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Review

Challenges in tidal energy commercialization and technological advancements for sustainable solutions

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https://doi.org/10.1016/j.isci.2025.112348

SUMMARY

With the intensification of environmental pollution and energy crises, people have increasingly emphasized the development and utilization of renewable energy. The ocean, as one of the regions with the richest resources on Earth, is also abundant in energy resources. Ocean tidal energy, as a high-quality renewable energy, has attracted significant attention. Its working principle is to convert the kinetic energy of seawater into electrical energy during the ebb and flow of tides. However, due to limitations in tidal energy technology and costs, its commercial development still faces challenges. The purpose of this article is to further promote the commercial development of tidal energy. The paper reviews the economic methods for evaluating ocean tidal energy, analyzes the economic benefits of tidal energy commercialization, and looks back at different tidal energy technologies at the present stage as well as the prospects for these technologies. The author employs an economic cost assessment model, taking into account various cost factors of tidal power generation, such as construction costs, maintenance costs, repair costs, and operating costs. By comparing the costs, the author deduces the advantages and disadvantages of different technologies and further analyzes their feasibility. Based on these analytical discussions, the article provides relevant development suggestions. To a certain extent, this article offers reference significance for policymakers, investors, and related enterprises.

INTRODUCTION

The ocean covers approximately 71% of the Earth's surface and is a vast treasure trove of resources, including biological,[1,2] energy,[3,4] spatial,[5,6] and chemical resources.[7,8] Figure 1 illustrates the global and Chinese ocean economy industries. The data in Figures 1 and 2 are sourced from the Organization for Economic Co-operation and Development (OECD),[9,10] while the data in Figure 3 are from the Ministry of Natural Resources of China. From Figure 1, it is evident that the global marine economy is on a continuous upward trend. Observations indicate that the share of renewable energy in the marine industry is on the rise, with growing attention being given to the development of marine renewable energy sources. However, the overall contribution of renewable energy to the marine sector remains relatively low. Currently, wind energy is the dominant form of marine renewable energy. Currently, in addition to offshore wind power, other offshore renewable energy technologies include solar photovoltaic (PV),[11,12] solar thermal,[13,14] wave,[15,16] tidal,[17,18] and bioenergy.[19,20] Figure 4 shows the investment in offshore renewable energy from 2012 to 2022, as reported by the International Renewable Energy Agency (IRENA),[21,22] while Figure 5 illustrates electricity generation from marine renewable energy sources. It is evident that the sector is experiencing significant growth. Among these, solar and wind energy are the most technologically mature and widely used renewable marine energy sources. However, both wind and solar energy are less stable and more unpredictable.[23–26] In contrast, tidal energy holds great potential as a marine renewable resource, and its development and application warrant further exploration.

Tidal phenomena are stable and predictable natural forces in the ocean, and there is an abundant amount of tidal current energy (see Figures 6 and 7). Thus, ocean tidal energy offers several advantages, including excellent stability, strong predictability, high energy density, and sustainability, making it an environmentally friendly and reliable energy source. However, the development of the tidal energy industry has been relatively slow and remains in the early stages of commercialization. This is due to several limitations and challenges, such as the complexity of equipment design and manufacturing, high maintenance and operational costs, and the potential impact on other marine industries.[27–29] Consequently, overcoming these challenges has become an urgent issue that requires immediate attention.

The purpose of this article is to contribute to the further commercialization of ocean tidal energy. By reviewing various

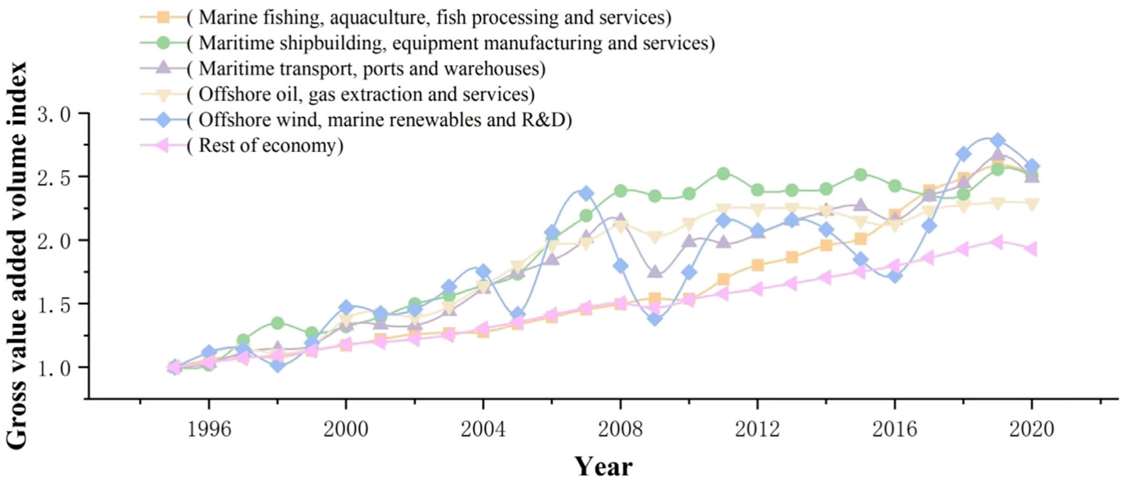

Figure 1. Global growth in production by ocean economic activities
Gross value-added volume index (1995 = 1).

methods for evaluating the economic benefits of tidal energy generation, as well as examining different conversion technologies and development trends, the article offers a discussion and analysis of tidal energy technologies based on an economic cost assessment model. The goal is to identify the key obstacles hindering the commercial development of ocean tidal energy and propose corresponding solutions and future prospects. In this regard, this article aims to serve as a valuable reference for advancing the commercial development of ocean tidal energy.

TIDAL ENERGY TECHNOLOGY VISION

Basic concept

Tidal currents are the horizontal flow phenomena of seawater caused by the ebb and flow of ocean tides. Their formation mainly stems from the gravitational effects of the Moon and the Sun on the Earth,[30–33] as shown in Figure 8. Under the influence of these dual gravitational forces, the seawater in the ocean exhibits periodic ebb and flow. When the seawater is rising tide, it surges toward the coast forming flood tidal currents; while during the falling tide, the seawater flows back to the depths of the ocean generating ebb tidal currents. These two types of flows together constitute tidal currents. The energy sources of tidal energy are rich and diverse. For example, the gravitational forces of the Moon and the Sun make the seawater possess different potential energies at different positions. As the seawater flows from a position with high potential energy to one with low potential energy, the potential energy is gradually converted into kinetic energy, providing a powerful driving force for tidal currents. Moreover, in places like narrow straits and bays, the speed of tidal currents will be accelerated and the energy will be more concentrated. The topography and geomorphology of the ocean also play an important role in this respect.[34–36]

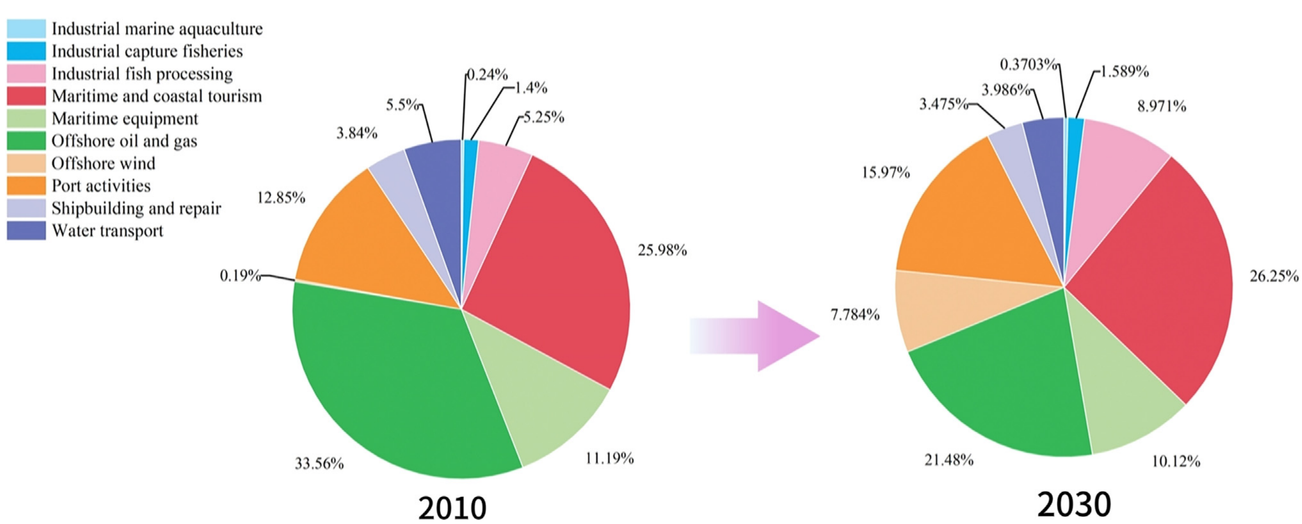

Figure 2. Value added of ocean-based industries in 2010 by industry. & Value added of ocean-based industries in 2030 by industry

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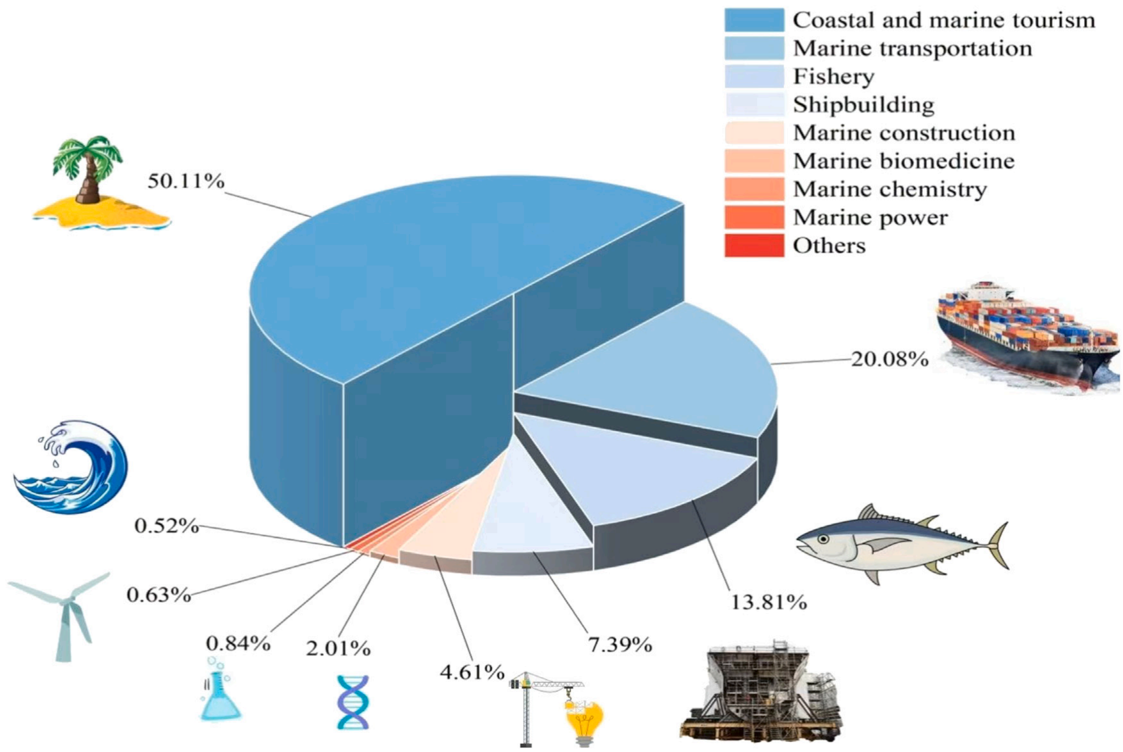

Figure 3. Economic structure of East China Sea in 2020

Resource assessment

Energy extraction from tidal streams has the following advantages.[37–41] Tidal currents have obvious periodicity and predictability,[42,43] which are basically consistent with the period of ocean tides. Generally, tidal currents appear in the form of semidiurnal tides or diurnal tides, with periods of approximately 12 h and 25 min and 24 h and 50 min respectively. The water flow and flow velocity of tidal energy are relatively large.[44] Compared with other new energy sources, tidal currents can provide more energy within the same unit volume and can utilize space resources more efficiently. Extracting energy from the ocean generally does not produce greenhouse gases such as carbon dioxide, sulfur dioxide, and nitrogen compounds or nuclear pollutants and has a relatively small impact on the marine environment.[45–49] Moreover, by

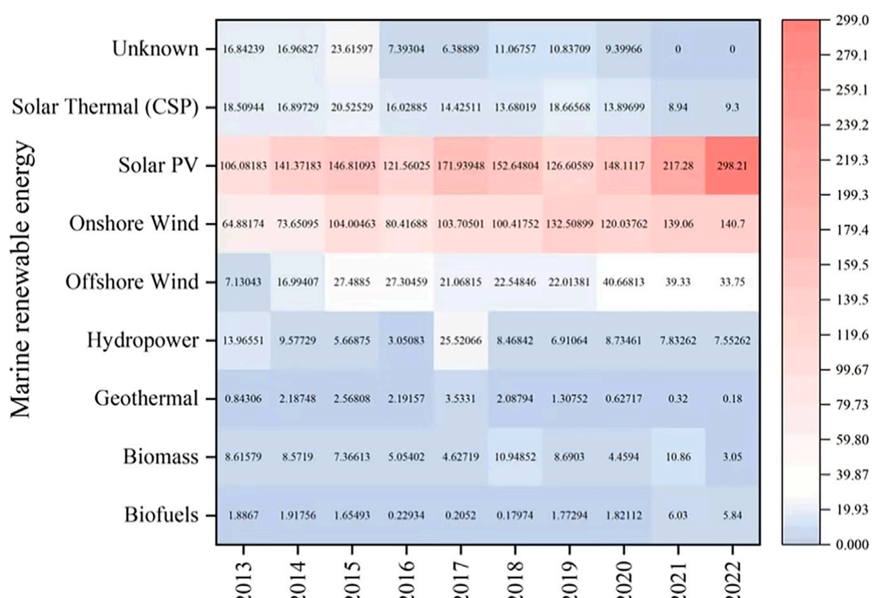

Figure 4. Global growth in production by ocean economic activities, 2012–2022

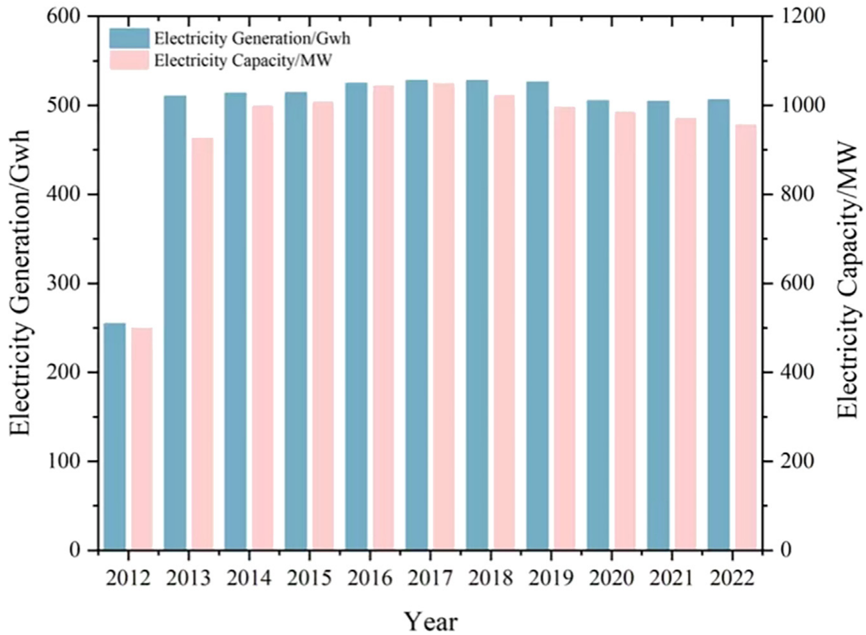

Figure 5. Renewable energy generation, 2012–2022

scientifically improving the shape and speed of the blades, tidal energy equipment can enable marine organisms such as fish to pass safely. In general, tidal energy technology, being underwater, is not affected by factors such as rain, fog, or clouds, while these factors can have a significant impact on other forms of renewable energy like solar energy or wind energy.

