2013	50 kW	RED

3. Current Development Status of Ocean Energy Industry

By the end of 2020, the global cumulative installed capacity of ocean energy had exceed 515 MW. More than 98% of this capacity is in operation with 501.5 MW from two large tidal barrage projects. By 2024, the newly added global installed capacity for ocean power generation is 624.6 MW, which is mainly located in Europe, particularly along the coast of Scotland.

According to IRENA forecasts, the global installed capacity of ocean energy is expected to reach 10 million kW by 2030. In recent years, countries in Europe and the United States have increased their support for ocean energy technology and demonstration, aiming to gain pioneering advantages in the international ocean energy industry [95,96]. For instance, the European Union (EU) has maintained its investment in ocean energy, with over EUR 850 million in public funds from 2007 to 2019, leveraging EUR 2.7 billion in private funds

for ocean energy technology research and development, demonstrations and power station construction. The United States “Marine and Hydrokinetic Program” has continued to increase its support for ocean energy technology and demonstrations, with the annual budget increasing to over USD 100 million in 2020.

China has made significant progress in the development of tidal currents and wave energy, with a cumulative installed capacity of approximately 4 MW, which accounts for approximately one-quarter of the global installed capacity for these kinds of ocean energy. The global ocean energy market is predicted to reach a scale of USD 560 million by 2029. An analysis from IRENA indicated that by 2030, the global cumulative installed capacity of ocean energy will exceed 70 GW, and it will surpass 350 GW by 2050.

3.1. Ocean Energy Industry Policy

Internationally, the European Union, United States, United Kingdom, and others are actively deploying research and development for efficient and reliable tidal currents, waves, and ocean thermal energy technologies based on the characteristics of ocean energy resources and are committed to promoting a rapid decrease in the LCOE for tidal current and wave energy. Since 2007, the European Union has provided over EUR 850 million for ocean energy technology research, development and demonstration, with approximately 87% of funds allocated to tidal current and wave energy technologies. While since 2008, the United States has provided over USD 560 million for ocean energy research and development, with approximately 60% of funds dedicated to develop tidal current and wave energy technologies. Since 2020, the U.S. Department of Energy’s annual budget for ocean energy research and development has exceeded USD 100 million, showing an increasing annual trend [97–99].

To achieve carbon neutrality goal by 2050, the European Union established the core objectives of the Green Deal in the form of law. In April 2021, the draft of the “European Climate Law” reached a provisional agreement and was submitted to the European Conference to ensure the development targets proposed by the “Offshore Renewable Energy Strategy”: 60 million kW of offshore wind power and 1 million kW of ocean energy will be installed by 2030, and 300 million kW of offshore wind power and 40 million kW of ocean energy will be installed by 2050 (Table 7). In 2021, the European Ocean Energy Industry received an investment of 70 million euros, representing a year-on-year increase of 55% [100].

The United States has repeatedly revised the relevant legislation to support the development of ocean energy. In February 2021, the National Renewable Energy Laboratory released a report titled “Opportunities for Ocean Energy Development in the United States.” In April 2021, the National Hydropower Association released the “Marine Energy Industrialization Strategy”, which set forth the medium- and long-term development goals for U.S. ocean energy: to reach 50 MW by 2025, 500 MW by 2030, and 1000 MW by 2035. In recent years, the United States has successively amended several acts, including the Marine Energy Research and Development Act (2019), Marine Clean Energy Act (2019), and Infrastructure Investment and Jobs Act (2021), to increase investment and policy incentives about ocean energy research and development, promoting the development of ocean energy technology towards low-cost and large-scale deployment [101].

The UK Renewable Energy Association has appealed to the goal that ocean energy would be competitive with other renewable-energy generation technologies by 2030. In May 2021, the UK Renewable Energy Association published a report suggesting that the UK government propose renewable energy development targets for 2030 at the 26th United Nations Climate Change Conference: 40 million kW of offshore wind power (including

2 million kW of floating wind power), 5 million kW of renewable energy for hydrogen production, and 1 million kW of ocean energy.

China's related ministries continue to support the independent innovation and demonstration application of ocean renewable energy technology, introduce policy measures and launch key national research as well as development programs for ocean renewable energy. By 2021, the national and related ministries had issued multiple policies involving the utilization of ocean renewable energy, including the "14th Five-Year Plan for National Economic and Social Development of the People's Republic of China", the "Action Plan for Carbon Dioxide Peaking Before 2030", and "Opinions on Comprehensively, Accurately, and Fully Implementing the New Development Philosophy to Do a Good Job in Carbon Peaking and Carbon Neutrality Work", continuously strengthening guidance on the development of ocean renewable energy utilization.

In terms of investment incentives, the European Union has provided strong financial support for the development of marine renewable energies through the establishment of a special fund, while the European Union has also provided low-interest loans through the European Investment Bank (EIB), which further reduces the cost of financing for enterprises and improves the economic viability of projects. The United States, on the other hand, has attracted private capital into the marine renewable energy sector through policies such as tax credits and accelerated depreciation. Enterprises developing and utilizing solar, wind, geothermal and tidal power generation are given a 25 per cent corporate income tax credit on the amount of investment, as well as a 30 per cent investment tax credit on the cost of equipment. China has established a dual market mechanism of "Green Power Trading + Carbon Trading", which provides an additional source of revenue for marine renewable energy projects. Through green power trading, marine renewable energy power generators can sell their green power certificates to companies that in need of them, gaining additional income. Meanwhile, companies can sell their reduced carbon emission credits, realizing the value of their carbon assets [102].

In terms of tariff formation mechanism, the United Kingdom has implemented the joint mechanism of Contract for Difference (CfD) and capacity market, which provides a stable tariff guarantee for marine renewable energy power generation. Under the CfD mechanism, the government signs long-term contracts with power generation companies on a fixed price for electricity. The U.S. adopts a compound pricing model of "fixed price + floating premium", which takes into account the cost recovery and market risk of power generation enterprises. The European Union is committed to promoting the construction of cross-border power trading platforms, promoting the consumption of offshore wind power, and forming reasonable electricity prices through market mechanisms [103].

Under the current global economic and political climate, feed-in tariffs (FIT) and subsidy policies are still feasible. In the economic aspect, policies can guide capital investment in renewable energy, promote energy transformation, drive the development of new energy industry and upstream and downstream, generate employment opportunities, boost the economy, and costs to achieve grid parity can be reduced in the long run with the expansion of industrial scale and technological progress. In the political aspect, FIT and subsidy can help countries to fulfill international climate commitments such as the Paris Agreement and strengthen international cooperation. At the same time, they are in line with the domestic energy strategy to optimize energy structure and ensure energy security. However, this policy is also facing challenges. There are problems such as heavy financial burdens and inefficient subsidies due to imperfect market mechanisms, resistance from traditional energy interest groups, international trade frictions and protectionism, which have affected the formulation, implementation and effectiveness of the policy.

The ocean energy industry policies introduced by governments around the world aim to ensure energy and environment security which needs clean energy diversification, and promote the sustainable development of economics and energy, bringing extensive social and scientific research benefits.

Table 7. International Ocean Energy Policy.

