Li et al. Energy, Sustainability and Society (2025) 15:47
https://doi.org/10.1186/s13705-025-00548-6

Energy, Sustainability and Society

REVIEW

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Analysis of the development of tidal energy and its implementation

Xiaochao Li[1,2*], Ye Zhou[2], Guanglei Xiao[3], Chun Gan[2], Zhiyang Lu[2], Shangqi Li[2], Zhongxin Gao[2], Hao Zhang[3], Minping Xie[4] and Yi Luo[5]

Abstract

Background In the recent years, owing to the increasing carbon emissions from anthropogenic activities, the challenges caused by global climate change, including the greenhouse effect, sea-level rise, and extreme weather events, have become increasingly severe. It is also an urgent task for many countries to develop clean energy, reduce carbon emissions, and establish a green low-carbon development structure. As a renewable and environmentally friendly energy source, tidal power is abundant in numerous coastal regions. Constructing tidal power plants to harness this renewable energy source not only provides substantial energy benefits but also plays a pivotal role in advancing green and sustainable development. Moreover, tidal energy has profound implications for societal transformation, fostering economic growth, and enhancing stability. Therefore, tidal energy is an indispensable component of clean power generation, paving the way for a more sustainable and equitable world.

Main text By summarising the ongoing research on tidal energy, this paper offers a comprehensive exploration of the current status of tidal energy development and crucial insights derived from tidal energy applications. The mechanism of tidal energy and the structural design of tidal power stations are systematically explained, and the characteristics of tidal energy use to generate electricity in different regions are introduced. Focussing on China in combination with other countries, the latest technological achievements are summarised, and corresponding improvement measures are proposed for tidal energy development and implementation.

Conclusions Tidal energy, characterised by zero-emission attributes, renewability, and operational reliability, offers a vital pathway towards sustainable energy systems. Despite mature technology with decades of commercial operation, its deployment has progressed slowly because of persistent challenges, including high capital costs and ecological impacts on marine ecosystems. Consequently, resolving these constraints necessitates notable advancements in policy frameworks and technological innovation. This paper could provide reference material for the increased popularization and sustainable development of tidal energy power generation technology.

Keywords Tidal energy, Marine energy, Tidal power station, Hydroelectric power, Clean energy technology, China

*Correspondence:
Xiaochao Li
hnscyxlxc@163.com
Full list of author information is available at the end of the article

Background

By the end of 2022, the United Nations released the latest global population data. With a global population reaching 8 billion people, there is an increased pressure on energy consumption, and the challenges to sustainable human development become greater. One of the key factors influencing human development and survival is energy, with the most representative one being traditional fossil energy, such as oil, coal and natural gas. How to promote the development of green energy and reduce the dependence on traditional fossil energy is a question for all countries today.

Our Earth has always been referred to as a water planet, as its surface is covered by only 29% land and 71% by water, making the latter an enormous repository of valuable resources [1]. With the continuous development of human science and technology and the increasing consumption of land resources, humans have gradually shifted their attention towards the ocean for energy, which has tremendous potential. Without considering the minerals and other forms of energy buried in the ocean, the energy contained in moving seawater alone is extraordinary. According to the International Renewable Energy Agency (IRENA), the theoretical annual power generation of the global ocean energy resource reserve is estimated to range from approximately 45000 ~ 130000 TWh, which is approximately twice the current global electricity demand [2, 3], while ocean energy is also renewable. Therefore, the development of marine energy is among the most important choices for eliminating the dependence on traditional fossil energy. Marine energy refers to the renewable energy contained in seawater and includes mainly tidal energy, wave energy, ocean current energy, salinity energy and thermal energy [4].

Wave energy is the energy of waves formed by wind blowing across the sea surface. The formation of wind is due to the airflow movement caused by different temperatures, whereas the temperature differences are caused by solar radiation; thus, wave energy is ultimately generated by solar radiation energy. The wave possesses both kinetic and potential energy. The energy of a wave is proportional to the square of its height, the period of its motion, and the width of its front. Wave energy has very large reserves, but it is also the most unstable energy among marine energy sources.

Ocean current energy is simply the energy generated by the flow of seawater. The current energy mainly refers to the kinetic energy of seawater flow, and it is proportional to the square of the flow velocity and flow rate. Seawater flow mainly arises through two processes. On the one hand, seawater flow is affected by both the rotation of the Earth, the rotation of the moon, and the revolution around the sun. On the other hand, this process is affected by the continuous blowing of wind. In addition, differences in seawater temperature, salinity and suspended matter result in seawater flow. Flowing seawater carries a large amount of energy. The relatively stable seawater flow in submarine channels and straits and the seawater flow caused by tides constitute the most valuable current energy. Owing to the complex causes of ocean circulation in the deep sea, the tidal phenomenon is only one of the factors, as there are many important factors, such as temperature and geographical location. Therefore, we classify the energy of deep-sea water flow as ocean current energy, while the energy obtained by shallow-sea water in tidal phenomena is classified as tidal stream energy (a kind of tidal energy).

The difference in energy due to ocean salinity is caused by the large amount of mineral salts in seawater. When two solutions with different salt concentrations are mixed, the salt will continue to penetrate along the high-concentration side to the low-concentration side until the concentration is balanced, and this penetration produces a difference in pressure. The use of chemical permeation membranes to separate concentrated and freshwater can result in differences in available salinity for power generation.

Ocean thermal energy is the energy due to the temperature difference between deep seawater and surface seawater. The ocean surface is subject to solar radiation, and heat is stored in the upper layer of the ocean, while the seawater near the freezing point flows slowly from the polar to the equator at a depth of less than 1000 m. Therefore, in many tropical or subtropical waters, there is a difference in vertical seawater temperature of more than 20 °C, which can be used to achieve a thermodynamic cycle and power generation.

Tidal energy is the energy produced by the periodic motion of seawater due to the gravity effect of celestial bodies. The tidal phenomenon is the periodic motion of seawater under the combined action of lunar and solar gravity. Seawater possesses kinetic energy and potential energy because of tidal phenomena, and the kinetic energy of seawater in shallow seas due to tidal phenomena is also called tidal stream energy.

Among all marine energy types, tidal energy is generated by celestial gravity. Tidal energy exhibits a predictable cycle and immense reserves, with a global potential estimated at 2.7 billion kilowatts. Moreover, its extraction technology is the most sophisticated among marine renewable energy sources. Global tidal power generation technology has already entered the stage of commercial operation [5]. Nevertheless, the current global tidal energy resources have not been effectively developed on a large scale.

Therefore, further research on tidal energy and promoting the sustainable development of tidal energy are important for reducing the energy pressure in various countries. In the face of the current increasingly tense energy situation, summarising and promoting the experience of existing tidal power stations is highly important for the construction and research of subsequent tidal power stations. Statistical analysis of tidal power stations can provide valuable reference information for the formulation of energy structure and tidal energy development policies in various countries. On this basis, this paper focuses on China and accounts for other countries to review and analyse the development of tidal energy.