When it comes to water currents, they take on multiple forms, each with its own unique formation mechanisms and characteristics. Among them, ocean currents, tidal currents, and river currents are the most important ones, as shown in Table 1. Since the flow and velocity of rivers are affected by multiple factors such as precipitation, evaporation, topography, and human activities, their stability is relatively low. Both ocean currents and tidal currents have obvious periodicity and can maintain relatively regular flow directions and velocities over a long period of time.[50] Moreover, the energy density of river currents is usually low. The velocity and flow of rivers are relatively limited and are greatly influenced by factors such as seasons and topography. Therefore, most

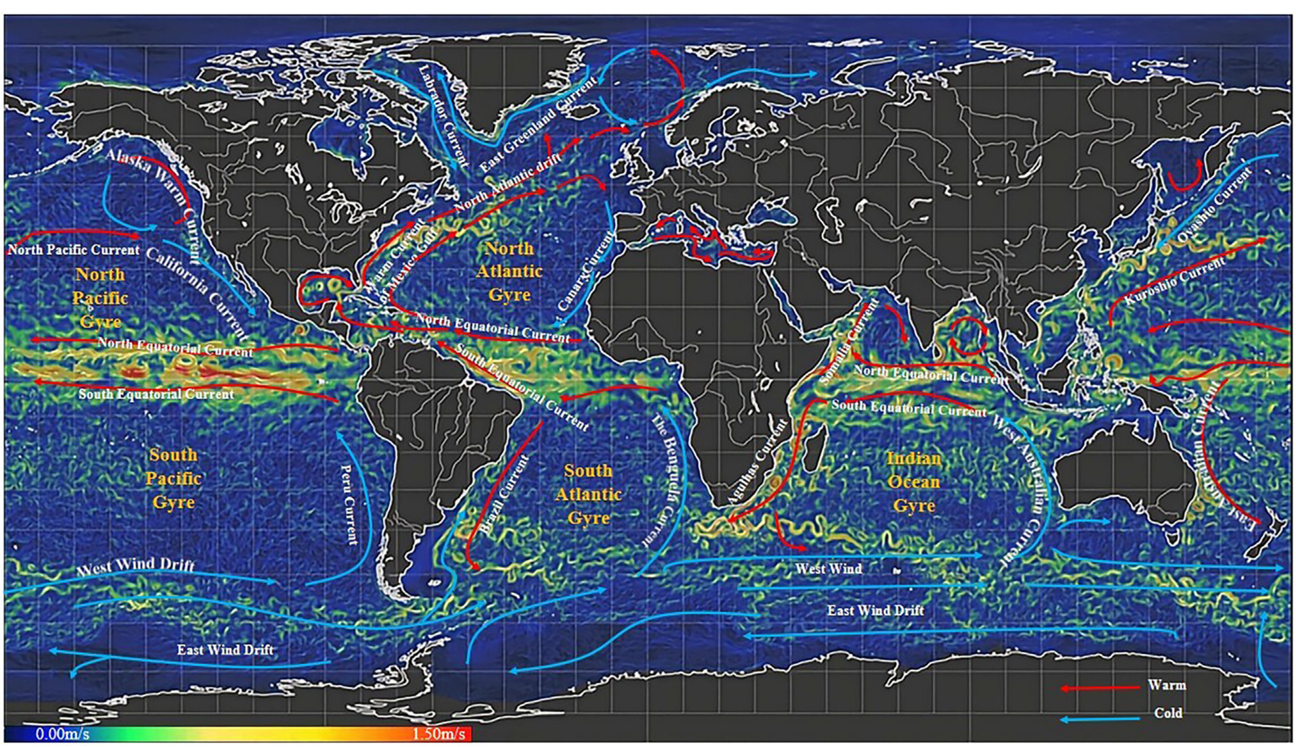

Figure 6. Visualization of global ocean currents

(Note: The red line is the warm current, the blue line is the cold current, the black part of the map is the mainland. The colors represent the approximate velocity of ocean currents in the area.).

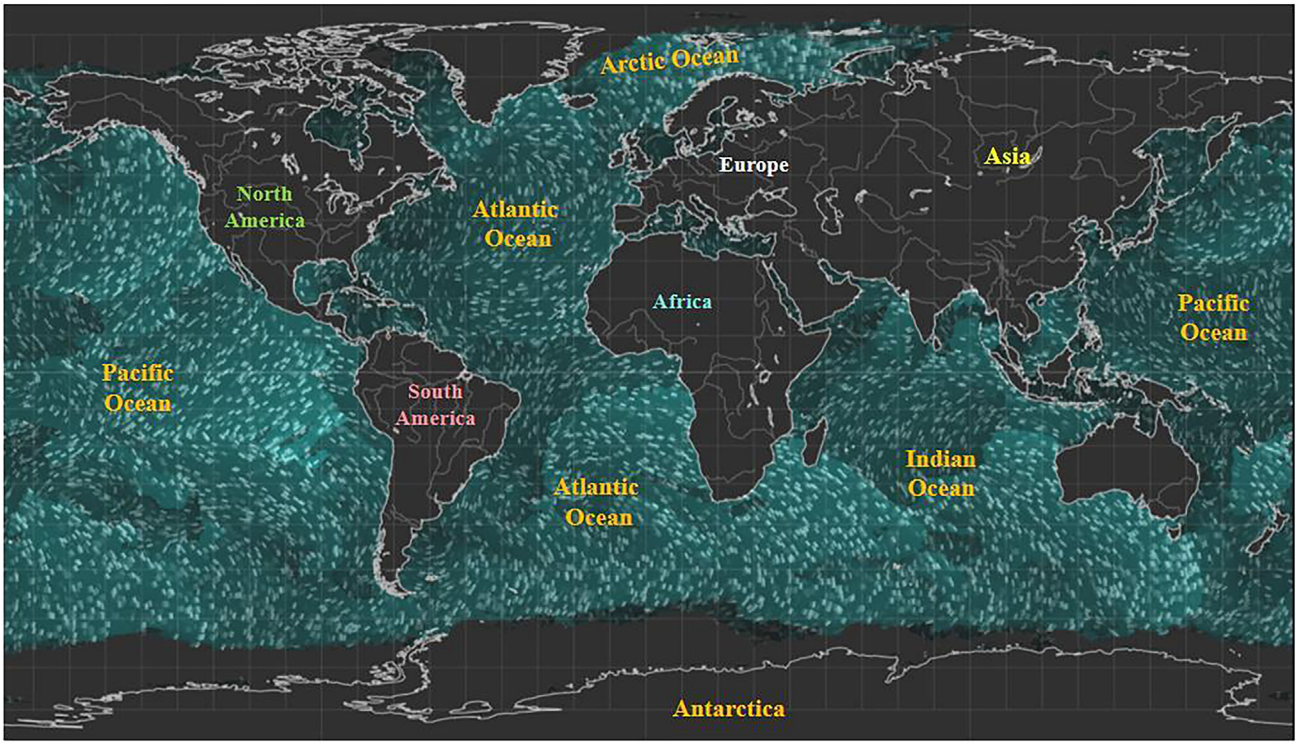

Figure 7. Global wave chart
(Note: Except for the black part of the continent, the rest are the appearance of waves.).

scientists are focusing on the development of ocean currents and tidal currents so that better prediction and management of ocean currents and tidal currents can be achieved.[51]

According to Bryans et al. and O'Rourke et al.,[52,53] the assessment of marine current energy resources can be divided into three main categories.

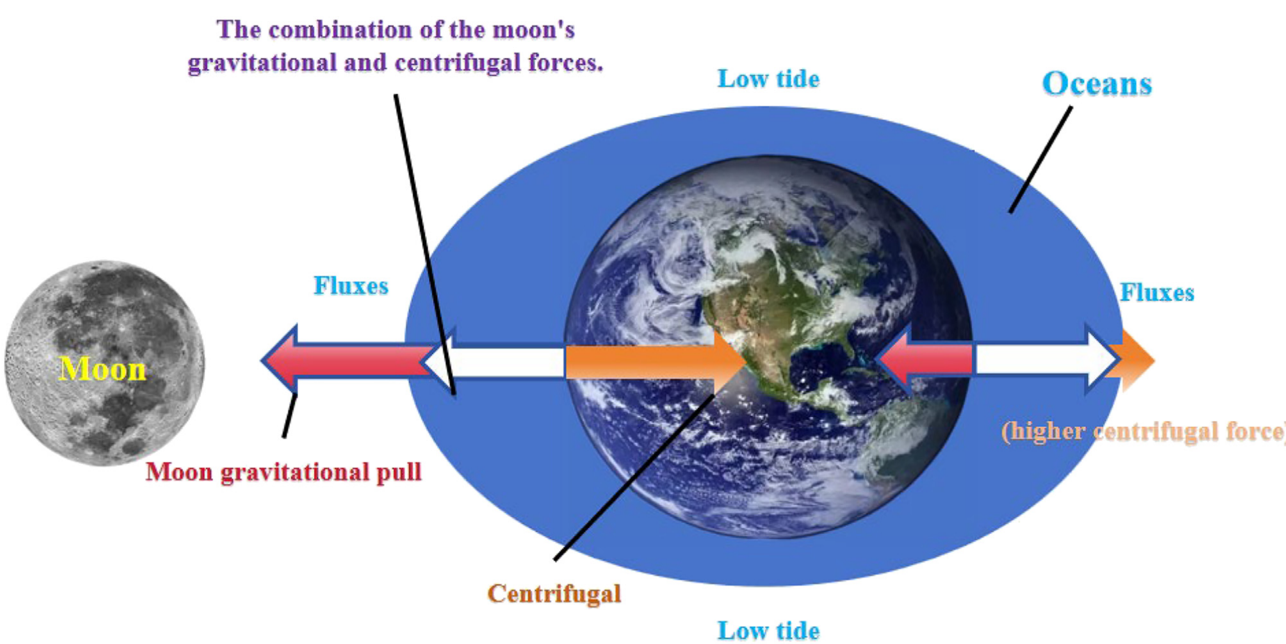

Figure 8. Causes of tidal phenomena

Table 1. Compare the characteristics of different water flows

Name of the water stream	Stability	Predictability	Energy density	Difficulty of exploitation
River currents	Relatively low	Relatively low	Relatively low	Relatively low
Ocean current	Relatively high	Relatively high	High	Relatively high
Tidal current	Medium	High	Relatively high	Medium

Resource quantity assessment[54–57] involves measuring the velocity and flow rate of ocean currents across different sea areas, depths, and times, using specialized instruments such as acoustic doppler current profilers (ADCP). In the practical development of ocean current energy, the ideal flow velocity typically ranges from 1.5 to 3 m/s. A flow velocity of 1.5 m/s is generally sufficient to generate a stable power output.[58,59] Areas where the tidal peak velocity exceeds 2.5 m/s are considered to have a high tidal energy utilization potential. However, when the flow velocity exceeds 3 m/s, it places increased stress on the energy extraction equipment, requiring stronger blades, enhanced equipment stability, and higher maintenance costs.

Stability assessment[60] involves conducting long-term observations of ocean current data, while analyzing the effects of factors such as seasonal and climate variations. This provides valuable information for the resource quantity assessment and helps inform development decisions.

Development potential assessment[61–63] evaluates whether current technological capabilities are sufficient to meet the needs of ocean current energy development. This includes assessing the development costs and benefits, analyzing the environmental impact, and conducting a comprehensive review of the potential energy resources.[64]

Notable tidal energy sites around the world include the Amazon River, the Arctic Ocean, the Bay of Fundy, the Bosporus Strait, the English Channel, the Strait of Gibraltar, the Gulf of Mexico, the Gulf of St. Lawrence, the Hebrides, the Irish Sea, the Florida Strait, the Taiwan Strait, the Mozambique Strait, the Skagerrak-Kattegat Strait, and the Strait of Magellan.[65]

Tidal energy converter technology

Tidal energy converters, developed to convert tidal energy into mechanical energy, are generally used in river currents, ocean currents, and tidal currents as mentioned above. To provide a comprehensive review of the main technologies in tidal energy converters, this paper classifies them based on different criteria. The first classification is based on equipment types. Based on our research in various papers, we identify five main forms.

(1) Horizontal-axis tidal current turbines.[66–69] As shown in Figure 9, the O2 tidal turbine developed by Scotrenewables Tidal Power in Scotland features a runner shaft that is perpendicular to the direction of water flow. This vertical structural arrangement allows the blades to more effectively capture the force of the water flow. Such turbines perform well in areas with relatively high and stable tidal currents and are typically installed in coastal regions with significant tidal current resources.