Region	Development Goals	Investment Incentives	Tariff Formation Mechanism
European Union	By 2030, the installed capacity of marine energy will reach 1 million kW. By 2050, 40 million kW.	Establishment of a special fund; low-interest loans through the European Investment Bank (EIB)	Promoting the construction of cross-border electricity trading platforms
United States	By 2025, the installed capacity will reach 50,000 kW; by 2030, 500,000 kW; by 2035, 1 million kW.	Use policies such as tax credits and accelerate depreciation to attract private capital.	Adoption of “Fixed Price + Floating Premium” Composite Pricing Model
United Kingdom	By 2030, the installed capacity of marine energy will reach 1 million kW.	—	Implementation of a joint mechanism for Contracts for Difference (CfD) and capacity markets
China	By 2030, 400,000 kW of ocean energy will be installed.	Dual market mechanism “Green Power Trading + Carbon Trading”	—

3.2. Maturity of Marine Energy Industry

Among the different types of marine energy, tidal energy technology has the highest level of maturity, as the barrage tidal energy technology achieving commercial operation decades ago. Current tidal energy technology is developing rapidly, with countries such as the UK, the Netherlands, and France achieving grid-connected operation of MW-class units, which are very close to industrialization. Wave energy power generation technology with different principles are at the stage of demonstrations in real sea condition. There are a few demonstration projects for power generation and comprehensive utilization of ocean thermal energy conversion technology, and only a small number of demonstration projects for salinity gradient energy [104].

China’s ocean energy has developed from the equipment research to the application demonstration phase. According to the International Energy Agency’s estimates, China has about 1.03 million kW of ocean energy generation capacity in operation or under construction, with wave energy accounting for 1260 kW, 4730 kW for tidal current energy, 4350 kW for tidal energy, and the annual grid-connected electricity generation is approximately 7 GWh [105].

Wave energy is considered one of the most reliable sources of energy because it can be predicted with considerable accuracy, with a power generation potential of approximately 29,000 TWh/yr [57]. In the worldwide, there are more than 200 different wave energy technological concepts. At present, wave energy lacks clear technological integration, and most devices are of the point-absorption type. Wave energy power generation technology has entered the pre-commercialization phase, with a global installed capacity of 2.5 MW (Table 8). However, the size and power rating of wave energy devices are continuously increasing, and approximately 100 MW of power is expected to be installed in the next few years.

Tidal power generation is currently a key field in the development and utilization of ocean renewable energy resources, with equipment technology nearly maturity and many pre-commercial projects underway. Europe is home to 41% of current global tidal energy developers, primarily located in the Netherlands and France. Other countries such as the United States, the United Kingdom and Norway also have high involvement in tidal current energy equipment technology.

Tidal energy is one of the most advanced and commercially available form of ocean energy. Tidal energy technology accounts for the majority of the globally installed ocean energy capacity of approximately 512 MW. Owing to the theoretically low power-generation potential of tidal energy with only approximately 1200 TWh/yr, only a few countries have deployed this technology.

Among all ocean energies, OTEC possesses the largest resource potential, with an annual capacity of approximately 44,000 TWh. By 2021, more than 20 commissioned OTEC projects are under construction or planned, with rated power ranging from 15 to 20 MW and a total installed capacity exceeding 150 MW. Countries such as the United States, Japan, France, South Korea and China have conducted extensive research on OTEC technology and built demonstrated OTEC power stations.

Currently, the maturity of salinity gradient energy technology is the lowest in marine energy, and it is still in the laboratory research stage. Countries such as the United States, the Netherlands, Norway and Sweden are relatively advanced in research on salinity gradient energy technology, whereas China and Japan have also conducted related studies. Currently, the 50 kW pilot project of the Dutch company REDstack is the world's first salinity gradient power generation facility and has been operating continuously since 2014.

Table 8. Comparison of technological maturity of international ocean energy equipment. Adapted from ref. [106].

Classification	Global Installed Capacity (MW)	Typical Project	The Maturity of Technology
Tidal energy	521.5	La Rance Power Station in France	Commercialization stage
Tidal current energy	10.6	MeyGen	Pre commercialization stage
Wave energy	2.31	Nankun Express	Research–Pre commercialization Phase
Temperature-difference energy	0.23	50-kW OTEC Demonstration Power Station	Engineering Demonstration–Pre Commercialization Stage
Salinity gradient energy	0.05	Dutch 50-kW RED device	Study phase

3.3. Economic Analysis of Ocean Energy

Countries such as the United Kingdom and Canada, have been promoting the large-scale development of ocean energy through the establishment of incentive-based FIT policies. Since 2015, the UK government has supported renewable energy generation technologies through a CfD policy. Nova Scotia, Canada, has established a fixed FIT policy for tidal energy that is applicable to developers of single generator units or arrays exceeding 500 kW. Both domestic and international technologies can be applied if power stations are deployed in the province. For approved tidal energy demonstration projects, the electricity price support period can be as long as 15 years. For projects with an annual power generation lower than 16 million kWh, electricity was purchased at a rate of 530 Canadian dollars per MWh (approximately 2.85 CNY per kWh), and any excess was purchased at a rate of 420 Canadian dollars per MWh (approximately 2.26 CNY per kWh).

The construction costs of ocean energy devices are high because of various factors. For example, wave energy devices need to be resistant to wind and waves, corrosion and maintenance difficulties, thus the construction and maintenance costs are both high. Tidal energy equipment submarine construction is complex, but the maintenance cost is slightly lower than that of wave energy. Tidal energy initially needs to invest in large-scale hydroelectric buildings and generator sets, and the later maintenance costs are lower.

Temperature difference energy relies on deep-sea pipelines and complex heat exchange systems, and immature technologies results in the low energy efficiency and high cost. Salinity gradient energy is still in the experimental stage, and the research and development cost focuses on semi-permeable membrane materials and system optimization, and the limited application scale further restricts the cost reduction. According to IRENA estimates, the current levelized cost of energy (LCOE) for tidal energy is approximately USD 0.20–0.45 per kWh, and for wave energy, it is about \$0.30–0.55 per kWh. The LCOE for tidal energy is expected to reach USD 0.11 per kWh between 2022 and the early 2030s, while wave energy is predicted to reach USD 0.22 per kWh by 2025 (Table 9) [92,107,108].

Table 9. Comparison of LCOE for ocean energy equipment technologies. Adapted from refs. [91,106,107].

Equipment Technology Type	LCOE/(\$/kWh)
Wave energy	0.30–0.55
Tidal current energy	0.2–0.9
Tidal energy	0.20–0.45
Temperature-difference energy	0.03–0.38
Salinity gradient energy	0.11–2.37

3.4. Operation and Maintenance of Ocean Energy

The operation and maintenance (O&M) of ocean energy is critical to ensure the long-term and stable operation of ocean energy equipment. This involves the installation, debugging, monitoring, maintenance, and repair of equipment. Ocean energy devices are typically deployed in harsh marine environments and thus require a high level of reliability and durability.

The intelligent operation and maintenance (IOM) of ocean energy is rapidly developing and includes technologies such as smart sensing, edge computing, and robotics. These technologies enable intelligent perception, monitoring, analysis and decision making for the operation and maintenance of ocean energy.