Fundamental principles and system characteristics of tidal energy

Generation mechanism of tidal energy

Tidal energy is generated mainly by the gravitational effect of the Sun and the Moon on the Earth's seawater. According to the law of universal gravitation, the following can be obtained:

$$F = \frac{Gm_1m_2}{r^2} \tag{1}$$

Parameter calculation reveals that the gravitational ratio of the moon and the sun to the earth is 11:5. During the movement of the Sun, the Earth and the Moon, if these three are in a straight line, the gravitational effects of the Sun and the Moon on the Earth are superimposed. At this time, the gravity of the Earth's seawater is the greatest, resulting in a spring tide phenomenon. There are two such situations in January. Therefore, the tide phenomenon generally appears on the first day and the fifteenth day of the lunar calendar every month. In contrast, when the gravitational direction of the Moon and the Sun on the Earth are perpendicular to each other, the resultant force is the lowest, and a neap tide phenomenon occurs. The occurrence time of the neap tide is approximately the eighth day and the twenty-third day of the lunar calendar every month.

Because the tidal force of the Moon is dominant, the Earth's rotation cycle is one day. For the same place on the Earth, there will be two times a day closest to the moon or farthest from the moon. At this time, the Earth's tidal force is the greatest in one day, so there are two flood tides in one day.

Distribution of tidal energy resources

The tidal movement of seawater is caused by changes in gravity; notably, rising and ebb tides occur. The water-level change value of the rising and ebb tides of seawater constitutes the tidal range, which is the key index for measuring the tidal energy reserve. If the tidal range of a certain area can reach more than 3 m, the tidal energy in this area can be developed and used [6]. The largest tidal range in the world is located in coastal areas between 40° N and 60° N in the Northern Hemisphere, such as the Severn Estuary in Britain, the Sea of Okhotsk in Russia, the Bay of Fundy in Canada, and the Bay of St. Malo in France. The average tidal range in these areas reaches 7 ~ 12 m, and the maximum tidal range is 15 ~ 17 m [7]. Simon P. Neill et al. calculated and analysed the distribution of global tidal energy and constructed a distribution map of global annual tidal power yield [8], as shown in Fig. 1.

Limited by its geographical location, the average tidal range in China is 5 m, which is half of the global mean, and the tidal range in the south-eastern coastal area is the greatest, at approximately 7 ~ 9 m. Gu Zhenhua et al. calculated and analysed the amount of tidal energy in the East China Sea, and the specific distribution is shown in Fig. 2a [9]. Wu He et al. reported about the tidal energy power density along the coast of China [10, 11], as shown in Fig. 2b. The analysis results presented in Fig. 2 reveal that China's abundant tidal resources are concentrated mainly in the south-eastern coastal provinces.

Combined with the *China's coastal tidal energy resources survey* [12] and *China's coastal rural marine energy resources zoning* [13], the tidal energy resources of China's coastal provinces were determined. As indicated in Table 1, Zhejiang and Fujian possess the most tidal energy, accounting for 88.3% of China's total tidal energy.

Operational characteristics of tidal energy systems

As a typical representative of renewable energy, tidal energy has the following characteristics. (1) Clean and pollution-free. Tidal energy originates from the tidal rise and fall of seawater and uses the tidal phenomenon of

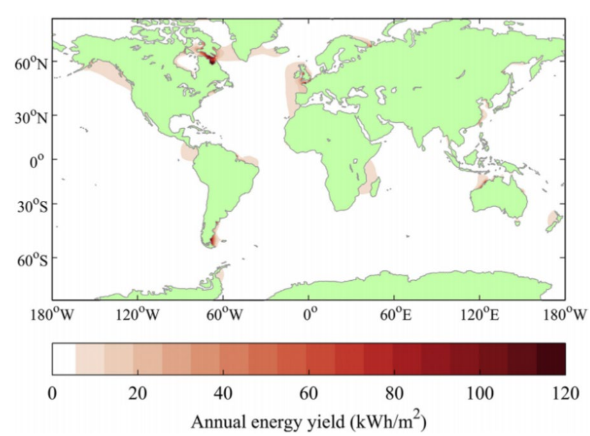

Fig. 1 The global theoretical tidal range energy resource is calculated as the annual energy yield (kWh/m^2) [8]

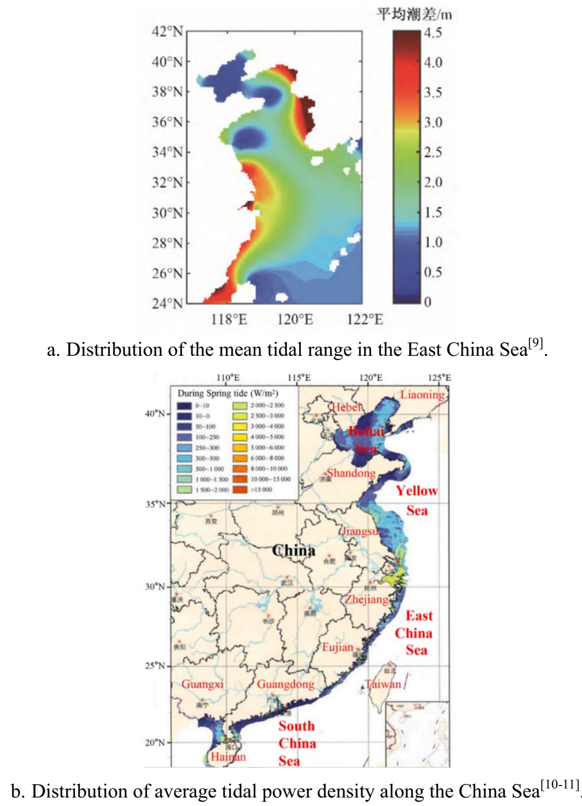

Fig. 2 Distribution of the mean tidal range along the coast of China. **a** Distribution of the mean tidal range in the East China Sea [9]. **b** Distribution of average tidal power density along the China Sea [10, 11]

Table 1 Tidal energy resources in coastal provinces of China [7, 14]

Province	Installed capacity(10^4 kW)	Potential annual production (10^8 kWh)
Liaoning	59.66	16.4
Hebei	1.02	0.21
Shandong	12.42	3.75
Jiangsu	0.11	0.06
Shanghai	70.4	22.8
Zhejiang	891.39	266.9
Fujian	1033.29	284.13
Taiwan	5.62	1.35
Guangdong	57.27	15.2
Guangxi	39.36	11.12
Hainan	9.06	2.29
Footing	2179.60	624.21

seawater to generate electricity. There are no problems, such as environmental pollution, and it is a green, clean energy source. (2) Renewable energy. Owing to the gravitational effect of celestial bodies, tidal phenomena occur every day; thus, tidal energy can be used every day, and tides contain sustainable and inexhaustible energy. (3) Stable and reliable. The generation of tidal phenomena is the result of the action of celestial bodies. As long as the Earth, Moon and Sun are in motion, a steady stream of tidal energy is generated every day. This energy does not exist in the wet or dry season. Whether it is windy, rainy, sunny or cloudy, it always comes as scheduled. Periodic fluctuations are very reliable and stable, and more accurate predictions can be made [15, 16]. (4) High safety. Because the development of tidal energy is characterised by a low water head, high flow, and coastal development, even if it is affected by natural disasters, such as earthquakes, and extreme events, such as dam breaks, the reservoir will not cause a wide range of disasters, but its storage will still return to the sea; thus, the safety factor can be extremely high in terms of current energy implementation.