(2) Vertical-axis tidal current turbines.[70–74] As shown in Figures 10 and 11, the runner shaft of these turbines is oriented perpendicular to the water surface, providing a central axis for blade rotation. The blades may be vertical or spiral to enhance their ability to capture water flow. However, since vertical-axis turbines require a relatively large starting torque and have difficulty starting in low-velocity tidal currents, they are typically located in areas with large tidal flows and complex tidal current directions.

(3) Axial-flow turbines.[75–78] As shown in Figure 12, the axis of the runner blades in these turbines is parallel to the direction of water flow, providing high conversion efficiency in environments with strong, unidirectional currents. These devices are similar in principle and structure to axial-flow wind turbines, but they are smaller and more efficient when operating underwater.

(4) Tubular turbines.[79–81] As shown in Figure 13, the water flow channels in these devices are straight, with the runner body shaped like a light bulb, resulting in relatively low hydraulic losses. Tubular turbines are better suited for areas with a large water flow but a relatively small tidal range. Therefore, they are commonly used in run-of-river power stations to generate electricity by harnessing the natural flow of rivers.

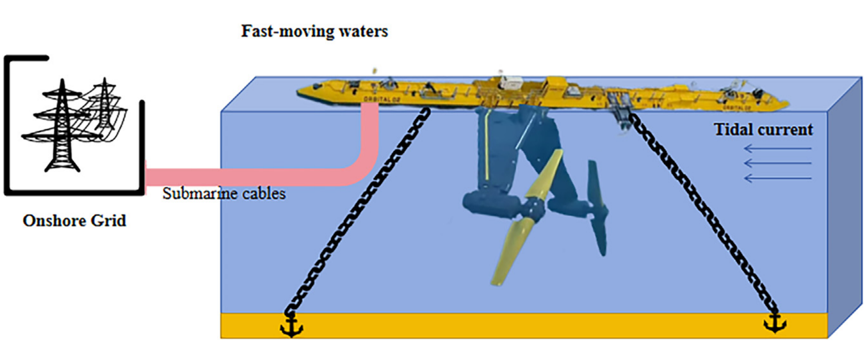

Figure 9. The O2 tidal turbine from Orbital Marine Power in Scotland

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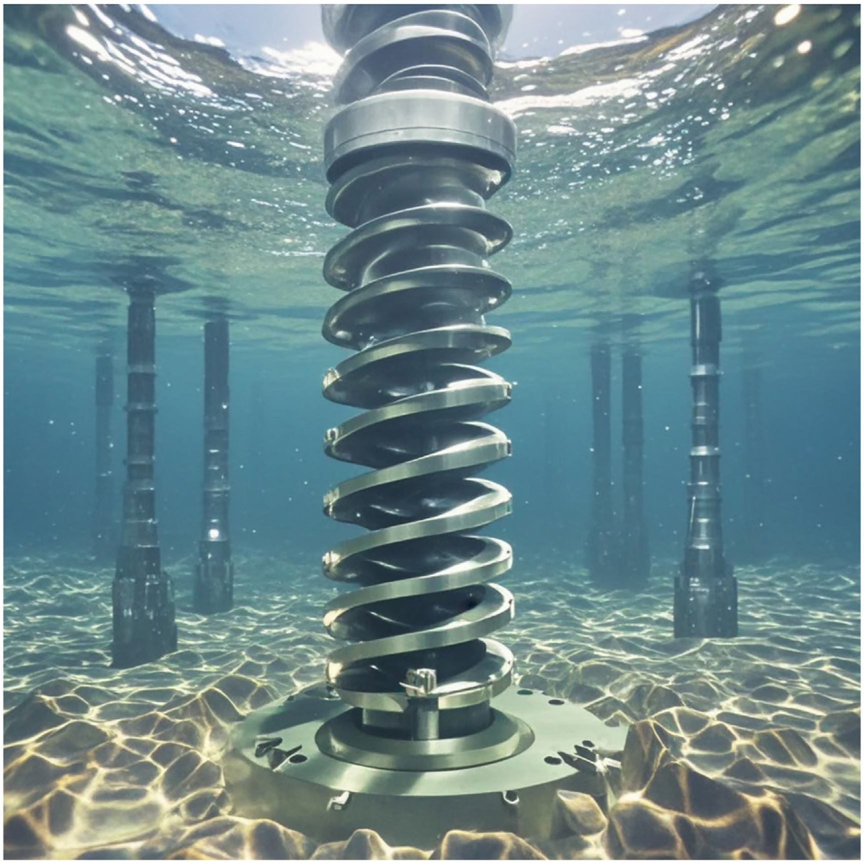

Figure 10. Vertical-axis tidal current turbine with spiral blades

(5) Other devices. These devices, still under continuous development, generate electrical energy through alternative mechanisms that differ from the categories mentioned above. Among these devices, we have identified the following prototypes in scientific literature:
(6) Oscillating hydrofoil devices.[82–85] As shown in Figure 14, these devices do not require high-speed rotating runners. Typically shaped like an airplane wing, they have excellent hydrodynamic characteristics. As water flows past the hydrofoil, a lift force is generated on the lower surface due to the pressure difference, facilitating energy conversion. Oscillating hydrofoil devices offer moderate strength and stability, and they are generally installed in areas with medium to low flow velocities.
(7) Pneumatic tidal devices.[86] These devices exploit the water pressure changes caused by tidal ebb and flow, using air pressure to drive turbines or other power devices to generate electricity.

The previous analysis highlights the variety of devices capable of converting tidal flow into energy, with performance analysis models based on common hydrodynamic principles. However, given that the energy conversion mechanisms of these devices differ, they can be further classified according to their energy conversion principles. One such classification is kinetic energy conversion technology[87–89] which focuses on harnessing the kinetic energy of tidal currents. The blades of these devices are designed with various hydrodynamic shapes to effectively capture the kinetic energy from tidal currents flowing in multiple directions (see Figures 9 and 10).

Considering that the shape and angle of the turbine blades have a significant impact on the energy conversion of tidal energy converters,[90–92] let the shape parameter of the blade be β (It can be a combination of several parameters such as the degree of curvature of the blade, the angle of twist, etc.). The angle between the blade and the tidal current is θ. Then, the energy conversion efficiency η of the hydraulic turbine can be expressed as $\eta = f(\beta, \theta)$.On this basis, the power equation of the tidal energy converter is given by:

$$P = \int_S \rho g v^2(S) \cdot f(\beta, \theta) dS \quad \text{(Equation 1)}$$

After discussing the shape of the blade, let us delve into it from another angle. The blade elements are tiny units of the impeller, and by analyzing the blade elements the performance of the whole impeller can be better analyzed, and according to the theory of the momentum of the blade elements, the total torque of the impeller can be calculated T and parameters such as output power. Let the chord length of the blade elements be c and the angle between the incoming velocity and the chord line of the blade elements be the angle of attack α. The formulae for lift and drag are:

$$L = \frac{1}{2}\rho V^2 c C_L(\alpha) \quad \text{(Equation 2)}$$

$$D = \frac{1}{2}\rho V^2 c C_D(\alpha) \quad \text{(Equation 3)}$$

L is the lift. D is the resistance, $C_L(\alpha)$ and $C_D(\alpha)$ are the lift and drag coefficients, respectively, and the torque dT of the blade elements can be calculated from the moments of the lift and drag forces on the radius r of the blade elements. That is, $dT = r(L\cos\alpha - D\sin\alpha)$. Integrating all the blade elements over the whole impeller, the parameters such as the total torque T and the output power P of the impeller can be obtained. These devices are mainly focused on the capture of tidal streams, and in order to understand the dynamic performance of different impellers, various research teams have explored equations for the dynamic response of tidal energy converters.[93,94] For example, the rotational moment of inertia of a tidal energy converter is J, the

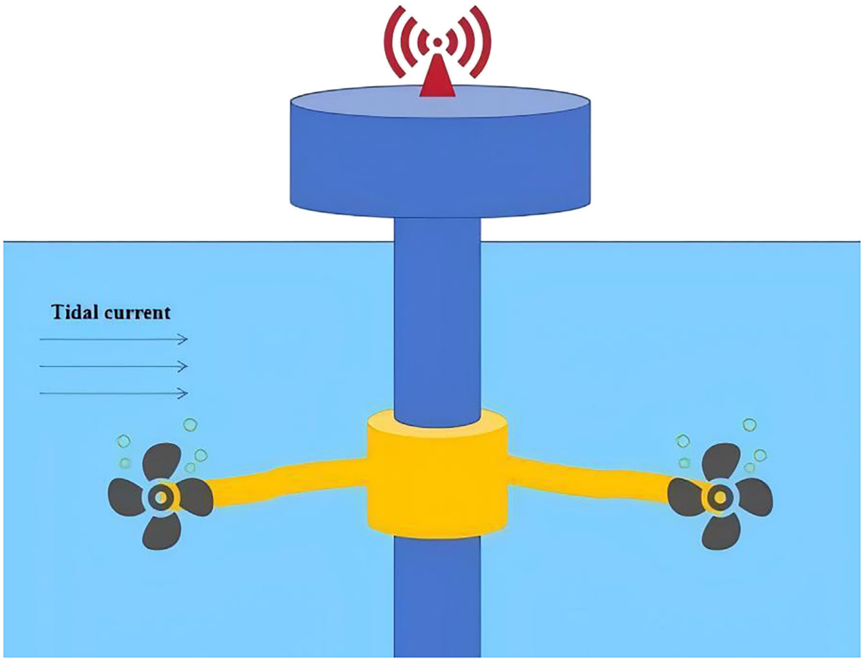

Figure 11. Vertical-axis tidal current turbine

The other classification is about potential energy conversion techniques;[96,97] energy conversion based on potential energy generated by tidal differences. For example, the oscillating hydrofoil device mentioned in the first category (see Figure 14), and the tidal-difference tidal energy converter (e.g., Figure 15), which stores seawater by constructing reservoirs, etc., and uses the difference in water level between inside and outside of the reservoirs at high and low tides to allow the water current to drive the turbine to rotate.

The formula for its generating power is as follows. P denotes the power generated by tidal energy, Δh is the mean tidal range, A is the area of the dam (or the effective area swept by the turbines), v is the sea water flow rate, and η is the total efficiency of the tidal energy generator.

$$P = \rho g \Delta h A v t \eta \quad \text{(Equation 7)}$$

torque of the tidal current acting on the converter is T_t, and the torque of resistance such as the friction torque inside the converter is T_r. The formula is as follows:

$$J\frac{d\omega}{dt} = T_t - T_r \quad \text{(Equation 4)}$$

Thus, the angular velocity as well as the output power at different moments are obtained. Based on the above-mentioned blade element momentum theory, the efficiency of the tidal energy capture device can then be expressed as:

$$\eta_1 = \frac{\sum_{i=1}^{n} dP_{out,i}}{\sum_{i=1}^{n} dP_{in,i}} \quad \text{(Equation 5)}$$

where $dP_{in,i}$ is the power output from a single blade element, $dP_{out,i}$ is the power input from a single blade element, and η is the number of blade elements.

However, in the actual marine environment, considering that the velocity distribution of tidal currents is not uniform and turbulence exists,[95] it will interact with the surrounding marine structures (e.g., dykes, bridges, etc.) and affect the flow field distribution of the tidal stream. Therefore, the calculation of its power is corrected. Let the velocity distribution function of the tidal current be $v(x,y,z)$, where x,y,z is the direction in 3D spatial coordinates, $h(x,y,z)$ is the change in water level height at the corresponding location (related to the tidal difference), V is the area of seawater volume affected by the tidal energy converter, and $\alpha(x,y,z)$ is the velocity correction factor due to marine structures. The formula is as follows:

$$P = \eta \int_V \rho g v(x,y,z) \cdot h(x,y,z) \cdot \alpha(x,y,z) dV \quad \text{(Equation 6)}$$

Since the tide level is constantly changing with time, both the tidal range and the height of the water level are constantly changing during a tidal cycle. Therefore, we need to analyze the power generation of this type of tidal energy converter based on the dynamic tide level changes.[98–100] Let the function of tidal level change be $H(t)$ and the function of tidal stream velocity related to tidal level change be $v(H(t))$. The average power P_{avg} over a tidal cycle T can be expressed as:

$$P_{avg} = \frac{\eta \rho g}{T} \int_0^T v(H(t)) \cdot H(t) dt \quad \text{(Equation 8)}$$

Although the tidal-range power generation technology based on reservoirs has the advantage of stability, its application still faces multiple constraints. First, the construction of large-scale barrages may damage the intertidal zone ecosystem, such as the habitats of benthic organisms and the migration routes of fish. Moreover, changes in hydrological conditions can lead to sediment deposition or coastal erosion. Next, this system depends on geographical conditions (for example, the tidal range needs to be greater than 5 m) and incurs high civil engineering costs (take the Rance Power Station in France as a case). Additionally, the generated power is restricted by the tidal cycle (approximately 4 times a day) and the dynamic water level difference.