Preventive maintenance strategies involve regular inspections of ocean energy power generation equipment to identify potential malfunction promptly. Based on historical operational data and experience, preventive repairs have been performed to reduce the occurrence of failures. A maintenance plan for the equipment is established, including cleaning, lubrication and tightening, to ensure that the equipment is in good condition.

Fault diagnosis and troubleshooting methods involve monitoring the operational parameters and abnormal signals of the equipment to identify the type and cause of equipment failure. The faults were locked with fault diagnosis techniques and tools, and the specific failure sites were determined. Depending on the category and location of the fault, the corresponding repair measures are taken to resolve these faults promptly.

The application of remote monitoring technology, such as THE Internet of Things (IoT) technology, enable real-time remote monitoring of ocean energy power generation equipment and capture operational data and status information. By processing and analyzing data, useful information can be extracted to provide a basis for fault diagnosis and preventive maintenance. Through a remote monitoring system, the equipment can be remotely controlled and operated to achieve remote diagnosis and maintenance.

4. Discussion and Analysis

4.1. Ocean Energy Conversion Efficiency

In marine energy conversion devices, the conversion efficiency and single unit power of each type of energy have their own characteristics. The conversion efficiency of wave energy is generally around 30–50%. The efficiency of different types of devices varies

with wave characteristics, device structure and other factors, and the single-unit power is relatively small, which is usually between dozens of kilowatts and hundreds of kilowatts. Tidal energy conversion efficiency is high with a range between 40–60% due to the stable flow rate. The high energy density and the mature conversion equipment technology, and the single-unit power is between dozens of kilowatts and megawatts. Tidal energy power generation technology tend towards maturity, and the efficiency can reach 70–80% which is similar to traditional hydropower. The single unit power can reach up to megawatts or even higher. Temperature difference energy conversion efficiency is low with a range between 3–7%, and energy density is low as there are still technical problems need to be solved, but the single unit power can be from dozens of kilowatts to a few megawatts. Salt difference energy theoretical conversion efficiency is between 20–30%, but due to the problems such as semi-permeable membranes, the efficiency is only 10%. The current salt difference energy generations, which are mostly in the experimental demonstration stage, are relatively small, and generally from a few watts to tens of kilowatts [109].

4.2. The Bottlenecks of the Development of Ocean Energy

In recent years, significant progress has been made in ocean energy power generation with experimental power stations to be put into commercial operations. However, owing to the harsh operating environment and difficulties in operation and maintenance, there are still technical and policy challenges in the process of scaling-up.

1. First, ocean energy encompasses a wide variety of complex and diverse technologies that pose significant challenges to research and development. Issues related to grid connections, operation and maintenance under harsh maritime conditions are particularly pronounced. There is a lack of testing of equipment functionality, performance and reliability under real ocean environmental conditions. At the same time, with the advancement of technology, ocean energy can also be developed in areas with harsh marine conditions, and there is an urgent need to solve the problems in wind and wave-resistant floating body technology, anti-marine corrosion technology and bio-attachment technology.
2. In the aspect of economy, the operation and maintenance of ocean energy is difficult, and requires substantial investment in technological research, development and equipment manufacturing. Moreover, ocean energy technology is not yet mature and has less price competitiveness with conventional energy generation.
3. In terms of policy, incentive policies during the industrial development of ocean energy are not well developed, and the incentives and support measures are insufficient to meet the growth needs of the ocean energy industry. It still needs a considerable amount of time to achieve a cost-competitive advantage for grid connection. Additional funds for renewable energy tariffs mainly are restricted to wind and solar energy, and do not cover ocean energy.

4.3. Trends of Ocean Energy Development

With continuous promoted by institutions and researchers, ocean energy technology is constantly developing to be mature, and the initial construction, operation and maintenance costs also have opened up a channel for reduction. In the future, ocean energy may exhibit the following developmental trends:

1. Development of distributed or upsized systems. To meet the demand for large-scale power generation, ocean energy plants will adopt the development path of arrayed distributed or upsized units. For example, wave energy has already shown a development route towards array-type and MW-level units.

2. Development of multifunction-coupled systems. To make full use of ocean resources, ocean energy has been integrated with fisheries, offshore mining, wind power generation and photovoltaic power generation to form a complementary pattern of industrial and multi-energy generation.
3. Focus on power supply for remote islands. In the mid-to-long term, the cost of generating power for ocean energy is higher than that of mature power generation technologies such as thermal power. Therefore, they cannot be massively grid-connected to supply power to large cities in the short term. However, it is suitable for islands that are far from the mainland power grid and do not have thermal power plants. Compared with the cost of diesel power generation (including fuel and transportation costs) on most islands, ocean energy power generation has an economic advantage and is suitable for providing electricity to remote islands.

Distributed ocean energy systems and multi-energy complementary systems have a very bright future, and with the growing global demand for clean energy and the continuous advancement of technology, these two areas are expected to occupy an important position in the future energy market. Taking Qingdao 500 kW ocean energy independent power system demonstration project as an example, the demonstration project is led by China National Offshore Oil Corporation, with ocean current energy device as the main part, supplemented by wind energy and solar energy, including three sets of 300 kW tidal current energy device, as well as 150 kW wind turbine and 50 kW solar energy device, which is focused on solving the bottlenecks such as poor reliability and maintainability of the ocean energy equipment, and unstable power generation, etc., and realizes independent, micro-grid and micro-grid system of ocean energy, which is expected to occupy the future energy market. It realizes independent, micro-grid and intelligent power supply for ocean energy.

In terms of market potential, according to the International Energy Agency (IEA), the global ocean energy market is expected to exceed \$50 billion by 2030, with a compound annual growth rate of more than 15%. In terms of multi-energy complementary systems, its share in the overall energy market is expected to exceed 30%. With the diversification of energy demand and the improvement of energy stability requirements, multi-energy complementary system can integrate various forms of energy, realize complementary advantages, which can meet the needs of different users, so it has huge market development potential. For example, the “Huanghai No. 1” floating photovoltaic platform for wind energy integration, which is invested and constructed by Huaneng Shandong Company and independently researched and developed by Huaneng Qingneng Institute, is the first set of non-waveable deep-distant sea floating photovoltaic platform in China. The platform is a truss steel structure, hexagonal in shape, with a main scale of 25 m × 25 m × 9 m, an empty ship weight of 320 tons, and a total installed capacity of 300,000 kilowatts. “Huanghai No. 1” realizes offshore wind power and photovoltaic in the same field, makes effective use of space resources, and pushes the development of offshore energy to the deep and distant sea.

In terms of technology trends, the application of nanomaterials is expected to significantly improve equipment efficiency. Nanomaterials have unique physical and chemical properties, such as high strength, high toughness, high conductivity and corrosion resistance, etc., and their application in ocean energy generation equipment can effectively improve the energy conversion efficiency and reliability of the equipment.

Blockchain technology will also play an important role in the field of energy transactions. Blockchain has the characteristics of decentralization, non-tampering, traceability, etc., which can provide a safe, transparent and efficient platform for energy transactions. In distributed ocean energy systems and multi-energy complementary systems, real-time

monitoring, metering and trading of energy can be achieved through blockchain technology, optimizing the allocation of energy resources and improving ocean energy utilization efficiency [110–112].