Tidal power generation has become the first energy source to enter commercial development in marine energy because of its clean and renewable characteristics. Compared with mainstream wind power generation, hydropower generation, thermal power generation and nuclear power generation, tidal power generation is still favoured because of its unique advantages. With respect to tidal power generation and wind power generation, tidal power generation is more stable and reliable than wind power generation because tidal energy can be accurately predicted at present, and the density of seawater is approximately 800 times that of air; thus, tidal energy has higher power generation efficiency and more power production. Compared with hydropower generation, tidal power generation does not cause a large amount of migration or inundation loss. The construction of tidal power stations directly in the bay area will not inundate the downstream area and cause large losses after the dam is damaged. Compared with thermal power generation, tidal power generation requires less expensive raw materials, such as seawater, and does not need to be transported, nor will it produce environmental pollution problems, such as acid rain or waste. Compared with nuclear power generation, tidal power generation does not result in the production of radioactive and chemical substances and does not require high protection costs for nuclear power plant construction, operation and maintenance, and demolition [17, 18].

China, endowed with an extensive and intricate coastline as well as vast territorial waters, harbours abundant tidal energy resources. Specifically, its theoretical reserve amounts to 110 million kW, with approximately 21.796 million kW already in exploitation. However, the geographical distribution of tidal energy resources is uneven. The coastal tidal range is greatest in the East China Sea, followed by that in the Yellow Sea, and smallest in the southern Bohai Sea and South China Sea. Tidal energy resources are most abundant in the Qiantang River estuary, followed by the Yangtze River estuary and then the Pearl River, Jinjiang River, Minjiang River and Oujiang River estuaries. In terms of regions, it is concentrated mainly in the coastal areas of East China, among which Fujian, Zhejiang and Shanghai have the most, accounting for 88% of the total amount of tidal energy that can be developed in China.

Development status of tidal energy

Classification and development of tidal energy implementation methods

At present, there are two ways to develop and implement tidal energy, i.e., tidal stream power generation and tidal barrage power generation. Tidal stream power generation aims to directly use the kinetic energy of the tidal stream to promote the rotation of the hydroelectric generation set. Such hydroelectric-generating units are usually arranged in shallow bays, estuaries and other areas with strong tidal streams. Tidal barrage power generation is similar to conventional hydropower generation. The power generation head is generated by building a dam, and the kinetic energy and potential energy are comprehensively used for power generation. Because tidal stream power generation uses only tidal kinetic energy, the energy usage rate is low. The energy usage rate of tidal barrage power generation is high, which is currently the main development form of tidal energy [19].

In the development process of tidal power stations, tidal energy is used to drive the unit to generate electricity through the construction of dams. The number of reservoirs is often divided into two development modes: single-reservoir and dual-reservoir. As the name suggests, the single-reservoir mode is to set up a reservoir, and the dual-reservoir mode is to set up two reservoirs. Because there is only one reservoir at a single-reservoir tidal power station and because the change in reservoir water level lags behind the ocean water level, the water head in the single-reservoir mode cannot generate electrical energy during some periods due to the periodic change in seawater. This means that the power generation of this kind of station is discontinuous. With respect to the power grid, the flexibility of the single-reservoir tidal power station is not high. The dual-reservoir tidal power station addresses the problem of intermittent power generation. The two reservoirs always maintain a high water level and a low water level to achieve continuous power generation. The specific structure is shown in Fig. 3. However, for the same area, owing to the change from a single reservoir to a double reservoir and the reduction in reservoir capacity, the working head is often lower than that of the single reservoir, and the total power generation is less than that of a single reservoir.

Single-reservoir tidal power stations are subdivided into single-reservoir one-way operations and single-reservoir two-way operations according to the different units. The specific structure is shown in Fig. 4 [20]. In the single-reservoir unidirectional type, the unit only generates electricity in one direction. The basic principle is that the reservoir stores water during flood tide and waits for the reservoir area and sea level to provide a power generation head during ebb tide; that is, a single-reservoir unidirectional tidal power station can generate electricity in only one direction. The two-way type of a single-reservoir configuration is a further improvement of the unit. When the tide is rising, the reservoir water level and sea level form the power generation head to generate electricity, and when the tide is falling, power generation can be achieved again, and the waiting time is reduced. This method can improve power generation, but the structure of the turbine unit of the two-way power generation is also relatively complex, and the work efficiency is lower than that of the one-way type [21].

In the current development and implementation of tidal energy, single- and double-reservoir systems have their own advantages and disadvantages. The dual-reservoir power station has the advantage of continuous power generation, but the efficiency of the single-reservoir power station unit is greater. To further improve the flexibility of the single-reservoir framework and increase the power generation of the dual-reservoir framework, a development mode of the large–small

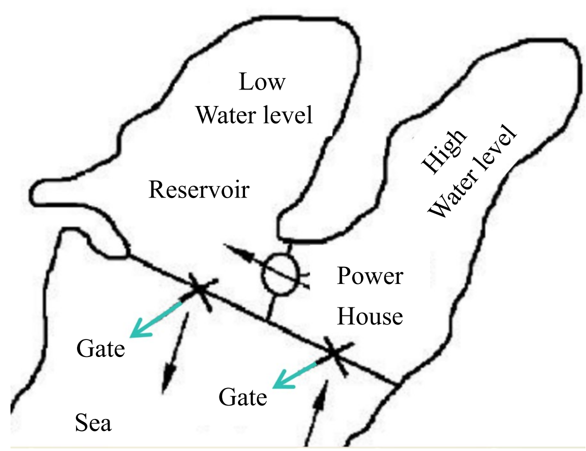

Fig. 3 Dual-reservoir tidal power station [20]