To accurately quantify the energy output under dynamic tide levels, it is necessary to expand the modeling methods. The turbine flow-rate constraint function $\Theta(Q_{\max} - Q(t))$ is introduced. The instantaneous flow rate is defined as

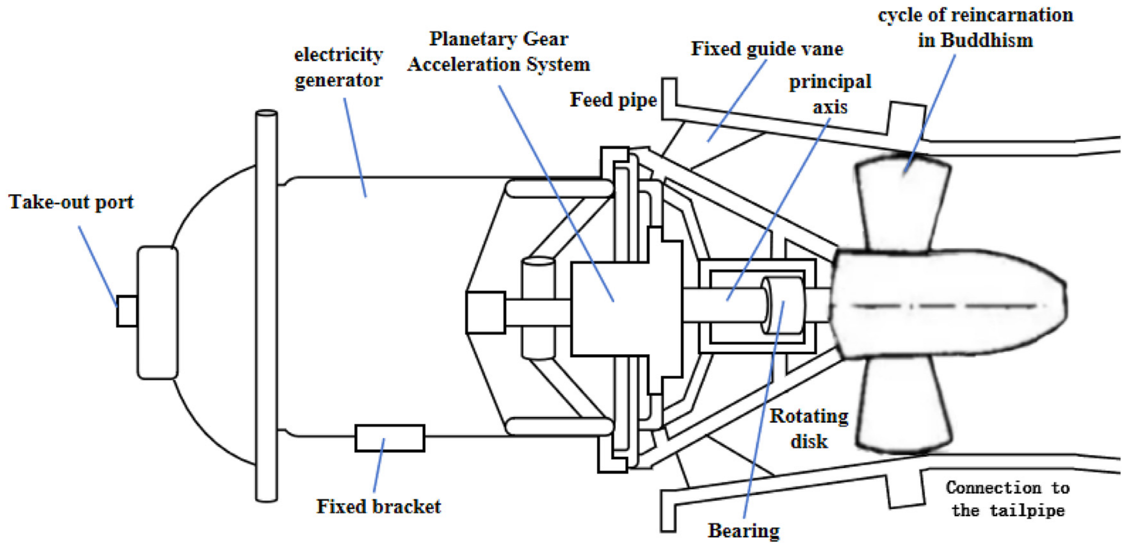

Figure 12. Axial-flow turbine

$Q(t) = A \cdot \frac{d\Delta H(t)}{dt}$ ($\Delta H(t)$ is the tidal level difference between the inside and outside). The power generation in a single cycle is modified to

$$E_{\text{cycle}} = \eta\rho g \int_0^T \Delta H(t) \cdot \min(Q(t), Q_{\max}) dt. \quad \text{(Equation 9)}$$

The above equations indicate that the system efficiency is jointly affected by the turbine capacity and the rate of change of the tide level and needs to be optimized through real-time control strategies.

We found that the efficiency of certain equipment varies depending on the installation location, with factors such as equipment strength, longevity, and maintenance requirements playing a significant role. Therefore, the third category can be further divided based on the installation location and deployment method: shore-based equipment,[101,102] which is fixed on land and utilizes tidal currents along the shore, offering easy maintenance and management; near-shore equipment,[103,104] which is moored on the sea surface with part of the structure secured to the seabed using monopile, gravity, or tripod foundations for tidal stream generation. Monopile foundations are cost-effective and easy to install but are limited to depths of up to 30 m, while gravity foundations offer stability through large concrete blocks, and tripod foundations provide enhanced stability in deeper waters. Lastly, offshore equipment, deployed at depths greater than 80 m,[105] captures stronger and more stable tidal resources, although it requires more advanced equipment and is costlier due to the harsher conditions at such depths.

Quantification methods of tidal-current energy

Tidal energy development,[106] as the name suggests, is the extraction of energy from the flow of tidal water. Similar to the development of wave energy, before deciding to develop tidal energy in a sea area, it is necessary to first count and estimate the tidal energy that can be contained in the sea area, and then make a decision on whether the tidal energy in the sea area is worth developing or not, taking into account the size of its reserves. Since the tidal current changes with time and is not stable, the output power of tidal power generation is also not very stable, so the quantification and estimation of tidal energy is particularly important. Therefore, experts and scholars at home and abroad have proposed a series of methods to estimate tidal energy, which are briefly introduced below.

Currently, tidal current energy estimation methods can be roughly divided into two types: methods based on energy flux and methods based on dynamic analysis. The former includes the farm method[107] and the flux method,[108,109] while the latter mainly refers to the new method proposed recently by Garrett and Cummins.[110]

(1) Farm evaluation method: The farm method mainly considers multiple tidal energy power generation devices as an integrated "farm" when calculating energy output. It estimates tidal current energy based on the layout of the entire device array, the mutual influence among devices, and the interaction between the array and the water flow environment. In the actual planning of tidal energy power plants, multiple turbines or energy conversion devices will interfere with each other and this interference will affect the energy acquisition efficiency of the entire power plant. The farm method aims to take these factors into account to accurately estimate the total tidal current energy.

For an individual device the power P_i can usually be expressed as a function based on the velocity v of the water flow. For example, a common simple form $P_i = 0.5\rho C_p A v^3$ where C_p is the power coefficient (reflecting the efficiency of the device in converting the energy of the water flow into electrical energy), ρ is the density of seawater, and A is the swept area of the device (e.g., the area covered by the rotation of the turbine blades).

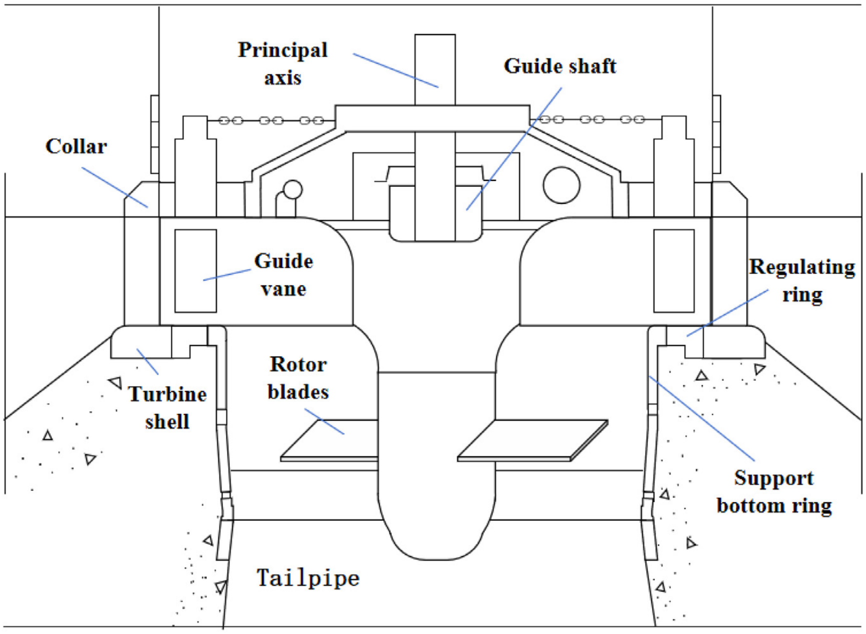

Figure 13. Tubular turbine

where x and y denote coordinates in the horizontal direction, z denotes coordinates in the direction of water depth, and v is the velocity of the water flow.

–Regarding the SIF Value: SIF (site investigation factor) is a parameter used to consider the impact of site characteristics on energy estimation when evaluating tidal energy resources. The SIF value depends on multiple factors, including seabed topography, the degree of turbulence of water flow, variations in seawater salinity, etc. For example, in areas with complex seabed topography, the SIF value may increase due to phenomena such as refraction, reflection, and eddies of the water flow. Generally speaking, the value range of SIF may be between 1 and 10, but the specific value needs to be determined according to detailed site investigations. These values are only approximate ranges. In practical applications, the SIF value needs to be accurately determined through on-site measurements (such as using a multi-beam echo sounder to measure the seabed topography and an ADCP to measure the water flow) combined with numerical models (such as computational fluid dynamics models, CFD) so as to estimate tidal current energy more accurately using the Flux method.

(3) The new method proposed by Garrett and Cummins: Their method takes into account that tidal current is a complex flow phenomenon, which is comprehensively affected by multiple factors such as topography, Coriolis force, and changes in seawater density, to estimate the tidal current energy that can be obtained in specific areas.

Also, when considering the "farm" composed of multiple devices, the mutual influence among the devices needs to be taken into account. Assuming there are n devices in total, the total power P_{total} can be expressed as:

$$P_{total} = \sum_{i=1}^{n} P_i(1 - \varepsilon_{ij}) \qquad \text{(Equation 10)}$$

Here, "ε_{ij}" represents the interference coefficient of device "i" affected by device "j". The calculation of this interference coefficient is rather complicated, as it is related to factors such as the spacing between devices, water flow conditions, and device types. For example, in a simple linear wake model, "ε_{ij}" can be calculated through the wake velocity deficit, and the wake velocity deficit is inversely proportional to the spacing between devices.

(2) Flux evaluation method: The flux method mainly determines tidal current energy by calculating the kinetic energy flux of water flow. It regards tidal current energy as the total amount of kinetic energy carried by the water flow passing through a cross-section perpendicular to the direction of the water flow.

In the general two-dimensional (2D) case, the tidal current energy flux P can be simply expressed as

$$P = \frac{1}{2}\rho \int_A v^3 dA \qquad \text{(Equation 11)}$$

In reality, it is usually a 3D situation, and the integration in the water depth direction z needs to be considered. The formula is as follows:

$$P = \frac{1}{2}\rho \int_x \int_y \int_z v^3 dxdydz \qquad \text{(Equation 12)}$$

In an ideal situation, the energy density E of tidal current energy per unit volume can be calculated using formula $E = \frac{1}{2}\rho v^2$. However, in actual estimations, due to the non-uniformity of water flow and complex boundary conditions, this formula needs to be modified. The Garrett and Cummins method takes into account the vertical distribution of water flow velocity (assuming that the water flow velocity varies in the vertical direction z) and introduces a vertical profile function $u(z)$. At this time, the formula for energy density can be written as:

$$E = \frac{1}{2}\rho \int_{z_1}^{z_2} [u(z)]^2 dz \times Q_{\max} \qquad \text{(Equation 13)}$$

where z_1 and z_2 are the lower and upper limits of the range of water depths considered, respectively, and Q_{max} is the maximum flow rate. In the estimation of tidal current energy on a large scale, the influences of the Coriolis force and topography need to be taken into account. The Coriolis force F_c will cause the

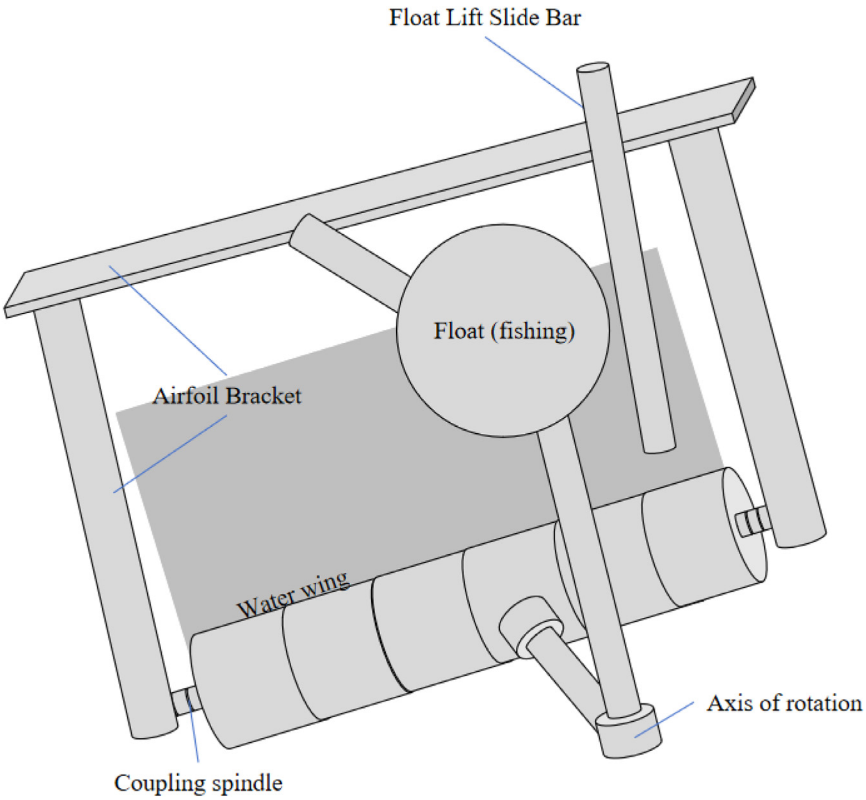

Figure 14. Oscillating hydrofoil device

water flow to deflect, and its magnitude is related to the angular velocity of the Earth's rotation ω, the local latitude ϕ, the seawater density ρ, and the water flow velocity v. Its general expression is $F_c = 2\omega v\rho \sin\phi$. The influence of topography on the water flow is reflected by changing the speed and direction of the water flow. Assuming that the acceleration or deceleration of the water flow caused by the topography can be represented by a topographic coefficient k_t, the actual water flow velocity v' can be expressed as $v' = v(1 + k_t)$. By taking these factors into comprehensive consideration in the energy density formula, tidal current energy can be estimated more accurately.

Among the several estimation methods mentioned above, the farm evaluation method is the most commonly used. The characteristic of this method is that its calculation concept is clear and easy to understand, but there is relatively large uncertainty in the actual application process. The flux method is simpler in calculation, but currently there is still a high degree of empiricism in determining the SIF value. The Garrett method is derived based on dynamic equations. Therefore, although simple models are adopted and numerous assumptions are made, this method still retains its physical significance. To estimate tidal current energy resources using this method, only two parameters, z and Q_{max}, need to be determined, so it has relatively strong practicability.

The main energy conversion device of a tidal-current energy power generation device is the water turbine. The water turbine can convert the fluid kinetic energy in the incoming flow into the energy of blade rotation, so that it can be utilized. From the simplest –1D momentum perspective, the horizontal - axis impeller is simplified into a –1D line, and this line can absorb the kinetic energy of the fluid, that is to say, the fluid will slow down when it flows through here. According to typical forms, water turbines can be divided into horizontal water turbines (Figure 4E shows one type of horizontal water turbines) and vertical water turbines (when the main shaft in Figure 4D is rotated to the vertical direction). Therefore, in this part, the conversion of tidal-current energy will also be introduced according to these two water turbine structures, respectively.

For horizontal water turbines, their energy conversion process can be analyzed from the perspectives of fluid mechanics and mechanical motion.[110–114] When the water flow rushes toward the blades of the horizontal water turbine, the momentum of the water flow changes. Suppose the initial velocity of the water flow is v_1 and the mass flow rate is $\dot{m}$ (the mass flow rate is equal to the product of the water flow densityρ, the cross-sectional area of water flow A and the water flow velocity v_1, that is, $\dot{m} = \rho A v_1$). After the water flow impacts the blades, the velocity drops to v_2. Then, the change in the momentum of the water flow is $\dot{m}(v_1 - v_2)$, and this change in momentum will exert a force on the blades, thus driving the blades to rotate. From the energy perspective, the kinetic energy of the water flow decreases after passing through the water turbine, and this reduced part of the kinetic energy is absorbed by the blades of the water turbine and converted into the rotational mechanical energy of the blades.