4.4. *The Ocean Energy and Sustainable Development*

As an important component of renewable energy, ocean energy, such as tidal energy and wave energy, has zero or low-carbon emission characteristics and can replace fossil energy, significantly reducing greenhouse gas emissions in the energy field and helping to achieve the “dual-carbon” goal. Its development process emphasizes ecological protection and is coordinated with the sustainable use of marine ecosystems. Not only that, with the advancement of technology, the leveled cost of electricity of ocean energy continues to decrease, and gradually become competitive in the market. At the same time, ocean energy can drive the synergistic development of high-end equipment, marine engineering, digital technology and other fields, creating a large number of high value-added jobs. Ocean energy can provide stable power for coastal and remote islands, improve local livelihoods and narrow the energy gap between urban and rural areas. In terms of policy, countries have reduced investment risks and guided capital flows to sustainable areas through subsidy mechanisms, green finance and cross-industry collaboration [113].

The development and utilization of ocean energy has the following important significance for alleviating the global energy crisis and reducing environmental pollution:

1. Ocean energy is a clean energy that can be used to reduce pollution. As an abundant renewable resource, it provides an effective solution for transformation of energy framework. Its development and utilization can decrease the use of non-renewable resource and reduce pollution, helping to protect the ecosystem and biodiversity.
2. Developing clean energy to alleviate energy shortages. The effective development and utilization of ocean energy can not only meet the demands such as the green energy supply for offshore production activities, electricity and seawater desalination for residents on isolated islands, but can also replace fossil fuels to provide a green power for marine equipment.
3. Promoting sustainable energy development. In recent years, ocean energy has been increasingly endowed with the profound connotations of green, clean, safe, and sustainable. The development and utilization of ocean energy are important ways to conduct and interpret the new concept of ocean development. With technological development, the utilization of ocean energy is expected to become a new hotspot for the green and sustainable development of the ocean economy.

4.5. *Suggestions for the Development of Ocean Energy*

1. Governments should lay down top-level design for the guidance and promotion of ocean energy. The scale of financial support for ocean energy should be extended and the support methods should be optimized. Adjustments to ocean energy electricity subsidy policies and the establishment of incentive-based feed-in tariff policies are required to promote the large-scale development of ocean energy.
2. Enhance reliability and efficiency of ocean energy equipment. Ocean energy technology is still in the developing stage, and the reliability and efficiency affect its market size and commercialization progress. Therefore, it is important to improve the durability, safety, operability and stability of ocean energy devices in marine extreme environments.
3. Reduce the operation and maintenance costs of ocean energy equipment. The key point of lowering the O&M costs of ocean energy is to ensure the endurance and function of ocean energy equipment in seawater. Integrated ocean energy systems

with monitoring module and automatic control module not only help to enhance the performance of ocean energy equipment but also reduce operational costs.

4. Extension the application fields of ocean energy. Applications in various fields, such as seawater desalination and cooling, hydrogen production from seawater, deep-sea development, island development and offshore energy supply should be actively extended. By constructing a multi-energy complementary ocean energy system and ocean energy transmission network on land, which can promote the clean ocean energy to be as a guarantee for remote islands and deep-sea activities.
5. Developing marine energy in remote areas. In terms of logistics, the modular equipment design is adapted to small ships, helicopters and other transportation modes, combined with intelligent remote operation and maintenance, material reserves of regional operation and maintenance centers, and training of local operation and maintenance talents, as well as reserving materials in advance and developing a local supply chain to guarantee supplies. In terms of finance, the company leverages governmental support and green financial financing, reduces costs by technological research and development, increases revenues by industrial integration, and realizes risk-sharing by using commercial insurance and risk funds.
6. Environment friendly development. The development and utilization of marine energy may have many adverse impacts on the ecological environment. For example, the noise from the operation of equipment interferes with the behaviour of marine organisms, and it also creates spatial competition with the traditional marine industry. To this end, targeted countermeasures can be taken: scientific planning and site selection, avoiding sensitive areas through comprehensive ecological assessment. Promoting technological innovation, research and development of low-noise, biophilic equipment and real-time monitoring of environmental impacts. Strictly enforcing environmental protection standards, and strengthening international cooperation to reduce the negative impacts of development activities on the ecological environment and to realize the sustainable development of the marine environment.

4.6. Initiatives to Optimize Ocean Energy Development

1. Scale development: through the plan and construction of large-scale ocean energy power generation projects to achieve scale advantages, make full use of marine resources, reduce the construction cost per unit of installed capacity, and enhance the bargaining power of operation management and equipment procurement. At the same time, promote the development of ocean energy industry clusters, promote the upstream and downstream of the industrial chain to collaborate and cooperate, share resources such as technology, talents and infrastructure, realize the specialization of division of labor, and enhance the industrial production and innovation.
2. Enhance equipment reliability: strengthen research and design on the reliability of ocean energy equipment to reduce the probability of equipment failure and maintenance costs. For example, make use of advanced sensors and monitoring technology to monitor the operating status of equipment in real time, identify potential problems in advance and carry out preventive maintenance. Meanwhile, optimize the structure and sealing design of equipment to improve its ability to withstand the harsh marine environment.
3. Improvement of conversion efficiency: strengthen research and development of more efficient marine energy conversion technologies, such as improving the design of tidal energy generators to enhance their power generation efficiency under different water speeds. Optimize the structure of wave energy conversion devices so that they can more efficiently convert the kinetic and potential energies of waves into electrical

energy, which can obtain more power output under the same conditions and reduce the cost of the unit of electrical energy.

4. Policy and market measurement: the government has introduced relevant policies such as financial subsidies, tax incentives and price support to encourage the construction and operation of marine energy development and utilization projects. It has implemented phased subsidies and risk compensation funds to reduce investment risks, promoted technology migration in the oil and shipbuilding industries, constructed regional testing centers to accelerate technology verification, and broadened financing channels with the help of carbon pricing mechanisms and green financial instruments such as blue bonds.
5. Global knowledge and resource sharing: through active international cooperation, introduce foreign advanced marine energy technology and management experience, and co-operate with international scientific research institutions and enterprises to overcome key technical problems and accelerate technological progress and cost reduction. At the same time, deeply participate in the formulation of international marine energy standards, promote the domestic industrial standards to meet international standards, enhance the versatility and interchangeability of equipment, and reduce the cost of manufacturing and maintenance.

5. Summary

Ocean renewable energy is abundant and can provide electricity to coastal areas, islands and offshore facilities. With the continuous in-depth research and demonstration application of ocean energy, the ocean renewable energy industry shows a rapid development trend. In particular, tidal energy has begun to be commercially installed on a large scale. However, some ocean energy technologies are still in the experimental stage with relatively lagging commercial applications and low industry maturity, which calls for further technological breakthroughs. This article summarizes and analyzes the developments of wave energy, tidal current energy, tidal energy, temperature difference energy and salinity gradient energy. Then the technical characteristics and current development status of ocean energy are summarized. This article also assesses the current state of industrial development and provides a general summary of the construction, operation and maintenance of marine renewable energy projects. Furthermore, the development trend and the importance of ocean energy to sustainability are illustrated. In the future, ocean renewable energy is expected to develop toward the fields of long-term maintenance-free, unmanned operation and maintenance, high reliability, highly environmental adaptability and multi-energy complementary structures. It is hoped that this article will provide references and inspiration for researchers and institutions of marine renewable energy, and contribute to the development of renewable energy.

