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Three Types of Marine Renewable Energy and Their Optimal Development Conditions

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Abstract. In the face of the urgent need for global energy transformation, marine renewable energy with huge reserves has become a key direction. Among them, tidal energy, thermal energy, and salt gradient energy have garnered significant attention. However, the development conditions for the three are different, and a clear adaptation strategy has not yet been formed. The article aims to systematically study the optimal development conditions for these three new energy sources, providing a basis for route selection in different sea areas. Through principal analysis and feature comparison, the study clarified the fundamental differences in energy sources and technological paths among the optimal sea area characteristics. The results indicate that tidal energy is suitable for bays and estuaries with significant tidal ranges and enclosed topographies. Thermal energy can be harnessed in deep-water areas where there is a stable temperature difference between surface seawater and deep seawater. Salt gradient energy is concentrated at the estuaries of rivers with large discharge volumes, relying on the continuous salinity gradient. The successful practice of typical cases has verified the adaptability and technical feasibility of the above-mentioned sea area conditions. The conclusion emphasizes that the development of marine energy must adhere to the principle of adapting to local conditions. In the future, it should be promoted gradually based on the conditions of the sea areas and the maturity of technology, to maximize the supportive role of marine energy in the global energy transition.

Keywords: Tidal Energy, Thermal Energy, Salt Gradient Energy

1. Introduction

The sharp decline in global reserves of traditional fossil fuels and the intensification of environmental issues have propelled renewable energy to become the core force driving the transformation of the energy system. Although mainstream renewable energy has achieved large-scale application, they are constrained by factors such as diurnal alternation, seasonal changes, and geographical distribution, resulting in shortcomings such as strong intermittency in energy output and difficulty in grid connection. Against this backdrop, the ocean, covering 71% of the Earth's surface area and containing energy reserves thousands of times greater than those on land, has become a key area for addressing the energy dilemma [1].

Among various forms of ocean energy, tidal energy, thermal energy, and salt gradient energy boast stable sources with significant development potential. All three rely on natural physical

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processes in the ocean to generate energy, sharing common characteristics of being clean, pollution-free, and renewable. However, due to differences in energy carriers and conversion logic, they exhibit distinct characteristics in terms of development technology and site selection conditions. Currently, tidal energy has entered the commercial demonstration stage, thermal energy is in the megawatt-scale experimental application phase, and salt gradient energy is still in the laboratory verification stage. One of the core reasons for the uneven development of the three lies in the insufficient understanding and adaptability to their optimal development conditions.

Based on this, this paper conducts research from three aspects: theoretical explanation, feature comparison, and sea area adaptation, aiming to provide a scientific basis for the selection of marine renewable energy development paths in different sea areas.

2. The energy conversion principles of three types of marine renewable energy

2.1. The principle of tidal energy

The essence of tidal energy lies in the mechanical energy contained in the periodic fluctuations of seawater induced by celestial gravitational forces. The gravitational forces exerted on Earth by the Moon and the Sun, combined with the inertial centrifugal force resulting from Earth's rotation, form a periodic tidal force. The tidal force causes seawater on the Earth's surface to gather along the direction of gravity, forming a vertical tidal level difference and a horizontal tidal current. Together, they constitute the energy carrier of tidal energy.

Its energy conversion process follows the basic path of converting mechanical energy into electrical energy. First, potential energy formed by tidal level differences of kinetic energy generated by tidal current is collected through hydraulic structures such as sluices and dams. Subsequently, the water level difference is utilized to drive the rotation of water turbines, or the blades of water turbines are directly rotated by tidal currents, converting the mechanical energy of seawater into rotational mechanical energy of the water turbines. Ultimately, the water turbine drives the generator, converting mechanical energy into directly usable electrical energy.

2.2. The principle of thermal energy

Thermal energy is contained in the temperature difference between the surface layer of the ocean and the deep seawater, and its energy source is essentially solar radiation. The sun continuously transfers heat to the surface of the ocean, resulting in higher water temperatures in the tropical and subtropical regions. However, due to the distance from solar radiation and low heat conduction efficiency, the deep ocean has lower water temperatures. This creates a stable temperature difference is the core energy source of thermoelectric power.