As shown in Figure 7, inside the water turbine, the blades are connected to the drive shaft through connecting parts such as the hub. When the blades rotate, they drive the drive shaft to rotate. The drive shaft is usually connected to a speed-increasing gearbox to increase the rotational speed so as to meet the working requirements of the generator. The rotational motion after speed increase is transmitted to the generator, and by using the principle of electromagnetic induction, the rotational mechanical energy is converted into electrical energy. Its energy conversion efficiency is closely related to the blade design of the water turbine (such as blade shape, angle, etc.), rotational speed, and the characteristics of the water flow (speed, direction, flow rate, etc.).

Vertical water turbines have similarities to horizontal water turbines in terms of energy conversion, but they also have their own unique characteristics.[115–117] When the water flow contacts the blades of the vertical water turbine, it is also the kinetic energy of the water flow that drives the blades to rotate. In the vertical

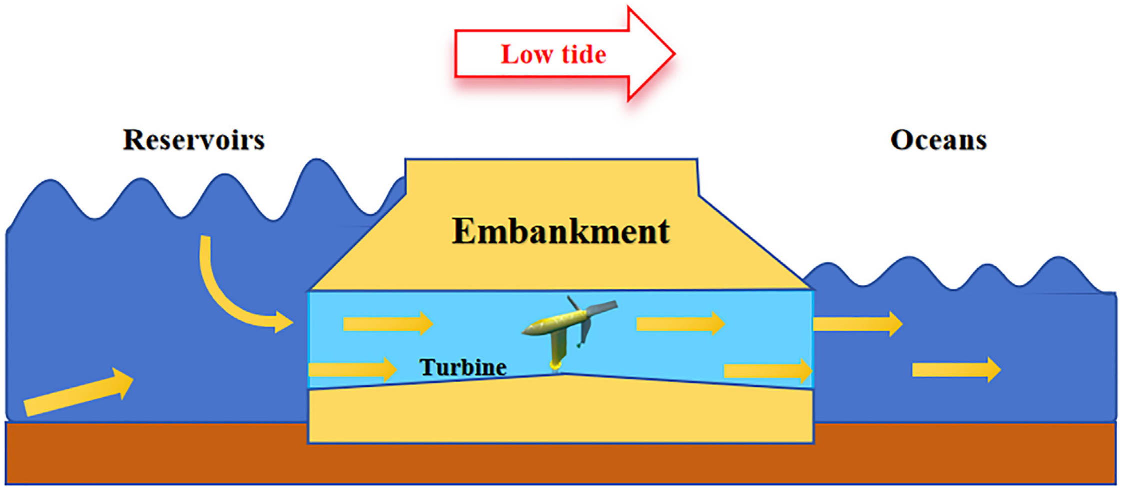

Figure 15. Principle of tidal power technology

direction, due to the effect of gravity, the force situation of the water flow when passing through the blades is more complicated.

From the perspective of energy conversion, part of the energy of the water flow appears as a mixture of gravitational potential energy and kinetic energy. When the water flow impacts the blades of the vertical water turbine, the total energy of the water flow changes. The kinetic energy part is similar to that of the horizontal water turbine. According to the change in momentum, a force is exerted on the blades to drive rotation. The part of the gravitational potential energy also participates in the work done on the blades during the process of the water flow falling, thus converting the gravitational potential energy of the water flow into mechanical energy.

Just like the horizontal water turbine (Figure 16), the rotation of the blades of the vertical water turbine drives the drive shaft. After a series of mechanical transmission links such as speed increase, it drives the generator to generate electricity. The energy conversion efficiency of the vertical water turbine is affected by its own structure (such as the distribution and shape of the blades in the vertical direction), the inlet conditions of the water flow (including the speed and pressure difference of the water flow above and below, etc.) and the operating parameters of the entire water turbine system. This special energy conversion mode gives the vertical water turbine unique advantages in some specific water flow environments (such as tidal areas with obvious water level drops).

The basic energy conversion efficiency formula for a water turbine is:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{2\pi nT}{\frac{1}{2}\rho A v^3} \quad \text{(Equation 14)}$$

Here, P_{out} is the output power of the water turbine, which can be calculated by measuring the torque T of the turbine shaft and the rotational speed n. P_{in} is the input power, ρ is the density of water, v is the water flow velocity, and A is the effective area where the water flow acts. But usually, the loss parts also need to be considered, such as the cavitation effect of the horizontal water turbine, the water flow stratification of the vertical water turbine, and the hydraulic loss.

(1) When the water flow velocity is high or the pressure is low, cavitation may occur inside the water turbine.[118–121] Cavitation will affect the performance and energy conversion efficiency of the water turbine. The cavitation coefficient σ is introduced, which is related to the inlet pressure p_1 of the water turbine, the vapor pressure p_v, the density ρ of water, and the water flow velocity v, that is:

$$\sigma = \frac{p_1 - p_v}{\frac{1}{2}\rho v^2} \quad \text{(Equation 15)}$$

When considering the influence of cavitation, the output power of the water turbine P_{out} will change as the degree of cavitation changes. An empirical formula can be used to represent this relationship, such as $P_{out} = P_{out0}$ (1-kσ), where P_{out0} is the output power without cavitation, and is a coefficient related to the structure of the water turbine and fluid characteristics. At this time, the energy conversion efficiency is:

$$\eta = \frac{P_{out0}(1 - k\sigma)}{\frac{1}{2}\rho A v^3} \quad \text{(Equation 16)}$$

(2) In the actual situation, the vertical water flow may have a stratification phenomenon,[122] and the water flow speeds and energies at different heights are different.[123] Suppose the vertical water flow is divided into n layers, the water flow speed of each layer is v_i, the height is h_i, and the mass flow rate is $\dot{m}_i$. Then the total input energy is:

$$E_{in} = \sum_{i=1}^{n}\left(\frac{1}{2}\dot{m}_i v_i^2 + \dot{m}_i g h_i\right) \quad \text{(Equation 17)}$$

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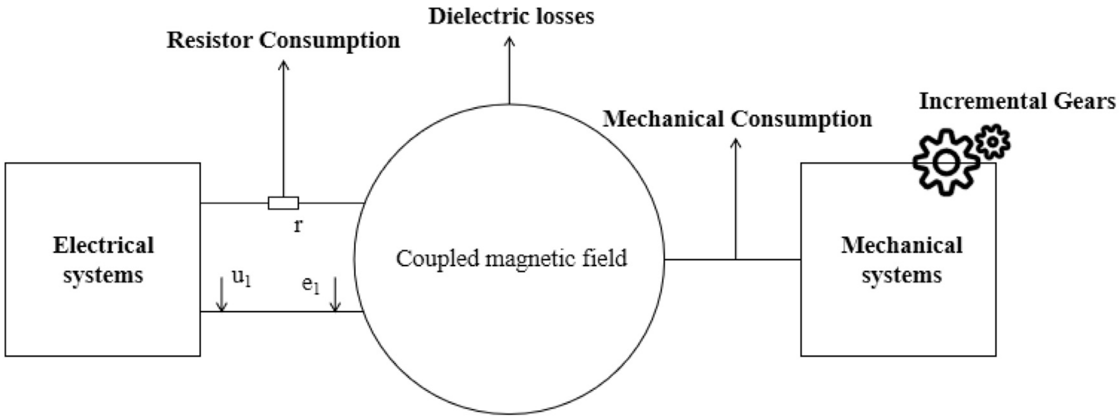

Figure 16. Electromechanical energy conversion diagram

Considering the hydraulic loss, it is necessary to introduce the hydraulic loss coefficient C_h, which is related to factors such as pipe friction and water flow turning. At this time, the output power is $P_{out} = 2\pi nT(1 - C_h)$, and the energy conversion efficiency is as follows:

$$\eta = \frac{2\pi nT(1 - C_h)}{\sum_{i=1}^{n}\left(\frac{1}{2}\dot{m}_i v_i^2 + \dot{m}_i g h_i\right)} \quad \text{(Equation 18)}$$

The hydraulic loss coefficient C_h can be determined through experimental measurements or model tests based on the principle of hydraulic similarity.[124,125] Taking horizontal axis turbines as an example, Noble et al. mentioned the MeyGen project in Scotland in the paper, and its measured data showed that the efficiency of horizontal axis turbines could reach 45% when the flow rate was 2.5m/s.[126] The measured data of the Sihwa Lake Tidal Power Station in South Korea proposed by Ko et al. further verified the applicability of Equation 14, and the error of its turbine annual power generation was less than 5%.[127] The data model proposed by Moreau et al., and the 1:7 scale model test of the European Marine Energy Center (EMEC) show that the correction of the cavitation coefficient σ in Equation 16 can improve the power prediction accuracy by 12%.[128]

Case analyses of typical tidal energy converters and power stations

To delve into the commercial potential of tidal energy technology, this section selects representative tidal power stations and converters both at home and abroad, analyzes their technical characteristics, economic indicators, advantages and disadvantages, and puts forward improvement suggestions.

Foreign typical cases

(1) La Rance Tidal Power Station in France.

- Technical characteristics: It adopts the barrage-type tidal energy technology. With an installed capacity of 240 MW, it is equipped with 24 bidirectional turbines and generates electricity by using the tidal water level difference.
- Economic indicators:
  - LCOE: Approximately 0.12–0.15 USD/kWh (considering a 50-year life cycle);
  - Built in 1966, the initial investment cost was up to 620 million francs (about 94.5 million euros), but operating costs were low (3% of capital expenditure). It pays for itself in about 20 years. The current kWh cost is about 0.12 euros/kWh, and the annual power generation income is about 60 million euros.
- Advantages: High operating stability, annual power generation 500–550GWh. Since it was put into operation, the cumulative operation time has exceeded 500,000 h, and the equipment integrity rate has reached more than 95%. Carbon dioxide emissions are reduced by about 5 million tons per year, providing a stable supply of clean energy for the local area.
- Disadvantages: In the 50 years after the operation of the power station, the estuarine sediments increased by about 1 million cubic meters, resulting in the reduction of some fish populations in the surrounding waters, such as the number of sardines decreased by about 30%, and some fish migration routes changed; the construction period is long (6 years), and there are strict geographical restrictions.
- Suggestions: Future projects should incorporate ecological restoration technologies (such as fish passage design) and optimize the site selection to reduce environmental impacts.

(2) MeyGen Tidal Array Project in the UK

- Technical characteristics: It is an array of horizontal axis tidal current turbines with an installed capacity of 398 MW, adopting modular installation technology.
- Economic indicators:
  - LCOE: 0.18–0.22 USD/kWh (in the initial stage);
  - In September 2014, MeyGen Phase a received £51.3 million (US $78 million) in financing, and when fully completed, the project is expected to provide clean energy to around 175,000 Scottish homes.
- Advantages: It is suitable for deep-water environments (>30 m), and the turbine efficiency is as high as 45%; the optimized array layout reduces the wake effect.

- Disadvantages: It has a high maintenance frequency (2–3 underwater inspections per year), and the equipment has insufficient corrosion resistance.
- Suggestions: Develop corrosion-resistant materials (such as carbon fiber composites) and promote remote intelligent operation and maintenance technologies.

(3) La Rance Tidal Power Station in France

- Technical characteristics: It adopts a single library unidirectional power generation mode and is equipped with 10 bulb tubular turbine generators with a capacity of 25.4MW. The use of breakwater construction effectively reduces the construction cost.
- Economic indicators:
  - LCOE: Approximately 0.12–0.20 USD/kWh;
  - The total investment in the plant is about $570 million. Since its operation in 2011, annual power generation has stabilized at around 550 million KWH.
- Advantages: Through the installation of artificial reefs on the basis of turbines, the survival rate of fish in the surrounding waters has increased by about 18%, which has improved the marine ecological environment to a certain extent. It also reduces carbon dioxide emissions by about 320,000 tons per year, effectively improving local air quality.
- Disadvantages: The unidirectional power generation mode limits the power generation efficiency and is about 20% less efficient than the two-way turbine unit. After the operation of the power station, the water flow and sediment movement in the local waters have changed, causing disturbances to the habitat of some marine organisms, such as shellfish and crabs, and the number of organisms has decreased by about 20%.
- Suggestions: The power station is upgraded to multi-library and multi-direction generation mode to increase power generation efficiency. Optimize the design and layout of artificial reefs to enhance their contribution to marine biodiversity. Consider a hybrid power supply to ensure a longer power supply.

Domestic typical cases

(1) Jiangxia Tidal Test Power Station in China

- Technical characteristics: It is a single-reservoir two-way barrage power station with an installed capacity of 3.9 MW, equipped with 6 bulb tubular turbines.
- Economic indicators:
  - LCOE: 0.25–0.30 USD/kWh;
  - The civil construction cost accounts for 60% of the initial investment, and the domestic equipment localization rate is 80%.
- Advantages: There has been a breakthrough in domestic technology, which is suitable for low flow–velocity areas in estuaries; the annual power generation is stable (about 7 GWh).
- Disadvantages: The power generation efficiency is low (<35%), and the sedimentation of reservoir is a serious problem, which causes the surrounding submarine environment to change from time to time, and makes the habitat of submarine organisms decrease day by day.
- Suggestions: Optimize the turbine design (such as adopting an adaptive blade angle adjustment technology) and introduce a dredging robot system.

(2) Rushan Tidal Power Station in Shandong, China

- Technical characteristics: It is a single-reservoir one-way tidal power station. With an installed capacity of 1.28 MW, it is equipped with 2 hydro-generator sets of 640 kW each. The turbines are of the bulb tubular type, featuring high energy conversion efficiency and good flow-passing performance, adapting to the local tidal characteristics and water flow conditions in Rushan.
- Economic indicators:
  - LCOE: Approximately 0.22–0.28 USD/kWh;
  - The initial investment cost is relatively low, and the domestic equipment localization rate is around 85%.
- Advantages: The project construction period is relatively short. It has good operational stability, with an annual power generation of about 2 million kWh.
- Disadvantages: The single-reservoir one-way power generation mode limits the power generation time, with about 6–8 h of power generation per day. It also has a certain impact on the surrounding marine ecological environment (changing the local sea area water flow and sediment movement).
- Suggestions: Research and improve the power generation mode, explore the feasibility of transforming to a single-reservoir two-way or multi-reservoir multi-way power generation mode. Strengthen the monitoring and protection of the surrounding ecological environment, and take measures such as fish stocking to restore fishery resources and reduce the ecological impact.