Author Contributions: Conceptualization, X.S. and X.W.; validation, J.C., C.X. and W.X.; formal analysis, L.Y.; investigation, X.S.; resources, J.C.; data curation, W.X.; writing—original draft preparation, X.S.; writing—review and editing, J.C.; visualization, L.Y.; supervision, J.C.; project administration, C.X.; funding acquisition, X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: All authors thank ocean energy device developers for providing the data and pictures. We also thank the reviewers for their reviews and recommendations.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Gill, A.B. Offshore renewable energy: Ecological implications of generating electricity in the coastal zone. *J. Appl. Ecol.* **2005**, *42*, 605–615. Available online: <http://www.jstor.org/stable/3505894> (accessed on 20 February 2025). [CrossRef]
- Appiott, J.; Dhanju, A.; Cicin-Sain, B. Encouraging renewable energy in the offshore environment. *Ocean Coast. Manag.* **2014**, *90*, 58–64. [CrossRef]
- Wang, Z.; Cariveau, R.; Ting, D.S.K.; Xiong, W.; Wang, Z. A review of marine renewable energy storage. *Int. J. Energy Res.* **2019**, *43*, 6108–6150. [CrossRef]
- Elghali, S.E.B.; Benbouzid, M.E.H.; Charpentier, J.F. Marine tidal current electric power generation technology: State of the art and current status. In Proceedings of the 2007 IEEE International Electric Machines & Drives Conference, Antalya, Turkey, 3–5 May 2007; Volume 2, pp. 1407–1412. [CrossRef]
- Aderinto, T.; Li, H. Ocean wave energy converters: Status and challenges. *Energies* **2018**, *11*, 1250. [CrossRef]
- Sheng, W. Wave energy conversion and hydrodynamics modelling technologies: A review. *Renew. Sustain. Energy Rev.* **2019**, *109*, 482–498. [CrossRef]
- Zhang, Y.; Zhao, Y.; Sun, W.; Li, J. Ocean wave energy converters: Technical principle, device realization, and performance evaluation. *Renew. Sustain. Energy Rev.* **2021**, *141*, 110764. [CrossRef]
- Akinyele, D.O.; Rayudu, R.K. Review of energy storage technologies for sustainable power networks. *Sustain. Energy Technol.* **2014**, *8*, 74–91. [CrossRef]
- Villate, J. Situación actual de las energías marinas y perspectivas de futuro. In *Seminario Anual de Automatica, Electronica e Instrumentacion*; SAAEI: Riyadh, Saudi Arabia, 2010; pp. 11–13.
- Ilyas, A.; Kashif, S.A.R.; Saqib, M.A.; Muhammad, M.A. Wave electrical energy systems: Implementation, challenges and environmental issues. *Renew. Sustain. Energy Rev.* **2014**, *40*, 260–268. [CrossRef]
- Gaspar, J.F.; Kamarlouei, M.; Sinha, A.; Xu, H.; Calvário, M.; Fay, F.X.; Soares, C.G. Speed control of oil-hydraulic power take-off system for oscillating body type wave energy converters. *Renew. Energy* **2016**, *97*, 769–783. [CrossRef]
- Rehman, S.; Alhems, L.M.; Alam, M.M.; Wang, L.; Toor, Z. A review of energy extraction from wind and ocean: Technologies, merits, efficiencies, and cost. *Ocean. Eng.* **2023**, *267*, 113192. [CrossRef]
- Hur, D.S.; Jeong, Y.M.; Lee, J.L.; Kim, I.H.; Lee, W.D. Energy generation efficiency due to wave overtopping on floating-overflow-type wave energy converter. *J. Coast. Res.* **2018**, *85*, 1341–1345. [CrossRef]
- Falcão, A.F.O. Wave energy utilization: A review of the technologies. *Renew. Sustain. Energy Rev.* **2010**, *14*, 899–918. [CrossRef]
- Lagoun, M.S.; Benalia, A.; Benbouzid, M.E.H. Ocean wave converters: State of the art and current status, International energy conference. In Proceedings of the 2010 IEEE International Energy Conference, Manama, Bahrain, 18–22 December 2010; pp. 636–641. [CrossRef]
- Barua, A.; Rasel, M.S. Advances and challenges in ocean wave energy harvesting. *Sustain. Energy Technol.* **2024**, *61*, 103599. [CrossRef]
- Zabihian, F. *Power Plant Engineering*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2021. [CrossRef]
- López, I.; Andreu, J.; Ceballos, S.; De Alegría, I.M.; Kortabarria, I. Review of wave energy technologies and the necessary power-equipment. *Renew. Sustain. Energy Rev.* **2013**, *27*, 413–434. [CrossRef]
- Drew, B.; Plummer, A.R.; Sahinkaya, M.N. A review of wave energy converter technology. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2009**, *223*, 887–902. [CrossRef]
- Wang, C.N.; Pham, T.D.T.; Nguyen, D.B. A study of appropriate wave energy technology for sustainable development in Australia. *J. Eng. Res.* **2024**, in press. [CrossRef]
- Clément, A.; McCullen, P.; Falcão, A.; Fiorentino, A.; Gardner, F.; Hammarlund, K.; Lemonis, G.; Lewis, T.; Nielsen, K.; Petroncini, S.; et al. Wave energy in Europe: Current status and perspectives. *Renew. Sustain. Energy Rev.* **2002**, *6*, 405–431. [CrossRef]
- Leijon, M.; Danielsson, O.; Eriksson, M.; Thorburn, K.; Bernhoff, H.; Isberg, J.; Sundberg, J.; Ivanova, I.; Sjöstedt, E.; Ågren, O.; et al. An electrical approach to wave energy conversion. *Renew. Energy* **2006**, *31*, 1309–1319. [CrossRef]
- Loh, T.T.; Greaves, D.; Maeki, T.; Vuorinen, M.; Simmonds, D.; Kyte, A. Numerical modelling of the WaveRoller device using OpenFOAM. In Proceedings of the 3rd Asian Wave & Tidal Energy Conference, Singapore, 25–27 October 2016.
- Clemente, D.; Rosa-Santos, P.; Ferradosa, T.; Taveira-Pinto, F. Wave energy conversion energizing offshore aquaculture: Prospects along the Portuguese coastline. *Renew. Energy* **2023**, *204*, 347–358. [CrossRef]
- Zhang, B.; Peng, W.; Li, Y. State of the Art in Wave Energy Conversion Technologies in China. *Mar. Energy Res.* **2025**, *2*, 10004. [CrossRef]
- China Foreign Agency Quality. Improvement and Efficiency Enhancement | Dongguan Foreign Agency Safely Operates China's First Independently Developed "Nankun" Platform. 2023. Available online: <https://mp.weixin.qq.com/s/zwg1Li92PC0RXRMFtCHZTA> (accessed on 27 February 2025).
- Sørensen, H.C.; Friis-Madsen, E. Wave Dragon 1.5 MW North Sea Demonstrator Phase 1. *EUDP J.* **2015**, 64010–0405.