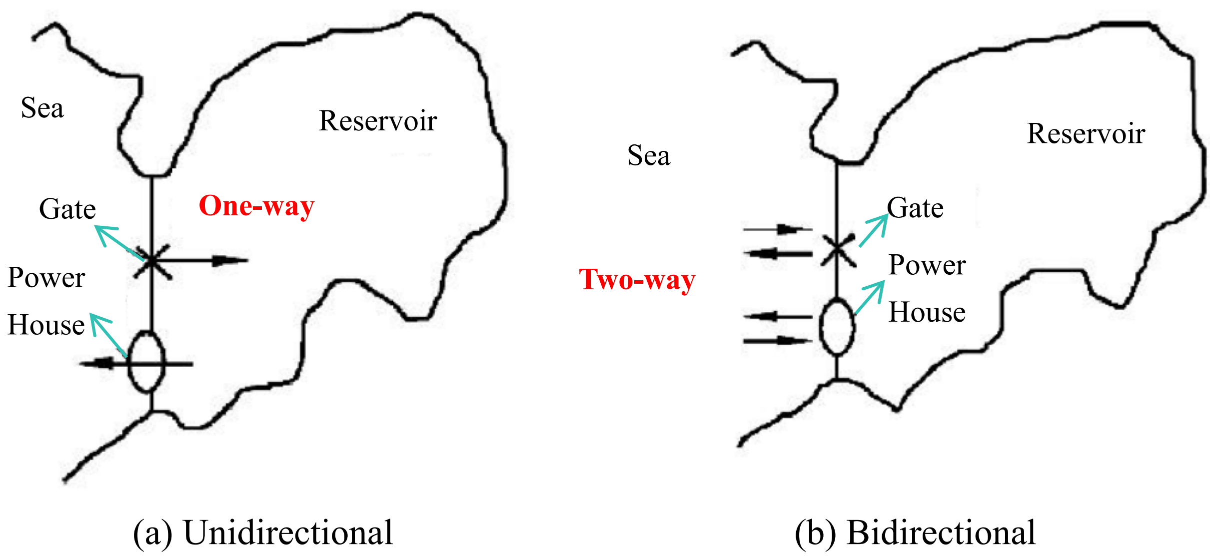

Fig. 4 Single-reservoir tidal power station [20]

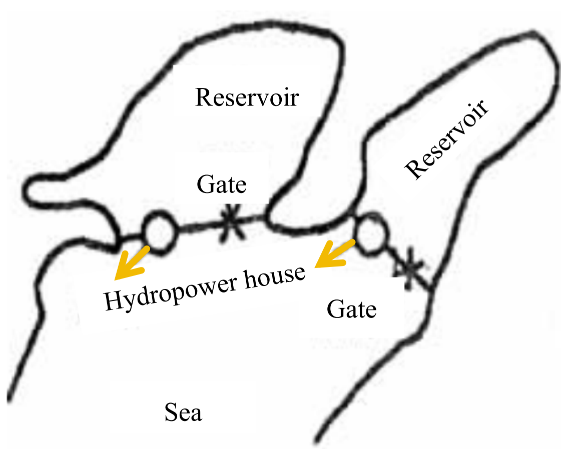

Fig. 5 Paired-reservoir tidal power station [20]

reservoir and the paired reservoir has been developed. The principle of the large–small-reservoir type is similar to that of the dual-reservoir type tidal power station. The only difference is that the size of the reservoir is no longer that of two reservoirs with similar areas but that of one large and one small reservoir. It can also be seen as setting up a small reservoir on the basis of a single reservoir. The role of this small reservoir is to adjust its water level to form a difference in head during the process of waiting for power generation in the large reservoir to achieve continuous power generation. The power generation principle of the paired reservoir development method is the same as that of a single reservoir, and the structural diagram is shown in Fig. 5.

The paired-reservoir framework is a combination of two single reservoirs, but the construction position of the two reservoirs could have been a tidal power station in the form of a dual-reservoir system. However, to improve the working efficiency and power generation of the unit, the two reservoirs are set up separately, but the water level of the two reservoirs is different; thus, to adjust the power generation time of the two single reservoirs, the two reservoirs can generate power in a tidal cycle, making up for the lack of intermittent power generation of single reservoirs.

Notably, in addition to the use of dams to form reservoirs for power generation, new tidal energy development methods, which include mainly lagoon-type tidal energy development and dynamic tidal energy development, have emerged. The goal of lagoon-type tidal energy development is not to construct artificial dams but to find natural reservoirs near the coast because of the movement of marine sediment itself. Through the processing of the naturally formed lagoon, the appropriate position of the alluvial dam is opened, and the tidal power unit is set to realise the use of tidal energy for power generation. The structure of the lagoon is shown in Fig. 6. A lagoon tidal power station has been constructed in practice.

The second new type of development method is dynamic tidal energy development. Both this method and the lagoon method further reduce the adverse ecological effects caused by the artificial construction of reservoirs to isolate flow exchange. However, this method differs from the lagoon method and the traditional dam development method. This method does not use a reservoir but instead directly sets up a dam along the direction

Fig. 6 Lagoon

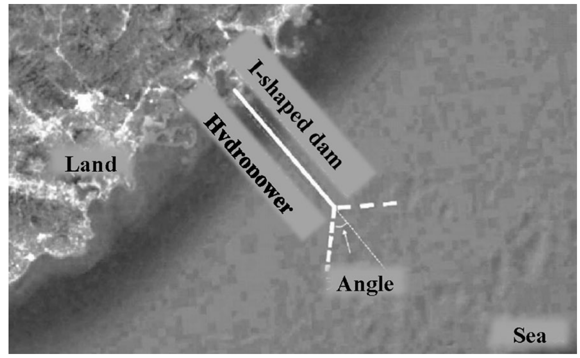

Fig. 7 Dynamic tidal energy development [30]

perpendicular to the coast. Because the tidal wave is transmitted parallel to the coast, the dam built perpendicular to the coast affects the transmission of the tidal wave. In this way, the phase difference of the tidal wave will be formed on both sides of the dam, which will cause the water-level difference to form the power generation head, and power generation will be achieved through the tidal power unit in the dam, as shown in Fig. 7. This method was invented by the Dutch scientist Hulsbergen et al. in 1997 [22–24], and the formation principle of the head difference was explained by the added mass theory, and the calculation and analysis of the water-level difference of the dynamic tidal energy dam were conducted. Mei explained the cause of water head differences from the perspective of tidal wave diffraction [25], and the conclusion is consistent with that of Hulsbergen [22–24]. This method has been studied by many researchers. Adema used Delft3D-Flow to evaluate the dynamic tidal energy reserves in the Chinese sea area [26]. Park analysed the influence of the geometric parameters of the seawall on the head difference [27]. Zheng Siming et al. studied the influence of the length of a T-shaped seawall branch on the water head [28]. Taking the Fujian area as an example, Zhao Jianchun et al. analysed the influence of the construction of a type I dynamic tidal energy seawall and reported that the construction of a dynamic tidal dam affects the original tidal characteristics of the area, and the influence range is approximately 3 times the length of the dam body [29]. Dai Peng et al. optimised the traditional seawall form. Through the calculation and analysis of different branch angles and lengths of the I-type seawall, it was found that when the branch angle was 45°, the peak power of the unit was greater [30].

Advancements in tidal barrage power generation systems

Amidst the energy crisis, nations globally have prioritised the advancement of marine energy. Consequently, coastal

Fig. 8 World's tidal hydropower plants [31]

countries have experienced a surge in their encouragement for tidal energy exploitation in recent years. The development and implementation of tidal energy play important roles in promoting national economic development and improving energy structure, especially for the development of coastal areas. At present, many countries have constructed tidal power stations. In 2006, Dr. Kyul-ho Kwak listed the countries that are building tidal power stations [31], as shown in Fig. 8. Currently, the number of countries that are building tidal power stations is likely greater.