By comparing domestic and foreign cases, the following trends and improvement directions are summarized.

a) Technical optimization:
   i. Horizontal-axis turbines are suitable for high flow–velocity and deep water areas, but their corrosion resistance needs to be improved;
   ii. Barrage-type power stations have a large ecological impact and need to be combined with dynamic water level control technology.

b) Economic improvement:
   i. Modular design and domestic production can reduce CAPEX (for example, Jiangxia Power Station saves 20% of the cost);
   ii. Intelligent operation and maintenance systems (such as MeyGen's AI - based fault prediction) can reduce OPEX.

c) Policy – ecology synergy:
   i. Government subsidies and long-term power purchase agreements (such as in South Korea) can significantly shorten the investment payback period;
   ii. Mandatory environmental assessments (such as in France) need to be combined with quantitative ecological compensation measures (such as fish survival rate monitoring).

ECONOMIC ASSESSMENT OF TIDAL ENERGY TECHNOLOGIES

Tidal energy, as a renewable energy source, has enormous potential. Conducting economic assessments on tidal energy technologies plays a crucial role in achieving the unified quantification of the costs of these technologies.[129,130] In this section, we will illustrate the life cycle of tidal energy power generation projects, compare the power generation costs with those of other renewable energy sources, and review the economic indicators usually used for decision-making.

Life cycle costs of tidal power generation projects

The life cycle refers to the entire process that a thing experiences from its emergence to its disappearance. If we focus on the economy of products or projects, then life cycle cost (LCC) is an approach that pays attention to all costs of products or projects throughout their life cycles. It is of great significance for optimizing product costs and enhancing market competitiveness, and it evaluates the economic benefits of products through long-term relevant cost predictions. Moreover, it is also a commonly used method for assessing the economics of energy technologies.[131] The components of LCC include upfront planning costs (i.e., various costs for resource exploration and assessment, product feasibility studies, and project design), construction costs (the main part of CAPEX), operation costs (the main part of OPEX), and decommissioning costs. Its formula is as follows:

$$LCC = CAPEX + OPEXtotal + DC \qquad \text{(Equation 19)}$$

Among them:

CAPEX: Capital expenditure, which is the one-time or concentrated costs invested in the early stage of project construction.

OPEX: The sum of operating expenditure, which is the total costs incurred during the entire operation cycle of the project.

DC: Decommissioning cost, that is, the costs needed for dismantling equipment, cleaning up the site, and restoring the environment after the project ends its operation.

The following part of this article will discuss the two main cost categories of tidal power generation project investment: Capital expenditure (CAPEX) and operating expenditure (OPEX).[132,133]

CAPEX refers to the one-time investments or expenditures that a company incurs during the construction phase of a project. It primarily includes costs associated with land and sea area acquisition, the purchase of core equipment such as hydro-turbine generator sets, auxiliary and mooring devices (e.g., variable speed devices and power transmission/distribution equipment), the hub platform for the technology farm, and the energy transportation system. Additionally, CAPEX covers civil engineering costs, equipment installation expenses, and general overhead costs.

OPEX refers to the ongoing costs incurred during the operation phase of a project necessary to maintain its normal functioning. Unlike CAPEX, OPEX is a recurring expense. It includes daily maintenance costs, personnel expenses (such as salaries, bonuses, insurance, and rents), equipment replacement and technology upgrade costs, and grid connection fees. OPEX is closely tied to the operational activities of the project, exhibiting both sustainability and uncertainty over time.

Certain general expenses within CAPEX, such as the customization of special equipment, environmental assessments, and project design optimization, are challenging to estimate universally because they depend on factors such as the project's scale, technological complexity, and geographical environment. The cost of customizing special equipment is typically a small portion of the Capital Expenditure (CAPEX), often around 4% in tidal power generation projects. Additionally, due to the ongoing development and innovation in tidal power generation technology, accurately estimating the cost of project design optimization is also difficult. Some studies on large tidal power generation projects suggest that, assuming active technological innovation and high project design standards, environmental assessment costs could account for approximately 3% of CAPEX. By integrating insights from other similar energy projects and tidal power research, these specific costs can be estimated more precisely. In this context, the project design optimization cost is estimated to be a small fraction of CAPEX (around 2%), while environmental assessment and approval costs are assumed to represent about 2.5% of the total project investment.

As for the costs with small percentage shares within OPEX, the cost of equipment performance monitoring and data analysis can be estimated as a small part of the capital expenditure cost (1%), the cost of personnel training and skill improvement is assumed to be a small part of the annual operating cost (2%), the cost of energy loss and efficiency reduction can be estimated as a small part of the power generation revenue (1.5%), and the cost of equipment aging and technology update (irregular expenditure) can be approximately estimated as a small part of the capital expenditure cost (1%). For some of these costs, such as water quality monitoring, marine ecological protection measures and other environment-related operating costs, it is difficult to determine a universal value because they depend on the ecological characteristics of the sea area where the project is located, the requirements of environmental protection regulations and the operation mode of the project. The cost of water quality monitoring is usually regarded as a small part of the Operating Expenditure Cost (COPEX) (0.8% in tidal power generation projects). Meanwhile, due to the complexity and dynamics of the marine ecological environment, it is also relatively difficult to accurately estimate the cost of marine ecological protection measures. Some studies on marine energy projects estimate that under the assumption of strict ecological protection requirements and frequent marine environment monitoring, other environment-related operating costs are 1.2% of the OPEX cost. By combining the analysis of relevant industry standards with the research on the actual operation of tidal power generation projects, these operating costs can be estimated more specifically. In this case, the cost of marine ecological protection measures can be estimated as a small part of the OPEX cost (1%), and the cost of water quality monitoring and data analysis is assumed to be a small part of the annual operating cost (0.5%).

Main economic indicators

After understanding the life cycle costs of tidal power generation projects, this article will continue to review the economic indicators usually used for decision-making. These indicators provide a comprehensive and dynamic economic guidance for the entire life cycle of the project, running through the whole project planning and enabling decision-makers to make scientific and reasonable judgments. Such economic indicators include return on investment (ROI), internal rate of return (IRR), net present value (NPV), discounted payback period (DPBP), cost-benefit ratio (CBR), debt service coverage ratio (DSCR), liability-debt ratio (LDR), and levelized cost of electricity (LCOE). The following part of this article will review in detail the five main economic indicators, namely ROI, IRR, NPV, DPBP, and LCOE.

NPV is usually used to analyze the feasibility of a project or projected investment. It represents the difference between the cash flow of a project and the present value of the investment, that is, the cash flow generated by the project minus the present value of the investment.[134–136]

Jahanshahi et al. provided an equation representing the NPV of a project, as shown in Equation 18.

$$NPV = -I_0 + \sum_{i=1}^{n} \frac{CF_i}{(1+r)^i} \quad \text{(Equation 20)}$$

Among them, I_0 represents the initial investment, CF_i represents the cash flow in the first year, r represents the discount rate, and n represents the number of years. They used the NPV formula to evaluate the economic feasibility of the proposed tidal energy project. They calculated the net present values of the project under different scenarios and compared them to determine the most favorable option.[137]

Another key indicator for analyzing investment feasibility is the IRR. It is the discount rate at which the net present value of a project is zero, taking into account the time value of money and reflecting the project's own profitability.[138]

Suppose the net cash flow in period i ($i = 1,2,3 \ldots$) of a project is CF_i, and the Internal Rate of Return is IRR. Then, when $NPV = 0$, it is obtained by means of the following expression:

$$NPV = -I_0 + \sum_{i=1}^{n} \frac{CF_i}{(1+IRR)^i} = 0 \quad \text{(Equation 21)}$$

ROI is an important indicator for measuring investment returns. It can intuitively reflect the profitability and efficiency of an investment. A high ROI indicates a wise investment decision and can bring substantial returns to enterprises.[139–141] Its formula is as follows:

$$\text{ROI} = \frac{\text{R} - \text{C}}{\text{C}} \times 100\% \quad \text{(Equation 22)}$$

Here, R represents investment income, which refers to all the revenues obtained through investment, such as profits, dividends and interest. C represents investment cost, which refers to all the expenses paid for making the investment, including the costs of purchasing assets, handling fees and taxes.

The DPBP is the number of years it takes for the sum of cash flows in each period to reach the initial investment cost. Suppose the initial investment of a project is I, the net cash flow in period t is NCF_t, the discount rate is r, and the discounted payback period is n. The formula can be expressed as:

$$\sum_{t=1}^{n} DNCF_t = \sum_{t=1}^{n} \frac{NCF_t}{(1+r)^t} \quad \text{(Equation 23)}$$

Since in actual calculations there is usually no integer n that makes the above equation hold exactly, the linear interpolation method can be used to estimate the discounted payback period n. If the cumulative discounted net cash flow in period m is less than the initial capital, while the cumulative discounted net cash flow in period m+1 is greater than the initial capital, the formula is as follows:

$$n = m + \frac{I - \sum_{t=1}^{m} \frac{NCF_t}{(1+r)^t}}{\frac{NCF_{m+1}}{(1+r)^{m+1}}} \quad \text{(Equation 24)}$$

The LCOE is one of the important indicators for evaluating the economic benefits of energy projects and also one of the standard methods for comparing the costs and benefits of different energy projects.[141–144] Its definition is the life cycle cost divided by the total power generation in that life cycle.

To optimize the design of tidal energy arrays while considering the location and quantity of equipment to maximize the economic benefits of the project, Goss et al. provided an equation for LCOE as shown in Equation 23. Among them, CA_f represents the fixed capital cost of the project, CA_t represents the variable capital cost of each turbine. The variable n_t indicates the number of turbines in the array. The variable O_f represents the fixed operating cost of the project, O_t represents the variable operating cost of each turbine. The variable r represents the discount rate used to account for the time value of money. The variable L represents the life cycle of the project and E_i represents the energy generated in the first year.[145]

$$LCOE = \frac{CA_f + CA_t \times n_t + \sum_{i=1}^{L} \left((O_f + O_t \times n_t) \Big/ (1+r)^i \right)}{\sum_{i=1}^{L} \left(E_i \Big/ (1+r)^i \right)} \quad \text{(Equation 25)}$$

Comparison of power generation costs of different energy sources

According to Tables 2 and 3, we can perform a good cost variance analysis.

(1) Tidal energy costs more

- Low technology maturity: Tidal energy technology is still in the early stages of commercialization, and equipment manufacturing, installation, and maintenance costs are high. For example, the cost of deepwater installation, the cost of corrosion protection materials, the cost of sediment treatment costs, etc., are not low-cost and efficient research, resulting in the generation cost of tidal power stations being higher than that of other energy sources.
- Geographical limitations: Tidal power stations need to be located in areas with large tidal ranges (e.g., La

Table 2. Comparison of LCOE of different energy sources

Name of energy source	LCOE(US$/kWh)	Typical project cases and LCOE (USD/KWH)
Dynamic Tidal Power	0.1–0.3	La Rance Power Station, France: 0.12–0.15
Solar Power	0.068–0.378	Centralized PV: 0.04–0.08 Distributed PV: 0.06–0.15
Wind Power	0.053–0.156	Onshore wind: 0.04–0.06 Offshore wind: 0.08–0.15
Coal - fired Power	0.055–0.153	Traditional coal-fired power plants: 0.05–0.15

Rance, France, with a tidal range of 8 m) or high flow rates (>2.5 m/s), resulting in increased exploration and infrastructure costs.

(2) Wind and solar cost advantages
- Scale effect: Wind power and photovoltaic have formed a mature industrial chain, and large-scale production has significantly reduced costs.
- Easy operation and maintenance: Wind power and photovoltaic equipment are low maintenance costs and less affected by the environment, while tidal energy equipment needs to deal with complex problems such as seawater corrosion and biological attachment.

(3) Coal is the cheapest but unsustainable source of electricity
- Although the LCOE of coal-fired power generation is low ($0.05 - $0.15/KWH), its carbon emissions and environmental externalities are not included in the cost and are not sustainable in the long term.

To sum up, the generation cost of tidal power station is closely related to its technical route. Therefore, this paper will study the differentiated impact of tidal energy technical route on the cost.

(1) Cost comparison between horizontal and vertical axis turbines
- Horizontal axis turbine (taking the UK MeyGen project as an example)
  i. CAPEX: The cost of a single 6 MW turbine is approximately $7.2 million, driven by deep water installation (>30 m water depth) and carbon fiber anticorrosive materials (15% of the equipment cost).
  ii. OPEX: Annual maintenance costs are around $240,000/unit, 40% of which is used to combat seawater corrosion and biological attachment (such as regular leaf cleaning).
  iii. Efficiency and benefits: In high-energy sea areas with flow rates >2.5 m/s, the efficiency can reach 45%, the annual power generation is about 26 GWh/unit, and the capacity factor is 35–40%.
  iv. Limitations: Frequent underwater maintenance (2–3 inspections per year) can cost up to $80,000 per dive.
- Vertical axis turbine (taking Sihwa Lake Project in South Korea as an example)
  i. CAPEX: A single 1.2MW vertical shaft turbine costs $1.14 million and is 20% less expensive to install than a horizontal shaft due to its simple structure and lack of deep-sea anchorage.
  ii. OPEX: Annual maintenance cost of $144,000/unit, low flow rate adaptability (1.5–2 m/s) reduces equipment wear, but efficiency is only 25–30%.
  iii. Scenario adaptation: In inshore areas with complex flow flows (such as estuaries), power generation

Table 3. Environmental externality cost comparison

Name of energy source	Implicit environmental cost LCOE(USD/kWh)	Major influence
Dynamic Tidal Power	0.02–0.05	Ecological disturbance (fish migration disruption, sediment migration) Noise pollution (low frequency vibration of turbines)
Solar Power	0.03–0.08	Carbon emissions from silicon production (30–50 gCO_2/kWh) Land use (desert ecosystem destruction)
Wind Power	0.01–0.03	Bird Strike Risk Landscape Damage (onshore wind)
Coal - fired Power	0.15–0.3	Carbon emissions (820–1200 gCO_2/kWh) Air pollution (sulfide, nitrogen oxides) ash disposal costs

If environmental externalities are taken into account, the actual LCOE of coal can reach US $0.20–0.45/KWH, which is much higher than tidal energy.

stability is improved by 10%, but more equipment needs to be deployed to fill the capacity gap.