28. Li, G.; Zhu, W. Tidal current energy harvesting technologies: A review of current status and life cycle assessment. *Renew. Sustain. Energy Rev.* **2023**, *179*, 113269. [CrossRef]
29. Qian, P.; Feng, B.; Liu, H.; Tian, X.; Si, Y.; Zhang, D. Review on configuration and control methods of tidal current turbines. *Renew. Sustain. Energy Rev.* **2019**, *108*, 125–139. [CrossRef]
30. Aly, H.H.H. Dynamic modeling and control of the tidal current turbine using DFIG and DDPMSG for power system stability analysis. *Int. J. Electr. Power Energy Syst.* **2016**, *83*, 525–540. [CrossRef]
31. Kangaji, L.M.; Raji, A.; Orumwense, E. Optimizing sustainability offshore hybrid tidal-wind energy storage systems for an off-grid coastal city in South Africa. *Sustainability* **2024**, *16*, 9139. [CrossRef]
32. Lafleur, C.; Truelove, W.A.L.; Cousineau, J.; Hiles, C.E.; Buckham, B.; Crawford, C. A screening method to quantify the economic viability of off-grid in-stream tidal energy deployment. *Renew. Energy* **2020**, *159*, 610–622. [CrossRef]
33. Jing, F.; Sheng, Q.; Zhang, L. Experimental research on tidal current vertical axis turbine with variable-pitch blades. *Ocean. Eng.* **2014**, *88*, 228–241. [CrossRef]
34. Li, Y.; Florig, H.K. Modeling the operation and maintenance costs of a large scale tidal current turbine farm. In Proceedings of the OCEANS 2006, Boston, MA, USA, 18–21 September 2006; pp. 1–6.
35. Ghosh, T.K.; Mark, P.A. Energy Resources and Systems. In *Energy Resources and Systems*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 159–279. [CrossRef]
36. Qin, Z.; Tang, X.; Wu, Y.T.; Lyu, S.K. Advancement of tidal current generation technology in recent years: A review. *Energies* **2022**, *15*, 8042. [CrossRef]
37. Salter, S.H.; Taylor, J.R.M. Vertical-axis tidal-current generators and the Pentland Firth. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2007**, *221*, 181–199. [CrossRef]
38. Derakhshan, S.; Ashoori, M.; Salemi, A. Experimental and numerical study of a vertical axis tidal turbine performance. *Ocean. Eng.* **2017**, *137*, 59–67. [CrossRef]
39. Uihlein, A.; Magagna, D. Wave and tidal current energy—A review of the current state of research beyond technology. *Renew. Sustain. Energy Rev.* **2016**, *58*, 1070–1081. [CrossRef]
40. Chen, H.; Tang, T.; Ait-Ahmed, N.; Benbouzid, M.E.H.; Machmoum, M.; Zaim, M.E.H. Attraction, challenge and current status of marine current energy. *IEEE Access* **2018**, *6*, 12665–12685. [CrossRef]
41. Kaldellis, J.K.; Apostolou, D.; Kapsali, M.; Kondili, E. Environmental and social footprint of offshore wind energy: Comparison with onshore counterpart. *Renew. Energy* **2016**, *92*, 543–556. [CrossRef]
42. Madsen, P.T.; Wahlberg, M.; Tougaard, J.; Lucke, K.; Tyack, P. Wind turbine underwater noise and marine mammals: Implications of current knowledge and data needs. *Mar. Ecol. Prog. Ser.* **2006**, *309*, 279–295. [CrossRef]
43. Titah-Benbouzid, H.; Benbouzid, M. Marine renewable energy converters and biofouling: A review on impacts and prevention. *EWTEC* **2015**, *9*, Paper-09P1-4-2.
44. Zhou, Z.; Sculler, F.; Charpentier, J.F.; Benbouzid, M.; Tang, T. An up-to-date review of large marine tidal current turbine technologies, international power electronics and application conference and exposition. In Proceedings of the 2014 International Power Electronics and Application Conference and Exposition, Shanghai, China, 5–8 November 2014; pp. 480–484. [CrossRef]
45. Allsop, S.; Peyrard, C.; Thies, P.R.; Boulougouris, E.; Harrison, G.P. Hydrodynamic analysis of a ducted, open centre tidal stream turbine using blade element momentum theory. *Ocean Eng.* **2017**, *141*, 531–542. [CrossRef]
46. Liu, X.; Chen, Z.; Si, Y.; Qian, P.; Wu, H.; Cui, L.; Zhang, D. A review of tidal current energy resource assessment in China. *Renew. Sustain. Energy Rev.* **2021**, *145*, 111012. [CrossRef]
47. Cheng, X.Q.; Zhang, X.; Yi, L.X. A Review on the Development of Tidal Energy in China. *Adv. Mat. Res.* **2014**, *953*, 637–649. [CrossRef]
48. Chen, H.; Li, Q.; Benbouzid, M.; Han, J.; Ait-Ahmed, N. Development and research status of tidal current power generation systems in China. *J. Mar. Sci. Eng.* **2021**, *9*, 1286. [CrossRef]
49. Zhang, J.; Ling, A.J.; Jin, X.Y. A review of marine tidal current energy generation technology. *China Ship Surv.* **2025**, *3*, 44–50.
50. Today's Motors. Harbin Electric Has Successfully Developed the Largest Tidal Current Energy Generator Set in China. 2020. Available online: <https://mp.weixin.qq.com/s/XhzDRF8yrgzuc7r4R-jENQ> (accessed on 27 February 2025).
51. Boretti, A. Trends in tidal power development, E3S web of conferences. *EDP Sci.* **2020**, *173*, 01003. [CrossRef]
52. Vandercruyssen, D.; Baker, S.; Howard, D.; Aggidis, G. Tidal range electricity generation: A comparison between estuarine barrages and coastal lagoons. *Heliyon* **2022**, *8*, e11381. [CrossRef] [PubMed]
53. O'Doherty, T.; O'Doherty, D.M.; Mason-Jones, A. Tidal energy technology. In *Wave Tidal Energy*; Wiley: Hoboken, NJ, USA, 2018; pp. 105–150. [CrossRef]
54. Waters, S.; Aggidis, G. A world first: Swansea Bay tidal lagoon in review. *Renew. Sust. Energ. Rev.* **2016**, *56*, 916–921. [CrossRef]
55. O'Rourke, F.; Boyle, F.; Reynolds, A. Tidal energy update. *Renew. Energy* **2018**, *87*, 451–476. [CrossRef]
56. Etemadi, A.; Emami, Y.; AsefAfshar, O.; Emdadi, A. Electricity generation by the tidal barrages. *Energy Procedia* **2011**, *12*, 928–935. [CrossRef]