Its energy conversion requires a secondary conversion process, which involves transforming thermal energy into mechanical energy and then into electrical energy. The core technological approach is a thermodynamic cycle system. First, high-temperature surface seawater is pumped through a surface water pump and used as a heat source to heat a circulating working fluid, such as ammonia or propane, which have low boiling points, causing the working fluid to evaporate into high-pressure steam. The high-pressure steam drives the turbine to rotate, converting thermal energy into rotational mechanical energy of the turbine. Subsequently, low-temperature deep-sea water is pumped up through a deep-sea pump and used as a cold source to cool the low-pressure steam discharged from the turbine, condensing it into a liquid working medium and completing the cycle.

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Finally, the turbine drives the generator to generate electricity, achieving the conversion of mechanical energy into electrical energy.

2.3. The principle of salt gradient energy

Salt gradient energy refers to the potential energy contained in the osmotic pressure generated by the difference in salinity between freshwater from rivers and saltwater from the ocean at their confluence. Its energy essence is the chemical energy released during the mixing process of the two water bodies. When seawater comes into contact with freshwater, water molecules migrate from the low-salinity freshwater side to the high-salinity seawater side due to osmotic pressure, generating osmotic pressure and forming potential energy capable of doing work, namely salt gradient energy.

The core of its energy conversion lies in the transformation of osmotic potential energy into mechanical energy, which is then converted into electrical energy. The mainstream technological approach is retarded osmosis (PRO) system [2]. First, fresh water is separated from seawater through a semipermeable membrane. Under the influence of osmotic pressure, the fresh water permeates through the semipermeable membrane towards the seawater side, causing the water level on the seawater side to rise. This process converts the potential energy of osmotic pressure into the potential energy of water level difference. Subsequently, the increased water level difference is utilized to drive the turbine to rotate, converting potential energy into mechanical energy. Ultimately, the turbine drives the generator to generate electricity. In addition, through ion exchange membranes, ions in seawater and freshwater can be directed to migrate, forming an electric current, which directly converts chemical energy into electrical energy. However, this technology is still in the laboratory research and development stage.

3. Common characteristics and differences analysis of the three types of marine renewable energy

3.1. Common characteristics

The core types of marine renewable energy, tidal energy, thermal energy, and salt gradient energy share three common characteristics. Firstly, it is clean and pollution-free. During the energy conversion process, no fossil fuels are consumed, and there are no emissions of pollutants such as carbon dioxide and sulfides. Only the development of salt gradient energy may involve a small risk of working fluid leakage. The overall environmental impact is far lower than that of traditional energy sources. Secondly, the resources are renewable. Tidal energy relies on celestial gravitation and the rotation of the Earth. As long as the celestial system remains stable, tides will persist. Thermal energy relies on solar radiation and ocean thermal reserves. The sustainability of solar radiation determines the continuity of its energy supply. Salt gradient energy originates from the continuous interaction between freshwater from rivers and saltwater from the ocean. As long as the water circulation system is not disrupted, the salinity difference will not disappear. Thirdly, it has a strong dependence on the ocean, as its energy carriers are all seawater (or a mixture of seawater and freshwater). Its development must rely on ocean space, and there are strict requirements for the natural conditions of the sea area (such as tidal level, water temperature, and salinity). It cannot be independently applied without relying on the marine environment.

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3.2. Differences analysis

3.2.1. Different conversion path

Due to their different energy forms, the three have significantly different conversion technology paths and maturity levels.