(2) Differences in infrastructure and ecological costs between dike type and tidal current type power stations

- Dyke Power Station (La Rance, France)
  - i. Infrastructure: 70% of the investment is for the construction of DAMS and gates (initial investment of 620 million francs), but the 50-year long life diluted cost, LCOE is only US $0.12–0.15.
  - ii. Ecological cost: Sediment treatment and fishway construction cost €3 million (approximately $0.03/kWh) per year, but through dynamic water level regulation, sediment migration is restored to 80% of its natural state.
  - iii. Scale effect: Annual power generation of 550 GWh, capacity factor 38%, unit power generation cost 60% lower than small tidal current power station.
- Tidal current power station (Jiangxia Test Power Station, China)
  - i. Equipment bottleneck: the efficiency of domestic bulb penetration unit is <35%, the civil construction cost accounts for 60% (the cost of sediment treatment accounts for 25% of OPEX), and the LCOE is as high as $0.25–0.30.
  - ii. Operating limitations: Dependent on natural tidal cycles, daily power generation time is only 6–8 h, capacity factor 26%, annual power generation of 7 GWh.

(3) Synergistic cost reduction effect of hybrid system innovation

- Tidal + Energy Storage (Tidal Siren project in Norway)
  - i. Storage costs: Liquid air storage (LAES) systems increased CAPEX by 15% ($120 million to $138 million), but reduced power abandonment rate from 12% to 5% and increased annual revenue by 18%.
  - ii. Combined benefits: LCOE increased by $0.05 to $0.17, but grid stability improved by 30%, reducing peak load costs by $0.03, and net benefits were flat.
- Multi-energy complementarity (Orkney Islands, Scotland)
  - i. Collaborative design: Tidal (6 MW), wind (12 MW) and photovoltaic (5 MW) share transmission facilities, saving 40% of grid-connected costs (from $32 million to $19.2 million).
  - ii. Capacity factor: Combined up to 68% (tidal 35% + wind 45% + PV 20%), LCOE down to $0.14, $0.06 lower than a single tidal project.
- Modular Technology (Sihwa Lake, Korea)
  - i. Installation optimization: The containerized turbine design reduces the installation cost of a single unit by $220,000, the localization rate of 85% reduces import tariffs and equipment transportation costs, and the CAPEX goes from $110 million to $93 million.
  - ii. Policy support: Government subsidy of $0.03/kWh + tax relief, project LCOE from $0.18 to $0.14, investment payback period reduced to 12 years.

According to the International Renewable Energy Agency (IRENA) 2023 report, the global average LCOE for horizontal axis tidal turbines is US $0.18–0.30, the vertical axis is US $0.15–0.25, and the dike type diluting cost can be as low as US $0.10–0.20 due to long period. Practical projects such as South Korea's Sihwa Lake demonstrate the potential of industrial chain integration by reducing costs by 30% through policies and localization. In the next decade, with material innovation (such as a 67% increase in the life of carbon fiber-titanium alloy bearings) and intelligent operation and maintenance (AI failure prediction reduces downtime by 60%), tidal energy LCOE is expected to break the $0.10 threshold and become an important supplement to base-load energy.

CURRENT STATUS OF TIDAL ENERGY

Currently, although certain progress has been made in the utilization of tidal energy, it is still in a relatively early stage of development on the whole. Some advanced tidal energy conversion systems are gradually advancing to the processes of offshore testing and pre-commercial demonstration. Nowadays, the enthusiasm for exploring mature and efficient tidal energy technologies among all sectors remains high. Globally, especially in regions like Europe, relevant scientific research frameworks and policy orientations are actively promoting the R & D and marketization processes of innovative, clean and sustainable tidal energy technologies.[146–149] For example, a series of initiatives such as the "European Green Deal" have further demonstrated the emphasis and investment in this field. The opportunities and positive benefits among them include creating more job opportunities, decarbonization, optimizing the global energy mix, and improving the stability and sustainability of energy supply. In the commercialization process of renewable marine energy utilization, the stakeholders involved include[150–152] (see Figure 17).

(1) Major Stakeholders

The development team: Responsible for the planning and construction of the project. It aims to realize new techno-economic design concepts, improve equipment performance and reliability, and conduct analyses of the marine environment.

The operation team: In cooperation with equipment suppliers, it is responsible for daily production and operation, equipment maintenance, power dispatching and other work after the project is completed.

Electricity consumers: Their demands and consumption behaviors directly affect the market development of renewable marine energy. Their participation and support are of great significance for the commercialization of renewable marine energy and can promote the formation and development of the market.

(2) Minor Stakeholders

Shareholders: They provide financial support for the project and receive dividends in the later stage.

Equipment suppliers: They provide key equipment for the project and offer better support for the installation and maintenance of the equipment.

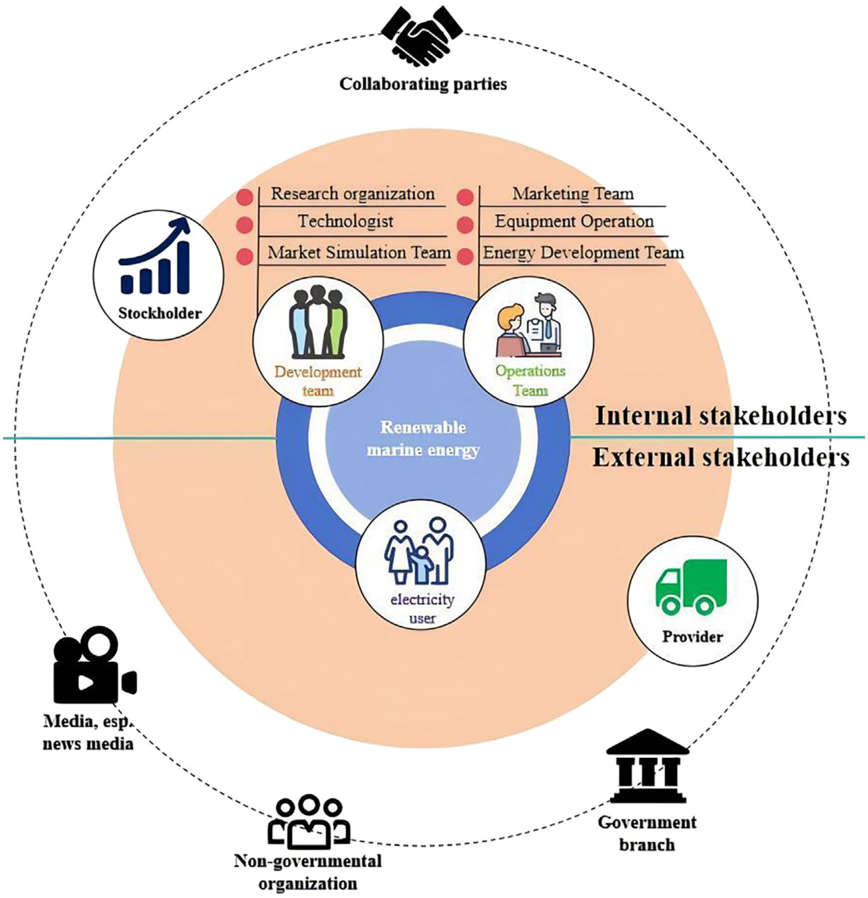

Figure 17. Stakeholders in the commercialization of renewable ocean energy

(Note: From inside to outside are Major Stakeholders, Minor Stakeholders, and Tertiary Stakeholders, which have less and less influence on the project).

(3) Tertiary Stakeholders

Governments, media, non-governmental organizations, etc. pay attention to the project but have relatively little impact on it. They play a certain role in the publicity and supervision of the project.

In summary, although various stakeholders have provided all kinds of cooperation for renewable marine energy projects, in the process of developing the commercialization of tidal energy, the following major risks still need to be carefully paid attention to: technology, economy, industrial chain and market, government, and environment. Figure 18 briefly illustrates what obstacles there are, and next this article will describe each point in detail.

Technical

In the process of the commercial development of tidal energy, the technological aspect is faced with numerous complex and intertwined risks and obstacles, which seriously restrict the transformation of tidal energy from its theoretical potential to large-scale commercial applications.[153–155] Therefore, the following technological fields all require in-depth research with emphasis.

Tidal energy technology is confronted with key issues such as equipment reliability, durability, and installability. To optimize these problems, we should focus on the innovation and optimization of technologies like equipment materials, water diversion structures, mooring devices, adaptive control technologies, the conversion efficiency of power take-off (PTO), and electricity storage. Among them, the energy storage issue can enable complementary power generation with other renewable energy sources (as shown in Figure 19). Through the coordinated work of multiple energy sources, the stability of power supply can be improved. In addition, the technology readiness level (TRL) is a good indicator for evaluating the maturity of a technology.[156] It is divided into levels 1–9 and can greatly assist developers and investors in assessing the development stage of tidal energy technology and determining the risk level of the technology in application.

Besides the optimization of equipment, its installation and deployment also pose a significant risk. Due to the lack of experience in the array deployment of multiple tidal energy converters, mutual interference may occur among the various power generation devices in the array.[157,158] For example, the wake effect of adjacent devices will reduce the water flow energy where the downstream devices are located, resulting in a decrease in the overall energy capture efficiency[159] (see Figure 20). The Jensen model illustrates the wake effect quite well. This model was initially applied to the calculation of the wake effect in wind farms and was later also used in the field of tidal energy. Its core formula is:

$$v_x = v_0\left(1 - \frac{1}{2}\left(1 - \sqrt{1 - C_T}\right)\left(\frac{d}{x}\right)^2\right) \quad \text{(Equation 26)}$$

Here, v_x is the flow velocity at a distance x downstream of the upstream turbine, v_0 is the incoming flow velocity (i.e., the flow velocity that is not affected by the upstream turbine), d is the diameter of the turbine, and C_T is the thrust coefficient of the turbine. In subsequent studies, it was found that the expansion effect of the wake and the influence of turbulence were not taken into account in the Jensen model. Based on the principle of conservation of momentum, a simplified form is derived as follows: ρ is the density of seawater, v is the flow velocity, A is the cross-sectional area of the wake, and A_t is the swept area of the turbine:

$$\frac{\partial}{\partial_x}\left(\rho v^2 A\right) = -\frac{4}{3}\rho v C_T A_t \quad \text{(Equation 27)}$$

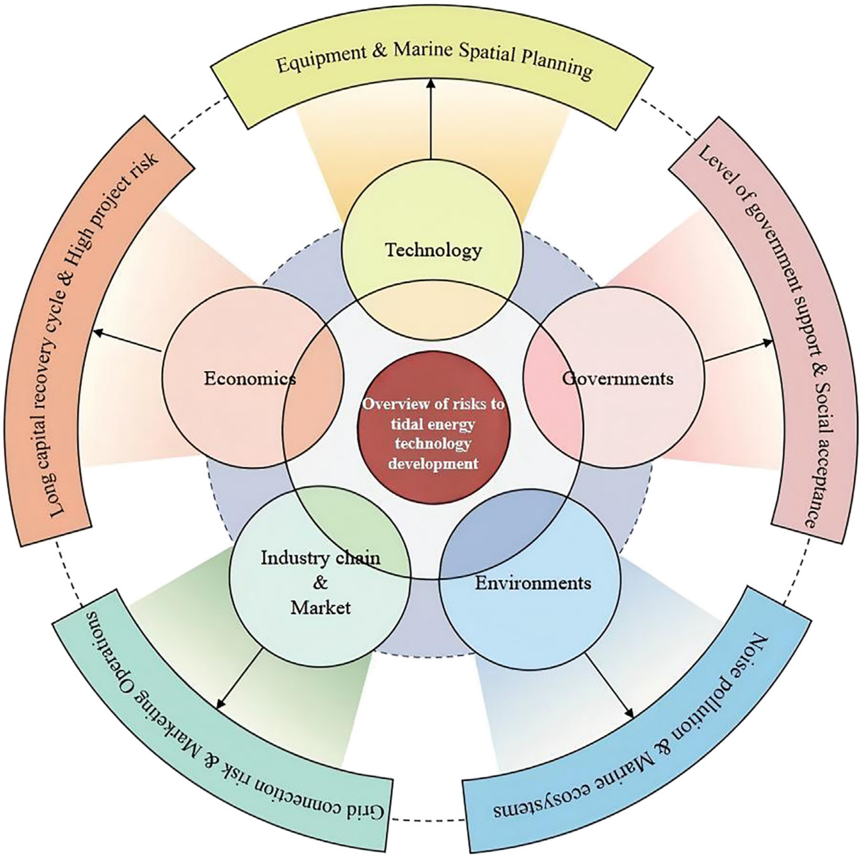

Figure 18. Summary of significant risks to the commercialization of tidal energy

Therefore, complex models and a large number of experiments are required to determine the optimal spacing and layout. Teams need to conduct rigorous simulation studies as well as small-scale experiments to reduce various risks in installing tidal energy converters and effectively help tidal energy move toward commercialization.

According to the field measured data of the European TIGER project, after optimizing the layout of 14 turbine arrays using Jensen model, the overall power generation efficiency was increased by 18%.[126] In the article written by Goss et al., CFD simulation of Fundy Bay in Canada shows that when turbine spacing is greater than 8 times rotor diameter, wake velocity loss is less than 10%.[160] In addition, the measured ADCP data of Uldolmok Strait in South Korea verified the applicability of Equation 26, and the velocity prediction error was less than 7%.[161]

Marine spatial planning: Currently, marine spatial planning in various countries is still not yet perfect, lacking reasonable planning and layout for tidal energy projects.[162,163] In order to achieve technological improvements and enhance the performance of existing renewable energy collection equipment, having an accurate understanding of the local resource distribution is fundamental.[164,165] However, due to the particularly scarce knowledge of resource mapping, the existing surveying and mapping technologies and the accuracy of data cannot meet the requirements, resulting in relatively large uncertainties in site selection and equipment layout planning, greatly reducing the degree of marine space development and posing obstacles to the analysis of the cost-effectiveness of development in certain areas.

Economic

In addition to some of the risks associated with tidal energy technology, there are also some factors that need to be addressed in its economic component.

According to the calculation of the LCOE formula, and as shown in Figure 21, the upfront costs of tidal energy are much higher than those of other renewable energy sources, resulting in many tidal energy power generation projects failing due to insufficient startup funds in the early stage. There are multiple reasons for these high costs.[166,167]

(1) The technology is not mature enough and there is a lack of experience. In the manufacturing and deployment of equipment, a large amount of manpower and material resources are required. The equipment needs to be stable and the deployment sites need to be carefully selected.
(2) There are significant differences in project cost strategies. Different developers and projects adopt different technological routes, equipment selections, and construction plans, making it difficult to unify and reduce costs.
(3) Costs are site-specific. In different tidal energy resource areas, there are large differences in marine environments, geological conditions, etc., which makes the project construction and operation costs vary from site to site, increasing the difficulty of cost prediction and control.