57. Meisen, P.; Loiseau, A. *Ocean Energy Technologies for Renewable Energy Generation*; Global Energy Network Institute: San Diego, CA, USA, 2009; Volume 27.
58. Rusdiansyah, A.; Tang, Y.; He, Z.; Li, L.; Ye, Y.; Yahya, S.M. The impacts of the large-scale hydraulic structures on tidal dynamics in open-type bay: Numerical study in Jakarta Bay. *Ocean. Dynam.* **2018**, *68*, 1141–1154. [CrossRef]
59. Todeschini, G. Review of tidal lagoon technology and opportunities for integration within the UK energy system. *Inventions* **2017**, *2*, 14. [CrossRef]
60. Khare, V.; Bhuiyan, M.A. Tidal energy-path towards sustainable energy: A technical review. *Clean. Energy Syst.* **2022**, *3*, 100041. [CrossRef]
61. Li, X.; Zhou, Y.; Li, S.; Lu, Z.; Luo, Y.; Tang, H.; Zhang, H.; Xiao, G.; Wang, S.; Gao, Z. *Progress in Development and Utilization of Tidal Energy, Conference Proceedings CP883*; The Institution of Engineering and Technology: Stevenage, UK, 2024; Volume 8, pp. 173–179. [CrossRef]
62. Denny, E. The economics of tidal energy. *Energy Policy* **2009**, *37*, 1914–1924. [CrossRef]
63. Bagher, A.M.; Vahid, M.M.A.; Reza, B.M.; Mohsen, M.; Mahshid, G. Tidal energy: Advantage and disadvantage. *Bull. Adv. Sci. Res.* **2015**, *1*, 4.
64. Zhang, J. The form, principle, utilization status and development trend of ocean energy. *AIP Conf. Proc.* **2024**, *3144*, 020007. [CrossRef]
65. Sheth, S.; Shahidehpour, M. Tidal energy in electric power systems, Power Engineering Society General Meeting. In Proceedings of the IEEE Power Engineering Society General Meeting, 2005, San Francisco, CA, USA, 16 June 2005; pp. 630–635. [CrossRef]
66. Bae, Y.H.; Kim, K.O.; Choi, B.H. Lake Sihwa tidal power plant project. *Ocean Eng.* **2010**, *37*, 454–463. [CrossRef]
67. Etemadi, A.; Emdadi, A.; AsefAfshar, O.; Emami, Y. Electricity generation by the ocean thermal energy. *Energy Procedia* **2011**, *12*, 936–943. [CrossRef]
68. Moreira, T.M.; de Faria, J.G., Jr.; Vaz-de-Melo, P.O.S.; Medeiros-Ribeiro, G. Development and validation of an AI-driven model for the La Rance tidal barrage: A generalisable case study. *Appl. Energy* **2023**, *332*, 120506. [CrossRef]
69. Zhejiang Red Resources Online. Jiangxia Tidal Pilot Power Station: The First Bi-Directional Tidal Energy Power Station in China. 2024. Available online: <https://mp.weixin.qq.com/s/nlc6Je74j8ug3sJ91IxNPA> (accessed on 27 February 2025).
70. Adiputra, R.; Utsunomiya, T.; Koto, J.; Yasunaga, T.; Ikegami, Y. Preliminary design of a 100 MW-net ocean thermal energy conversion (OTEC) power plant study case: Mentawai island, Indonesia. *J. Mar. Sci. Technol.* **2020**, *25*, 48–68. [CrossRef]
71. Kim, A.S.; Kim, H.J.; Lee, H.S.; Cha, S. Dual-use open cycle ocean thermal energy conversion (OC-OTEC) using multiple condensers for adjustable power generation and seawater desalination. *Renew. Energy* **2016**, *85*, 344–358. [CrossRef]
72. Faizal, M.; Ahmed, M.R. Experimental studies on a closed cycle demonstration OTEC plant working on small temperature difference. *Renew. Energy* **2013**, *51*, 234–240. [CrossRef]
73. Quinby-Hunt, M.S.; Sloan, D.; Wilde, P. Potential environmental impacts of closed-cycle ocean thermal energy conversion. *Environ. Impact Assess. Rev.* **1987**, *7*, 169–198. [CrossRef]
74. Abbas, S.M.; Alhassany, H.D.S.; Vera, D.; Jurado, F. Review of enhancement for ocean thermal energy conversion system. *J. Ocean. Eng. Sci.* **2023**, *8*, 533–545. [CrossRef]
75. Wilberforce, T.; ElHassan, Z.; Durrant, A.; Thompson, J.; Soudan, B.; Olabi, A.G. Overview of ocean power technology. *Energy* **2019**, *175*, 165–181. [CrossRef]
76. Liu, W.M.; Chen, F.Y.; Wang, Y.Q.; Jiang, W.J.; Zhang, J.G. Progress of closed-cycle OTEC and study of a new cycle of OTEC. *Adv. Mat. Res.* **2012**, *354*, 275–278. [CrossRef]
77. Liu, W.; Xu, X.; Chen, F.F.; Liu, Y.; Li, S.; Liu, L.; Chen, Y. A review of research on the closed thermodynamic cycles of ocean thermal energy conversion. *Renew. Sustain. Energy Rev.* **2020**, *119*, 109581. [CrossRef]
78. Chiesa, P.; Astolfi, M.; Giuffrida, A. Blue Energy: Salinity Gradient for Energy Conversion. In *Process Intensification for Sustainable Energy Conversion*; Wiley: Hoboken, NJ, USA, 2015; pp. 267–298. [CrossRef]
79. OTEC. Okinawa Ocean Thermal Energy Conversion Demonstration Facility. 2024. Available online: <http://otecokinawa.com/en/> (accessed on 27 February 2025).
80. Nakib, T.H.; Hasanuzzaman, M.; Rahim, N.A.; Habib, M.A.; Adzman, N.N.; Amin, N. Global challenges of ocean thermal energy conversion and its prospects: A review. *J. Ocean Eng. Mar. Energy* **2024**, *11*, 197–231. [CrossRef]
81. Chen, J.N. China's First 50-Kilowatt Ocean Temperature Difference Energy Generation Test Successful. 2023. Available online: <https://aoc.ouc.edu.cn/2023/0831/c9828a440257/page.htm> (accessed on 27 February 2025).
82. Xue, H.F.; Liu, Y.J.; Hou, Y.X. Research and Progress of Closed Cycle of Ocean Temperature Difference Energy. *J. Mar. Technol.* **2018**, *37*, 109–121. [CrossRef]
83. New Perspectives on Energy. The Largest in China! 50 kW Ocean Temperature Difference Energy Generation System Successfully Generates Electricity. 2023. Available online: https://mp.weixin.qq.com/s/dtfseWsFBb9BT_2q2n_JEA (accessed on 27 February 2025).
84. Schaetzle, O.; Buisman, C.J.N. Salinity gradient energy: Current state and new trends. *Engineering* **2015**, *1*, 164–166. [CrossRef]