Firstly, tidal energy conversion technology is the most mature, with the core being the water turbine-generator system. Its technical principle is highly similar to hydropower generation. Mature water turbine models, such as axial-flow and tubular turbines, have been developed, and the technology of hydraulic structures (dams, sluices) in tidal power stations can directly draw on the experience of hydraulic engineering. Currently, many commercial tidal power stations have been built worldwide, such as the Lens tidal power station in France and the Sihwa Lake tidal power station in South Korea, both of which have a long technical lifespan. Research results on tidal energy power stations along the Andaman Sea coast in southern Thailand indicate that a composition of 10 tidal current turbines, each with a capacity of 103kW, can achieve a maximum annual power generation of 160MWh [3]. And using the most efficient tidal current turbine studied, the annual power generation in a large area of the southern Andaman coast can reach 79 MWh per year [3].

Secondly, the conversion technology of temperature difference energy is currently in the megawatt-scale demonstration stage, with the core being the thermal cycle system. Three major challenges need to be addressed: efficient transportation of high-temperature surface seawater and low-temperature deep seawater, stable circulation of working fluids, and improvement of heat transfer efficiency. A study indicates that optimal system performance can only be achieved by carefully adjusting the mass flow rate of warm or cold seawater. For practical applications, it is recommended to maximize the mass fraction of hydrate and minimize the degree of supercooling [4]. Currently, established demonstration projects such as the OTEC-1 power station in Hawaii, USA, and the temperature difference energy test power station in Kagoshima, Japan, have achieved stable power generation. However, the heat exchange equipment is bulky, energy-intensive, and the commercialization cost is high, which have become challenges that need to be overcome in subsequent research.

The conversion technology of salt gradient energy is still in the laboratory verification stage. Its core lies in the semi-permeable membrane and osmotic pressure conversion system, which requires breakthroughs in three major bottlenecks: high permeation flux of the semi-permeable membrane, low pollution and clogging, and long lifespan. At the same time, it needs to address the energy loss issue during the mixing of seawater and freshwater. The full-cell fiber-like RED device can achieve an output power density of 1.88 W/m2 under a 50-fold concentration gradient, but it can only operate stably for 30 days [5].

3.2.2. Different requirements for site selection

The three have essential differences in their site selection requirements for the natural conditions of the sea area, and their adaptability characteristics to typical application cases are significant.

Firstly, the energy source of tidal energy is the gravitational force of celestial bodies combined with the rotation of the Earth. The magnitude of tidal force is directly related to the relative positions of the Moon and the Sun, and is also influenced by the Coriolis force generated by the rotation of the Earth. Therefore, its resource distribution is mainly concentrated in the low- and mid-latitude seas where the linear velocity of the Earth's rotation is high, as well as in enclosed areas such as bays and estuaries where tidal energy converges, such as the United Kingdom and France along the

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Atlantic coast, and China and South Korea along the Pacific coast. Some researchers implemented a regional-scale 3D hydrodynamic modeling framework in Cook Inlet, Alaska, to predict tidal flow and turbulence characteristics. They validated the model results using various datasets collected by bottom-mounted acoustic Doppler current profilers and velocimeters, demonstrating the importance of flow and turbulence conditions in the energy system. Therefore, the core of its site selection lies in tidal range and topographical conditions, requiring a large tidal range in the sea area, as well as pocket-shaped topographies such as bays and estuaries, which facilitate the construction of dams for reclamation to form reservoirs and gather tidal energy [6].

Secondly, the energy source of thermoelectric power is solar radiation, and the temperature of surface seawater is the core factor determining the amount of thermoelectric power resources. Therefore, its resources are mainly concentrated in tropical and subtropical seas, where the annual average surface water temperature ranges from 25 to 30°C and the deep water temperature ranges from 4 to 6°C, forming a stable temperature gradient [7]. Such as the Hawaiian Islands in the Pacific Ocean, the Maldives in the Indian Ocean, and the Gulf of Mexico in the Atlantic Ocean. Therefore, the core of site selection lies in the water temperature gradient and water depth. The sea area should have a depth that facilitates the extraction of deep cold water, while avoiding areas where extreme weather, such as typhoons and storm surges, occur frequently.