With respect to China, the south-eastern coastal areas opened earlier, and the economy is more developed, such as in Shanghai, Zhejiang, Jiangsu and other places, but the resources in the south-eastern coastal areas of China are relatively scarce. Therefore, the developed south-eastern coastal economy has a high demand for energy but lacks energy in its region, which promotes the development and u of rich tidal energy in the area, and the development of tidal energy has become an important choice to promote the further development of the region. In the coastal areas of Shandong, the use of tidal power generation can change the traditional energy structure of local coal-fired power generation, promote green development, improve the ecological environment, as well as be important for the construction of a new type of power system based on clean energy. For many islands in coastal areas, the in-situ development of tidal energy not only saves the expensive cost of erecting power grids but also provides convenient and abundant supplementary resources for island construction. Therefore, harnessing and using tidal energy can provide a vital supplementary energy source for coastal defence projects and the daily lives and production activities of coastal region residents [32]. The development and implementation of tidal energy can further promote green development, accelerate the transformation to new clean energy power systems, and accelerate the early realization of the dual-carbon goal.

Humans have a long history of using tidal energy. In ancient times, tidal mills, which leveraged tidal energy to power stone mills, were already in existence. However, since 100 years ago, only modern countries have started to use tidal energy to generate electricity. In 1920, the United Kingdom proposed the use of tidal energy to generate electricity. China built many small tidal power stations around 1956; unfortunately, they failed to maintain operation. By 1968, the La Rance tidal power station was built in France [33, 34], and the commercial operation of tidal power generation was realised for the first time in the world. Since then, Russia's Kislaya tidal power station [35], Canada's Annapolis tidal power station [36], China's Jiangxia tidal power station [37], and South Korea's Sihwa tidal power station have been established. This is also the only five tidal power stations with installed capacity at the MW level in the world as of 2024. The parameters of the power station are shown in Table 2.

Globally, the development of tidal energy is highly important for the development of national energy. Table 3 lists the main harbour sites with rich tidal energy resources in the world [7, 8, 39, 40]. As indicated in Table 3, tidal power stations have been built at La Rance Port, Fundy Port, Severn Port, White Sea, Sihwa Lake, Sanmen Bay and other sites. However, the current development of tidal energy is far from the actual amount of development.

The data in Tables 2 and 3 indicate that many countries worldwide are implementing new tidal power station construction plans. For example, the British Severn estuary [41], Canada's Fundy Bay, Russia's Mezeh Bay and Tugar Bay, South Korea's Garlolim Bay, India's Kutch Bay [42, 43], Australia's Secure Bay and Brazil's Sao Luis [40] are all studying the construction of tidal power stations.

Owing to its heavy dependence on traditional fossil energy, South Korea has experienced two fossil energy crises. However, South Korea's fossil energy is still very dependent on imports. To this end, the Korean government has developed the National Master Energy Plan, which aims to increase the share of new and renewable energy by more than 11% by 2030 [44, 45]. The western coast of South Korea has a tidal range of nearly 10 m, which is among the most abundant tidal resources worldwide. Owing to its energy demand and geographical advantages, South Korea has made outstanding achievements in the development and implementation of tidal energy. At present, it has the largest total installed capacity of the tidal power station—the Shihua Lake power station. In the research and development of tidal units, a complete analysis process from numerical simulation to physical experiments was established. Many studies have been performed, from airfoil design to blade force analysis and interaction to unit power curve analysis. The capacity of the designed tidal unit is also increasing [45, 46].

In addition, with respect to the development and implementation of dynamic tidal energy, there is no actual engineering construction within the scope of the author's knowledge. The construction of lagoon tidal power stations began in the UK [47]. The Swansea Bay Lagoon Tidal Power Station, the first tidal lagoon power station in the UK, was initially approved by the government for construction in 2017 [48]. The power station was originally planned to be put into operation in 2019, but it was repeatedly delayed because of environmental protection issues. The annual power generation of the power station can reach 49.5 MWh. It has been proposed that only the tidal barrage power station on the Severn River can provide 5% of the UK's electricity supply [49]. The construction of the power station has a cost of up to 1 billion pounds, but it is estimated that the actual investment of the power station may be approximately 34 billion pounds because of environmental protection factors [50, 51].

Owing to China's vast territorial sea area and long coastline, combined with the data in Table 3, we can see that China's tidal energy resources are relatively rich. In fact, China began to use tidal energy to generate electricity very early, and many tidal power stations have been constructed. However, only the Jiangxia tidal power station and Haishan tidal power station are currently in operation, and other tidal power stations have been abandoned. Both the Haishan tidal power station and the Jiangxia tidal power station are located in Zhejiang Province. The Haishan tidal power station is being updated, with an installed capacity of 500 kW after the update. Owing to the rich experience accumulated in China's conventional hydropower development, the construction experience and operation data of many tidal power stations are combined. China is also constantly conducting innovation and optimization of tidal technology. At present, the Oufei tidal power station, with an installed capacity of 450 MW, is under construction as a new large-scale tidal power station in China [52]. After completion, its total installed capacity may be the largest in the world. In addition, the tidal stations in Fujian, Shanghai and other provinces in China are under development and demonstration, and some projects have begun preliminary construction.

With respect to the development situation of global tidal power stations, it is expected that global tidal energy will enter a new development period in the next 10 years.

Advancements in tidal stream energy conversion technologies

With respect to tidal stream-generating units, seawater flow drives hydroelectric-generating units to generate electricity. Because tidal stream power generation uses only the kinetic energy of water flow, its energy utilisation rate is low. Tidal stream power generation is similar to wind power generation, but the former is water, and the latter is air. Owing to the different characteristics of the medium, the structure of the unit is also different.

Overall, tidal stream generator units can be divided into two types: those with horizontal and vertical axes. The difference between these two types is whether the direction of the shaft is parallel to the direction of the water flow.

With respect to the development of tidal stream power generation technology, the UK has always been at the forefront. In 2003, the UK Marine Company of Turbine installed the first 300 kW SeaFlow tidal stream generator set. In 2008, a 1.2 MW SeaGenS tidal stream generator unit was connected to the grid [53]. At present, the floating tidal stream power generation device, the SeaGenU unit (3 MW), which can be applied to deep-water areas, is being tested [54]. The MeyGen project, established in 2010 and situated in Pentland Firth, is the largest tidal stream project in the world. The site has consent awarded for 86 MW, and the option to develop up to 398 MW. The project has been delivered in phases with the 1st phase operational since 2018, with four 1.5 MW turbines [55]. As of December 2024, phase 1 has delivered more than 70 GWh of clean, predictable electricity to homes and businesses, with 10 GWh produced in 2024 alone [56].

Since 2010, Europe has introduced numerous plans to promote the research and development of marine renewable energy, reflecting the importance of marine renewable energy in Europe. Among them, the EU Horizon 2020 program sponsors many projects, including the development of 2 MW ATIR tidal power units in Spain and the PTO project in Scotland. By the end of 2019, the total installed capacity of tidal stream energy in Europe reached 27.7 MW, and the total power generation reached 49 GW·h [57].