85. Emami, Y.; Mehrangiz, S.; Etemadi, A.; Mostafazadeh, A.; Darvishi, S. A brief review about salinity gradient energy. *Int. J. Smart. Grid. Clean. Energy* **2013**, *2*, 295–300. [\[CrossRef\]](#)
86. Yip, N.Y.; Brogioli, D.; Hamelers, H.V.; Nijmeijer, K. Salinity Gradients for Sustainable Energy: Primer, Progress, and Prospects. *Environ. Sci. Technol.* **2016**, *50*, 12072–12094. [\[CrossRef\]](#)
87. Suzuki, T.; Kakihana, Y.; Higa, M. Recovery of Salinity Gradient Energy by Reverse Electrodialysis (RED): Principle, Recent Developments, and Challenges for Commercialization. *Salt Seawater Sci. Technol.* **2021**, *1*, 46–60. [\[CrossRef\]](#)
88. Gonzales, R.R.; Abdel-Wahab, A.; Adham, S.; Han, D.S.; Phuntsho, S.; Suwaileh, W.; Hilal, N.; Shon, H.K. Salinity gradient energy generation by pressure retarded osmosis: A review. *Desalination* **2021**, *500*, 114841. [\[CrossRef\]](#)
89. Seyfried, C.; Palko, H.; Dubbs, L. Potential local environmental impacts of salinity gradient energy: A review. *Renew. Sustain. Energy Rev.* **2019**, *102*, 111–120. [\[CrossRef\]](#)
90. Li, J.; Ma, X.; Wang, X.; Qiu, H.; Ma, C. Analysis of China's Marine Renewable Energy Current Situation, Web of Conferences. *EDP Sci.* **2024**, *478*, 01005. [\[CrossRef\]](#)
91. Estes, M.A.; Faria Ribeiro, A.C.; Haghi, A.K. *Chemistry and Chemical Engineering for Sustainable Development: Best Practices and Research Directions*, 1st ed.; Apple Academic Press: Cambridge, MA, USA, 2020.
92. EU Commission. Offshore Renewable Energy. Available online: https://energy.ec.europa.eu/topics/renewable-energy/offshore-renewable-energy_en (accessed on 1 March 2025).
93. Skillhagen, S.E. Osmotic power—A new, renewable energy source. *Desalination Water Treat.* **2010**, *15*, 271–278. [\[CrossRef\]](#)
94. Domingo, J.M. Energy Generation from Salinity Gradients with Reverse Electrodialysis: Fouling Management and Process Design. Ph.D. Thesis, University of Twente, Enschede, The Netherlands, 2018. [\[CrossRef\]](#)
95. MacGillivray, A.; Jeffrey, H.; Hanmer, C.; Magagna, D.; Raventos, A.; Badcock-Broe, A. *Ocean Energy Technology: Gaps and Barriers*; SI Ocean: Manzanillo, Mexico, 2013.
96. Khan, M.Z.A.; Khan, H.A.; Aziz, M. Harvesting energy from ocean: Technologies and perspectives. *Energies* **2022**, *15*, 3456. [\[CrossRef\]](#)
97. Chakraborty, S.; Dwivedi, P.; Gupta, R.; Das, S. An Overview of Ocean Energy Policies Across the World. *Water Energy Int.* **2021**, *64*, 38–46.
98. Spring, C.R.; Cirella, G.T. Fostering sustainable development: Green energy policy in the European Union and the United States. Human settlements: Urbanization, smart sector development, and future outlook. In *Human Settlements*; Springer: Singapore, 2022; pp. 101–137.
99. He, G.; Zhao, C.; Liu, C.; He, R.; Luan, Z. Power absorption and dynamic response analysis of a hybrid system with a semi-submersible wind turbine and a Salter's duck wave energy converter array. *Energy* **2024**, *305*, 132210. [\[CrossRef\]](#)
100. Jeffrey, H.; Sedgwick, J.; Gerrard, G. Public funding for ocean energy: A comparison of the UK and US. *Technol. Forecast. Soc. Chang.* **2014**, *84*, 155–170. [\[CrossRef\]](#)
101. Irena, S. *Offshore Renewables: An Action Agenda for Deployment*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2021.
102. Tapoglou, E.; Tattini, J.; Schmitz, A.; Georgakaki, A.; Długosz, M.; Letout, S.; Grabowska, M. *Clean Energy Technology Observatory: Ocean Energy in the European Union-2023 Status Report on Technology Development, Trends, Value Chains and Markets*; European Union: Maastricht, The Netherlands, 2022. [\[CrossRef\]](#)
103. Yang, X.; Liu, N.; Zhang, P.; Guo, Z.; Ma, C.; Hu, P.; Zhang, X. The current state of marine renewable energy policy in China. *Mar. Policy* **2019**, *100*, 334–341. [\[CrossRef\]](#)
104. Khan, N.D.; Kalair, A.; Abas, N.; Haider, A. Review of ocean tidal, wave and thermal energy technologies. *Renew. Sustain. Energy Rev.* **2017**, *72*, 590–604. [\[CrossRef\]](#)
105. Hao, W.; Qiang, Y.; Donju, W.; Yiru, W.; Jianhui, Y.; Hao, Z. The status and prospect of ocean energy generation in China. In Proceedings of the 2009 International Conference on Sustainable Power Generation and Supply, Nanjing, China, 6–7 April 2009; pp. 1–6.
106. International Renewable Energy Agency (IRENA). Offshore Renewables 2021. In *Offshore Renewables: An Action Agenda for Deployment*; International Renewable Energy Agency (IRENA): Masdar City, United Arab Emirates, 2021.
107. Xiao, C.; Gulfam, R. Opinion on ocean thermal energy conversion (OTEC). *Front. Energy* **2023**, *11*, 1115695. [\[CrossRef\]](#)
108. Ma, C.; Zhang, C.; Gao, Y.; Li, X. Analysis of Tidal Current Energy Technology and Industry in China, SHS Web of Conferences. *EDP Sci.* **2023**, *154*, 03019. [\[CrossRef\]](#)
109. Aderinto, T.; Li, H. Review on power performance and efficiency of wave energy converters. *Energies* **2019**, *12*, 4329. [\[CrossRef\]](#)
110. Fard, R.N.; Tedeschi, E. Integration of distributed energy resources into offshore and subsea grids. *CPSS Trans. Power Electron. Appl.* **2018**, *3*, 36–45. [\[CrossRef\]](#)
111. Sun, M.; Lin, H. Current Situation and Prospect of Multi-energy Complementary Tidal Power Station Under Dual Carbon Background. In Proceedings of the 13th International Conference on Computer Engineering and Networks, Wuxi, China, 3–5 November 2023; Springer Nature: Singapore, 2023; pp. 163–172.

112. Zhao, Y.; Yuan, H.; Zhang, Z.; Gao, Q. Performance analysis and multi-objective optimization of the offshore renewable energy powered integrated energy supply system. *Energy Convers. Managem.* **2024**, *304*, 118232. [[CrossRef](#)]
113. Zhu, Z.; Zhu, Z.; Yuan, S.; Yan, W.; Su, P.; Liu, P. Review of the Marine Clean Energy Resources and Development Status Along the Maritime Silk Road. In Proceedings of the International Association for Engineering Geology and the Environment, Chengdu, China, 21–27 September 2023; Springer Nature: Singapore, 2023; pp. 533–549.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.