The energy source of ocean thermal energy conversion (OTEC) ultimately stems from the salinity difference between freshwater and seawater. Its resource distribution is entirely dependent on river estuaries. Only when rivers with large runoff and stable seawater salinity meet the ocean can a continuous salinity gradient be formed. Therefore, it is mainly concentrated near the estuaries of major rivers, such as the Amazon River estuary, the Congo River estuary, and the Yangtze River estuary. Therefore, the core of site selection lies in the salinity difference and runoff volume. It is required that the annual runoff of rivers can ensure a continuous supply of fresh water, and the salinity of the estuary sea area can maintain a stable osmotic pressure, with a flat terrain and shallow water depth (conducive to the construction of semi-permeable membrane devices).

4. Three typical cases of marine renewable energy development

4.1. Tidal energy

The SeaGen tidal power plant in the UK is the world's first tidal power plant, installed in place at Stratford Bay, UK, in 2008 [8]. This power plant can generate electricity for 1,140 households when the bay experiences high and low tides, demonstrating its potential [8]. Located at the mouth of a 500-meter-wide channel, it fits perfectly into the pocket-shaped terrain [8]. Frenkel stated that this generator has a power generation capacity of up to 1.2 megawatts, making it the world's first industrial-scale device system to harness tidal power for electricity generation [8].

4.2. Thermal energy

As a clean energy technology, ocean thermoelectric power generation also faces some technical challenges, such as the low temperature difference between surface and deep seawater, which results in poor efficiency of the power generation system. Therefore, researchers have concluded through simulation using AspenPlus software that the Kalina thermoelectric power generation system achieves the maximum power output when using a mixture of 95% ammonia and water under the conditions of a superheat temperature of 60°C (working fluid temperature after low-temperature seawater condensation: 11°C, working fluid temperature after superheat in the evaporator: 30°C, and

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temperature after superheat in the superheater: 90°C) [9]. However, in commercial operation, there are still practical production issues such as complex pipeline layout, large pipe diameters, and high power consumption of seawater pumps [9].

4.3. Salt gradient energy

In recent years, researchers have successfully prepared MXene/TiO2 composite materials (MA-P70) by utilizing plasma technology to assist in the in-situ oxidation of MXene. The MA-P70 exhibits improved hydrophilicity on its surface while retaining high electrical conductivity, which facilitates the wetting of electrolyte solutions, reduces interfacial contact resistance, and ensures rapid ion transport. When tested for salt difference power generation performance, it demonstrated excellent concentration difference response voltage (294 mV) and short-circuit peak current (8.0 mA cm-2) [10]. Under an external resistance of 90 Ω, it exhibited a high average power density of 805.8 mW cm-2 through two-step cycling, and maintained high cycling stability of 95.2% after 100 cycles [10]. This effectively addresses the issue of the short service life of some semipermeable membranes [10].

5. Conclusion

Tidal energy, temperature difference energy, and salt difference energy, as three types of marine new energy, have the characteristics of cleanliness and renewability, but the essential differences in energy sources determine the significant differentiation of their development paths. Firstly, tidal energy should be adapted to enclosed bays and estuaries in mid to low latitudes, with a core condition of large tidal level differences and pocket-shaped terrain. The current technology is the most mature, and commercial-scale development can be prioritized on the west coast of Europe and the east coast of China. Secondly, temperature difference can rely on deep waters in tropical and subtropical regions, requiring certain temperature and depth requirements. Although the cost is high, it has a first-mover advantage in tropical islands such as Hawaii and the Maldives, where conventional energy sources are not available. Salt difference can focus on the estuary of large runoff rivers, and the key lies in salt difference and semi-permeable membrane technology. Although it is currently in the experimental stage, the resource endowment of the Amazon River and the Yangtze River estuary has the potential for industrialization. In the future, it is necessary to break through the bottleneck of semi semi-permeable membrane lifespan and cost.

The development of the three should follow the principle of "adapting to local conditions and differences", combined with the natural conditions of the sea area and the gradient of technological maturity, in order to maximize the supporting role of marine new energy in the global energy transition.

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