In 2023, the Korea Ocean Research and Development Institute installed the first tidal stream energy generator set. It was the first vertical axis tidal device of a 100 kW helical turbine in Korea. In 2008, the first horizontal axis tidal device, 25 kW, was evaluated. In addition, South Korea plans to develop tidal stream power generation projects with installed capacities of 300 MW and 200 MW in Wando, Incheon and other places [46].

Research on tidal energy in China has developed rapidly since 2010. From 2014 to 2019, Zhejiang University successively assessed and generated horizontal axis tidal stream generators with single-unit capacities of 60 kW, 120 kW, 650 kW and 300 kW [58, 59]. In 2019, the 600 kW bottom-mounted tidal current turbine developed by Harbin Electric Machinery Co., Ltd., passed the acceptance inspection, which is the largest power tidal stream turbine in China with fully independent intellectual property rights [60].

As shown in Fig. 9, the LHD Zhoushan tidal stream power station has maintained stable operation and has been in operation for more than 7 years. In March 2022, the Endeavour turbine, China's first MW-level tidal stream energy generator developed and built by the project, was successfully deployed and connected to the grid. China's first MW-class tidal stream energy-generating unit is currently China's largest single-power unit [62]. As of the end of 2024, the generator has been in continuous operation for more than 30 months, with cumulative grid-connected power generation of more than 4.5 million kWh [61].

Table 2 Global capacity of the top five tidal power stations [38]

State	Name	Mean range (*m*)	Installed capacity (MW)	Completion time
France	La Rance tidal power station	8.4	240	1968
Russia	Kislaya tidal power station	2.3	0.8	1968
Canada	Annapolis tidal power station	6.4	20	1984
China	Jiangxia tidal power station	5.08	4.1	1985
South Korea	Sihwa tidal power station	5.6	254	2011

Table 3 Major worldwide tidal barrage sites

Location		Mean range (*m*)	Potential mean power(MW)	Potential annual production (GWh/year)
North America	Passamaquoddy	5.5	1800	15800
	Cobscook	5.5	722	6330
	Bay of Fundy	6.4	765	6710
	Minas-Cobequid	10.7	19900	175000
	Amherst Point	10.7	256	2250
	Shepody	9.8	520	22100
	Cumberland	10.1	1680	14700
	Petitcodiac	10.7	794	6960
	Memramcook	10.7	590	5170
South America	San Jose, Argentina	5.9	5870	51500
United Kingdom	Severn	7.0	8640	17000
	Mersey	6.5	700	1500
	Solway Firth	5.5	1200	10000
	Thames	4.2	230	1400
France	Aber-Benoit	5.2	18	158
	Aber-Wrac'h	5	6	53
	Arguenon	8.4	446	3910
	Frenaye	7.4	148	1300
	La Rance	8.4	349	3060
	Rotheneuf	8	16	140
	Mont St Michel	8.4	9700	85100
	Somme	6.8	466	4090
Ireland	Strangford Lough	3.6	350	3070
Russia	Kislaya	2.4	2	22
	Lumbouskii Bay	4.2	277	2430
	White Sea	5.65	14400	126000
	Mezen Estuary	6.6	370	12000
Australia	Kimberley	6.1	630	5600
South Korea	Garorim Bay	6.7	520	950
	Sihwa Lake	7.8	254	553
	Incheon	7.7	1320	2214
	Kanghwa	7.6	840	1556
	Chonsu	5.9	720	1207
China	Qiantang River Estuary	4.5	5360	16110
	Sanmen Bay	4.5	1940	5340
	Xinghua Bay	5.5	2397	6592
	Sandu Bay	5.34	1293	3557
	Fuzhou Bay	4.55	1199	3297
	Fuqing Bay	4.21	1156	3179

Even if the influence of tidal stream power generation on the marine environment is small [63], compared with previous data, the single-unit capacity of tidal stream power generation is relatively small. In addition, owing to the high cost of offshore installation and maintenance, the tidal stream generator unit has not yet entered large-scale commercial operation. However, owing to the development of wind power technology, the development of tidal stream energy units is accelerating. In recent years, it has received increasing attention and has made great technological progress.

With the continuous progress of tidal energy development and implementation technology, the annual power generation growth rate has increased significantly [64].

Fig. 9 LHD Zhoushan tidal stream power station in operation [61]

However, there is still a large gap from the target of a 23% annual power generation growth rate set in the International Energy Agency's 2030 Sustainable Development Scenario [65, 66]. This requires us to continuously accelerate the iterative application of technology, summarise the existing technical problems, and accelerate the high-quality development of tidal energy.

Critical challenges in tidal energy deployment

Since the usage of tidal power stations was put forward over the past century, and although tidal power station construction projects have been implemented, large-scale development and usage have not been achieved until now. There are only five tidal power stations with installed capacities of more than a MW worldwide. Because tidal energy, which contains abundant clean energy, has not yet been ushered in large-scale development and usage, through the author's in-depth investigation and analysis, the following main problems have been identified.

Technical limitations

The construction and implementation of tidal power stations require a series of complex technologies and equipment. Owing to the electrochemical effects of seawater ions and microbial adhesion, developing, applying and maintaining equipment for tidal power generating units is very difficult. The construction of tidal power stations needs to be matched with the construction of local power grids to ensure that the generated electric energy can be consumed in time. However, because tidal power stations are usually built in sea areas far from land, the cost of grid access is high, and long-distance transmission technology is challenging. In addition, the current calculation method is not mature for the accurate prediction of tidal energy reserves. To accurately calculate tidal energy with existing hydrological observation data is also an important challenge.

Economic barriers

The construction and operation of tidal power stations require large capital investments. Owing to the higher performance requirements of their units, their production costs are also higher [67, 68]. According to statistics, the unit cost of tidal power stations is approximately 2 ~ 3 times that of traditional hydropower units [69, 70]. In addition, because tidal power stations are usually built in sea areas far from land, the cost of grid access is high, and the distance of transmission lines is long, which leads to the high cost of corresponding facilities such as substations. Moreover, owing to the vulnerability of tidal units to natural disasters such as waves and storms, the cost of operation and maintenance during the later period and the risk of safe operation increase sharply [71].

The increase in production costs makes tidal electricity prices relatively expensive. A report revealed that the power generation cost of lagoon power stations in the UK is approximately 1.68 yuan/kWh [72]. The current price range of tidal power stations in China is 1.386–2.6 yuan/kWh, which is equivalent to the international price but still higher than other renewable energy prices [73].

Environmental concerns

The construction and operation of tidal power stations may have irreversible negative effects on coastal ecological environments [74–78]. For example, dam construction can change the flow characteristics of estuaries and coastal areas and may affect the habitats and migration routes of fish and other marine organisms. The paint on the tidal unit equipment is toxic. The current and magnetic field generated by tidal power stations also have important effects on marine organisms. Moreover, the dam affects seabed sediment movement, thus causing serious sediment deposition at the dam site and even affecting the normal operation of the unit [79].

Policy and planning gaps

The development and exploitation of tidal energy, with a high degree of cleanliness, is important for alleviating the global energy crisis, and provides a solid energy guarantee for the development of coastal countries. However, the government's policy system, laws and regulations for the development and usage of tidal energy are still not perfect at present, and owing to the high investment cost and long construction period of tidal power stations, enthusiasm for tidal energy development is not strong. The extensive development and application of tidal energy cannot be separated from the guidance and support of the government. Governments should provide corresponding financial support or policy guidance to promote the market-oriented development of tidal energy, formulate corresponding incentive policies, and promote the rational and orderly development of tidal energy [80].

Systemic challenges: coordination of multienergy integration

Bays near tidal power stations are usually rich in marine energy, such as offshore-wind energy, wave energy, and thermal energy, and there is great randomness and inhomogeneity between different marine energy sources over time. Owing to changes in sea conditions, tidal power stations are bound to have an impact on other marine energy sources while developing and using tidal energy. Therefore, when developing tidal energy, it would be advisable to focus on maximising the use of marine energy in this area rather prioritising one over another. In China, there is extensive experience in construction and operation of tidal power stations, and many valuable insights have been reported.

Many tidal power stations were built between 1950 and 1990, but by 2024, but only the Jiangxia and Haishan tidal power stations are still in operation, and the reasons are complex. Setting aside the background of the times, China's lack of knowledge in geological surveys, environmental impact, sediment movement and other data before the construction of tidal power stations has led to the inability of sediment storage reservoirs to operate after the completion of some tidal power stations. The actual benefits are therefore not high, and it is difficult to maintain operation. As a result, in order to achieve large-scale development and implementation of tidal energy, we should give attention to the solution of the above problems.

Strategic pathways for sustainable tidal energy development

Under the predicament of the energy crisis, with the continuous development of renewable energy, humans have mastered the technology of development and implementation of tidal energy and have planned and constructed many typical tidal power station projects. In the process of the continuous development and exploration of tidal energy, many experts and scholars have gained some experience as follows.

Cost reduction and revenue enhancement strategies

Reducing the construction cost of tidal power stations and obtaining more benefits are the primary issues in the development of tidal energy. In actual construction and operation, some experiences have been gained. For example, during the construction of tidal power station dams in Russia, prefabricated floating settlement construction technology is adopted. This method does not require the establishment of cofferdams; it directly transports prefabricated concrete components to designated *locations* through ships and then settles them to the required parts. This method not only greatly shortens the construction period but also reduces the construction cost by approximately 45%. Improving the tidal power station turbine unit is also being conducted. The cost of a full-flow turbine unit in Canada is approximately 20% lower than that of an ordinary turbine unit [81]. Because a tidal turbine unit is characterised by a low head and high flow, its low working head also makes the pressure of the flow components relatively low. The use of new materials, such as tempered plastic, to replace steel and the replacement of concrete dams by rubber dams in shallow-sea areas can reduce costs [82]. Men Chuangshe et al. [83] proposed a variable-speed technology based on hydropower units and studied and analysed the variable-speed characteristics of tidal power units. The power generation of variable-speed units is 3.65% greater than that of constant-speed units, and the power generation of units under the reverse power generation condition is increased by 10.4%. This provides a good way to further increase income and reduce the cost pressure on tidal power stations.

Eco-compatible technology development

The impact of tidal power stations on the environment is an important factor hindering the development of tidal energy. We have also been working on the development of environmentally friendly tidal power stations. At present, the impact on the environment can be reduced by developing technologies such as lagoons, dynamic tidal energy, and fish-friendly turbines. Lu Jiahao et al. proposed the development and verification of a fish-friendly turbine for tidal power stations [84]. This scheme incorporates the Archimedes spiral pump to design and verify a fish-friendly turbine. The low-pressure zone of the turbine is smaller, and the low-pressure zone is larger; thus, it is friendlier to fish. The efficiency of the turbine is 3.5% higher than that of the prototype turbine. In addition to the development of hydraulic turbines, fishways are very important for fish protection. Through the analysis and verification of fishway facilities, Ivanlov et al. proposed appropriate fishway setting parameters [85].

Technological innovations in resource assessment and design

The accurate study of tidal energy should be based on accurate hydrological statistics through the analysis of measured hydrological data to further explore the mechanism of tidal change. With the help of acoustic Doppler velocimeters and current profilers, James et al. discussed the turbulent characteristics of water flow in the Salish Sea of the United States during the tidal cycle. The turbulence intensity and turbulence loss in different regions are introduced, and valuable original data are accumulated [86].

In view of the backward research methods, the rapid development of computing technology can be used. Through professional knowledge of the relevant calculation software and professional adjustment of the software structure, the tidal energy problem can be better managed, and data can be accurately calculated. With the help of calculation software, Zhu Xueming, Gao Fei and Gu Zhenhua et al. conducted numerical simulation analyses of tidal energy in China's coastal areas and achieved good results [9, 87, 88]. Alessandro et al. also used the Regional Ocean Model System (ROMS) to evaluate the tidal potential of the Brazilian Equatorial Shelf and reported that the tidal range of three regions exceeded 3 m and that the tidal range of some regions could reach 4–5 m [89]. Via the use of the ROMS and surface-water modelling system methods, Narit et al. simulated and analysed the tidal stream velocity and tidal energy density on the southwest coast of the Andaman Sea in Thailand. The feasibility of building tidal power stations in some areas has been analysed [90].

In addition, it is necessary to increase the research and development of new materials and new processes. To improve the corrosion resistance and maintenance cycle of hydraulic turbines and other facilities, their operating life should be enhanced. It can also alleviate the technical problems associated with long-distance transmission lines. Moreover, it is necessary to connect with the local power grid management department, deploy and build supporting facilities, fully utilise the locally built facilities, and ensure the consumption of electric energy.

Engineering optimization for sediment management

The construction of tidal power stations inevitably affects the sediment-carrying movement of seawater. The key is to ensure that the reservoir area of the power station does not deposit silt to ensure the normal operation of the tidal power station. In practice, it is possible to avoid high sediment areas by selecting a reasonable reservoir address, such as the location of the La Rance tidal power station and the Jiangxia tidal power station. The port exhibits a low sediment content. In addition, through the reasonable design of the inlet and outlet gates, the ebb flow velocity can be greater than the flood flow velocity, thus solving the problem of sediment deposition. The problem of sediment deposition in the reservoir area of tidal power stations can also be alleviated by setting corresponding gates for flushing and dredging to ensure the normal operation of hydropower units [91]. Matthew Willi Brand et al. created a high-resolution 3D hydrodynamic model to analyse the tidal energy in south-eastern Alaska's studied sites with abundant tidal energy [92].

Policy-driven planning and market incentives

Currently, nations are vigorously pursuing renewable energy alternatives to minimise the reliance on fossil fuels. With respect to tidal energy advancements, developed nations, such as the United Kingdom and Canada, have sustained significant investments in R&D for pioneering tidal energy technologies. It also provides corresponding policy assistance to tidal energy developers, optimises the electricity price mechanism and marine energy development licensing system, and formulates relevant bills to ensure the extensive development and implementation of tidal energy [48]. China's *14th Five-Year Plan for Renewable Energy Development* also clearly highlights that it is necessary to steadily promote tidal power generation and the development of marine energy [93, 94]. Lekelia investigated the construction of tidal power stations in different regions of the United States. This study revealed that there was overall support in a smaller community isolated from municipal power sources that had a demonstrated need for energy. Areas that do not lack energy have weak support to new energy construction [95]. Therefore, it is necessary for the state to plan and guide the construction of tidal energy and coordinate the development of tidal energy from the overall level of the country.

Synergistic use of marine energy resources

Owing to the vicinity of the bay, there are usually abundant marine energy sources, such as tidal energy, offshore-wind energy, wave energy, and thermal energy, and there is a large degree of randomness and inhomogeneity between different marine energy sources over time. Ensuring the maximum development and usage of marine energy and maximising the benefits are the most critical development goals. At present, some countries are actively implementing both the offshore wind and wave energy bases, as well as joint operations involving offshore wind, tidal and wave energy.

The complementary mechanism of multienergy development includes rational and efficient use of marine energy, which not only improves economic benefits but also ensures power quality. In addition, the experience in the operation of the Lance and Jiangxia tidal power stations shows that the tourism and aquaculture income brought by the construction of tidal power stations often exceed the power generation benefit. Therefore, it is necessary to conduct sufficient energy assessment and analysis in the development area and implement comprehensive development and efficient usage of energy. Moreover, the joint scheduling technology of different power stations should also be optimised. Luo et al. reported that optimization simulation of power dispatching allowed the daily power generation of tidal power stations to be increased by 14.55% by optimising the power system dispatching technology [96]. In the development and implementation of tidal power stations, the focus of numerous researchers has been on increasing power generation.

Zhang Bin et al. referred to the operation experience of the La Rance Power Station and reported that after the end of ebb tide power generation or flood tide power generation, the water level in the reservoir area can be further reduced or increased by a water pump to increase the power generation head. Because the pump works under low water head, and a raised water head can generate more power in the power station, this method can improve the benefit of the power station. In addition, because tidal power stations lack flexibility, intermittent power generation has always been a problem in the context of the power grid. The use of reservoir pairing has been mentioned above, but owing to geological conditions and other reasons, few tidal power stations with such conditions may exist. Some researchers have proposed coordinating tidal power stations with pumped storage power stations in the region to compensate for the intermittent power generation of tidal power stations [97]. In fact, to compensate for the problem of intermittent power generation in tidal power stations, many power companies use wind power, hydropower, photovoltaic power and other renewable energy sources to operate together with tidal power stations. In 2022, China's Jiangxia tidal power station successfully added a photovoltaic power generation module with an installed capacity of 100 MW, which realised complementary tidal and solar power generation. The average annual power generation can reach 100 million kWh, saving approximately 31,654 tons of standard coal. The average frequency modulation effect can reach more than 95%, and the response level can be increased to milliseconds. This provides a compelling argument for enhancing the power quality of tidal power stations and optimising the exploitation of marine resources.

Summary

The rapid development of tidal energy, a form of clean energy, can significantly reduce carbon emissions, mitigate the greenhouse effect, and alleviate energy crises in certain regions. The development and implementation of tidal energy can increase the momentum of coastal regions, especially by increasing the economic development of coastal port areas [98]. Choosing China in a case study, this paper provides a comprehensive overview of the development of tidal energy worldwide. By introducing the generation mechanism of tidal energy, the principles of tidal power stations, and the latest technologies for tidal energy development and its implementation, this paper delves into the characteristics and challenges of tidal power generation technology. The latest parameter statistics of existing tidal power stations provide a technical reference for the future development and usage of tidal energy. The conclusions are as follows.

(1) Global tidal energy reserves are exceptionally abundant, offering a viable alternative for traditional fossil energy.
(2) Tidal energy is characterised by its cleanness, non-polluting nature, renewability, stability, and reliability. As the most mature technology in marine energy applications, it has achieved large-scale commercial development.
(3) Tidal power stations are characterised by a variety of development methods, and the global tidal power station construction process is accelerating, with good development prospects.
(4) The development and implementation of tidal power stations face significant challenges, such as high investment costs and potential changes in the ecological environment, which developers should carefully address.
(5) In the face of many technical problems in the development and implementation of tidal energy, researchers have proposed many improvement measures. These include the adoption of advanced units and innovative construction methods to reduce costs, as well as dynamic tidal energy development and lagoon tidal energy development to reduce environmental impacts. Countries worldwide are gradually improving their own marine energy policy systems and are continuously enhancing scientific guidance for the comprehensive development of tidal energy.

Conclusions

Owing to the limited global energy development, some countries are actively promoting the development of marine energy resources, such as tidal energy. To promote greater development of the tidal energy development technology, strengthening future research in the following directions is suggested.

(1) The optimization of the construction process of tidal power stations should be enhanced, with greater emphasis on the overall planning of the comprehensive development and implementation, in order to maximise the benefits of power station development.
(2) Research efforts for the design and materials of tubular turbines and dams should continue to increase, and the research and development of new tidal power generation technologies, such as environmentally friendly turbines and variable-speed operation, should be promoted.
(3) The leading role of the government should be strengthened by using scientific planning and implementation of tidal power station construction and macro adjusting development directions, fostering a favourable environment for tidal energy development, advancing new technological progress, and promoting the healthy development of the industry.

Acknowledgements

When writing the manuscript, the author used DeepL Write to check grammar and spelling and to make minor improvements to readability and style. After using this tool, the author checked the content and edited it where necessary. He takes full responsibility for the content of the publication.

Author contributions

Xiaochao LI, Chun GAN, Shangqi LI and Hao ZHANG contributed equally to this paper. Conceptualization: Guanglei XIAO, Hao ZHANG Methodology: Xiaochao LI, Guanglei XIAO, Hao ZHANG Investigation: Yi LUO, Zhiyang LU, Shangqi LI Visualization: Zhiyang LU, Shangqi LI Supervision: Minping XIE Writing—original draft: Xiaochao LI Writing—review & editing: Ye ZHOU, Zhongxin GAO, Chun GAN

Funding

The authors are grateful for the financial support provided by the China Institute of Water Resources and Hydropower Research (HM110145B0012023).

Data availability

The survey data used for the analysis in this study is available upon request from the authors, provided that disclosure does not violate data protection regulations.

Declarations

Ethics approval and consent to participate

The authors declare that they have adhered to the ethical standards of research.

Consent for publication

The authors declare their consent for publication.

Competing interests

The authors declare no competing interests.

Author details

[1]State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Beijing 100038, China. [2]China Institute of Water Resources and Hydropower Research, Beijing 100038, China. [3]State Grid Xinyuan Company LTD, Beijing 100032, China. [4]North China University of Water Resources and Electric Power, Zhengzhou 450045, China. [5]China Three Gorges Corporation, Wuhan 430010, China.

Received: 19 January 2025 Accepted: 13 October 2025
Published online: 06 November 2025

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