Calculations based on the IRR and the DPBP show that it takes a relatively long number of years for the sum of cash flows in each period of tidal energy power generation projects to reach the initial investment cost. Meanwhile, electricity prices are affected by multiple factors such as market factors and policy factors. If electricity prices fluctuate or decline, the capital recovery period will be further extended. For example, if there is an oversupply of electricity in the market or if there are changes in the subsidy policies for renewable energy, it may affect the project's earnings and capital recovery situation. Therefore, it is necessary to draw the attention of the government and investors so that tidal energy equipment can participate in the market competition of renewable energy.

Figure 19. Complementary tidal, wind, and solar power generation
(Note: It consists of a tidal generator at the bottom, a solar panel laid on the tidal generator and a wind wheel installed on the tidal generator).

Tidal energy technology still entails high risks, whether for investors or insurance companies.[168] It can be divided into two aspects.

(1) Cost risks. This is mainly reflected in aspects such as high project construction costs, great cost uncertainty, and a long cost recovery period. As mentioned previously, tidal energy projects require huge upfront investments, including infrastructure construction, equipment procurement, etc. Moreover, due to various factors, it is difficult to accurately predict and control costs.
(2) Revenue risks. These are related to factors such as market demand, electricity price fluctuations, and technical reliability. The power output of tidal energy power generation is greatly affected by natural conditions, featuring intermittency and instability, which may lead to a mismatch between power generation and market demand. Meanwhile, electricity prices are affected by factors such as market competition and policy adjustments and are also subject to uncertainties. If the technical reliability is insufficient and the equipment failure rate is high, it will increase maintenance costs, reduce power generation efficiency, and further affect project revenues.

Industry chain and markets

Commercializing tidal energy requires not only the optimization and innovation of technology but also the technological updates in the aspects of industrial chain and market are of great importance.

The output power of tidal energy fluctuates with the ebb and flow of tides, and its voltage and frequency are unstable. If this unstable electrical energy is directly connected to the power grid, it may cause the voltage deviation and frequency fluctuation of the power grid to exceed the allowable range, which will further affect the normal operation of the electrical equipment of other users in the power grid. In severe cases, it may damage the equipment.[169,170] Referring to "Tapping Ocean Potential: Strategies for integrating tidal and wave energy into national power grids" will help optimize the structure of the national power grid and facilitate the utilization of renewable marine energy.[171]

The manufacturing of tidal energy equipment usually requires special materials. If the supply of these raw materials is limited or their quality is unstable, it will affect the production quality and progress of the equipment. Midstream equipment manufacturing and integration risks. If the manufacturers in the supply chain are not technically competent, it will lead to poor performance and low stability of the equipment, thus making tidal energy projects unsustainable. Therefore, strict control over the supply chain will help with the expansion and deployment of tidal energy projects and also enhance the confidence of investors in the market competition.[172,173] Moreover, in the renewable energy market, tidal energy needs to compete with other energy sources. Compared with solar energy and wind energy, tidal energy may be at a disadvantage in terms of cost, technological maturity, etc., and thus faces the risk of being marginalized. Therefore, referring to Sections technical and economic will greatly improve the technology and cost of tidal energy.

The harsh conditions of the marine environment make the maintenance of tidal energy facilities extremely difficult.[174] Besides the routine regular maintenance of tidal energy equipment, due to the complexity of the marine environment and the randomness of the equipment's status, a specialized department is needed to conduct monitoring, quickly diagnose the causes of failures, and promptly dispatch personnel for repairs to minimize equipment damage. However, merely meeting the above conditions is not enough. When carrying out maintenance operations at sea, technicians have limited operating space and may face severe sea conditions, which increases the risks and costs of maintenance. Moreover, if spare parts are insufficiently stocked or not transported in a timely manner, it will further prolong the downtime of the equipment and bring economic losses to the project.

Governments

Cost-effective tidal energy technologies can help reduce the damage caused by greenhouse gas emissions, air pollution, and acid rain, and assist countries in alleviating environmental problems. Therefore, the following points still need to be emphasized:

Policy stability is of vital importance to the commercial development of tidal energy. If the government's energy policies change frequently, it will bring great uncertainties to tidal energy projects.[175–177] If subsidy policies are reduced or canceled, the economic benefits of the projects may be seriously affected causing investors to shy away.

Developers of tidal energy technologies must take this important issue into account in their designs. The construction of tidal energy projects may change the local coastline landscape, affect

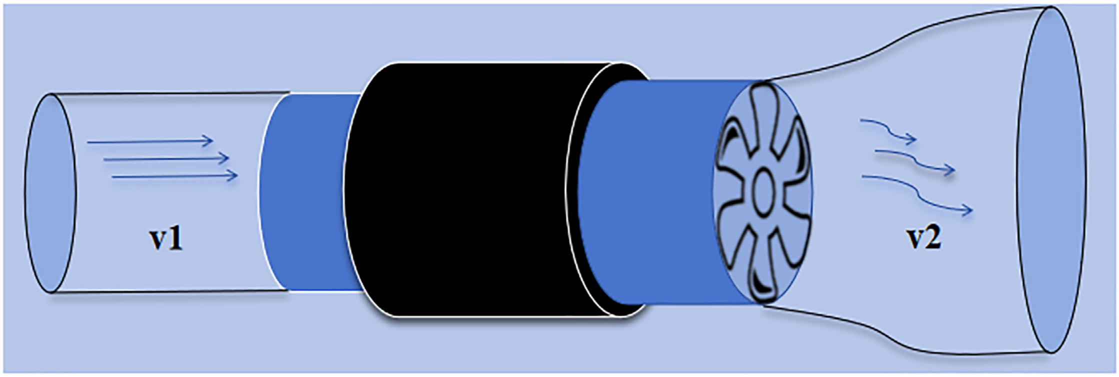

Figure 20. Wake effect (meteorology)
(Note: v1 is the speed and direction of the water flow without passing through the tidal power generation equipment, v2 is the speed and direction after passing through the tidal power generation equipment).

the recreational activities of coastal residents, or some members of the public may have limited knowledge of tidal energy as a new energy source and may have resistance due to misunderstandings. As a result, the development of tidal energy projects may be postponed or even blocked by local communities. Therefore, it is essential for government departments to conduct educational publicity, ensure information transparency, and provide employment opportunities for local residents.[178–181]

The government's administrative examination and approval and licenses are also potential risks. The construction of tidal energy projects requires the approval of multiple departments, including aspects such as the marine environment and land use.[182,183] If the government's approval procedures are complicated, take too long, or are too demanding, it will lead to delays in project progress, an increase in upfront costs, and missing the best market opportunities.

TRENDS IN TIDAL ENERGY TECHNOLOGY

Tidal energy, as a clean and renewable energy source, has enormous potential. However, current tidal energy technologies still face numerous challenges in practical applications. From a technological perspective, the efficiency of existing tidal energy conversion equipment needs to be improved, the costs are relatively

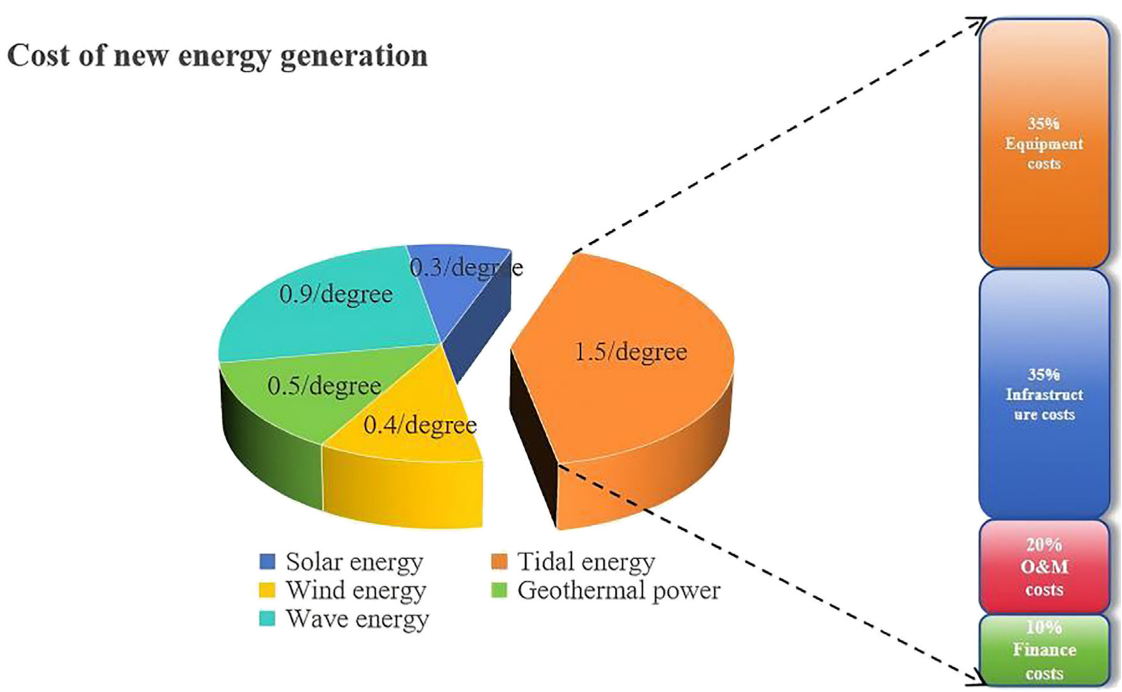

Figure 21. Cost of new energy generation and cost components of tidal energy generation projects

high, and its reliability and durability in harsh marine environments are insufficient. In addition, the distribution of tidal energy is geographically limited, and not all regions can conveniently utilize it. In terms of environmental impacts, large-scale tidal energy development may cause certain disturbances to the marine ecosystem, such as affecting the migration and habitats of marine organisms. Moreover, compared with other mature energy technologies, tidal energy is at a disadvantage in market competition and lacks sufficient policy support and investment attractiveness. Therefore, in order to fully exploit the advantages of tidal energy and overcome the existing problems, tidal energy technologies are bound to develop in other directions.[184–188] As shown in Table 4, the development trends of tidal energy technologies are discussed, and new technological paths are explored with the aim of achieving the dual goals of sustainable energy supply and environmental protection.

Future challenges of tidal energy

As a renewable resource with great potential, tidal energy has a promising development trend. To achieve sustainable development, tidal energy must address the following technical and non-technical challenges: Figure 22 outlines the main challenges that need to be addressed, and the following text will describe these challenges.

(1) Tidal currents are intermittent. Optimizing turbine design (e.g., using bidirectional adjustable-blade turbines) and implementing coordinated control with energy storage systems are key to achieving stable power generation. Recent studies show that coupling LAES with tidal power plants can reduce power fluctuations by 37%.[189] The European TIGER project demonstrated that a group control strategy for 14 turbines reduced the standard deviation of grid-connected power from 18.7% to 5.3%.[190] Additionally, advanced grid dispatch algorithms based on coupled meteorological-hydrological prediction models can increase the capacity factor of hybrid wind-solar-tidal systems to 68%. From the above data, it is found that cooperative control of energy storage systems can optimize the indirectness of tidal energy.

(2) The installation of tidal energy equipment involves a large amount of underwater construction. The construction conditions in the underwater environment are harsh, with poor light, high water pressure, and being subject to the interference of waves, tidal currents, and marine meteorological conditions. The AI-assisted underwater welding robot developed by France's HydroQuest team achieved positioning accuracy within ±5 cm during the construction of the Normandy tidal power station.[191] Scotland's Pentland Firth project utilized 3D-printed coral-like foundation structures, reducing seabed adaptation construction time by 40%. Consequently, future efforts should focus on modular prefabrication technologies, such as the "caisson-turbine" integrated lifting solution used in South Korea's Sihwa Lake project, which reduced installation costs by $220,000 per unit.

(3) Nowadays, the predictability of tidal currents is well known. However, great efforts are still needed to enhance the understanding of the influence of turbulence and its impact on the fatigue life of components. The turbulent-fatigue life mapping model (T-FLM v2.1) developed by Tsinghua University using LSTM neural network was verified by the field data of Pingtan Tidal Power Station in Fujian Province, and the accuracy of blade fracture prediction reached 91%[192] (see Figure 23); In a 1:1 sea trial with EMEC, Norway's Deep Green system from Minesto was able to reduce the failure rate to 0.13 cycles per 1000 h after using this model.[126] Field tests at the European Marine Energy Centre (EMEC) in 2023 showed that installing vortex suppression shrouds extended the mean time between failures (MTBF) of drive systems to 21,000 h (compared to 15,300 h in baseline groups). The above data is a good indication that real-time stress field simulation technology based on digital twins is becoming an industry standard.

(4) Since the development and application of tidal energy are still in the early stage, the standardization degree of its equipment is relatively low, and the system integration of tidal equipment is rather complicated. The following are all good examples of the positive effects of equipment standardization: The EU Tide-EC standardization protocol has unified 23 interface specifications, reducing system integration costs by 19% at the 5 MW Orkney Islands power station. Modular design trends are evident, such as GEK Wave's containerized power units, which feature plug-and-play interfaces compliant with ISO 14617-7 standards. China's "Standard Unit Certification System" at the Wenzhou Tidal Test Site improved interoperability between equipment from different manufacturers to 83%.

(5) The research team conducts experiments and research on tidal energy equipment with different system integrations. By calculating parameters such as the mean time between failures (MTBF) and the expected lifespan, screening is carried out to ensure the sustainability of the tidal energy equipment. For example, accelerated aging tests at the China-UK Joint Laboratory demonstrated that carbon fiber/titanium alloy composite bearings have a projected lifespan of 25 years in salt spray environments (a 67% improvement over traditional materials). Norway's Minesto achieved the world's first IEC/TS 62600-200 reliability certification for its Deep Green system through 1:1 ocean testing, with a failure rate of only 0.13 incidents per 1,000 h. Therefore, a life cycle reliability assessment framework is needed, such as the "Three-Phase Verification System" developed by Canada's FORCE test site.

(6) Develop automation technologies and intelligent fault prediction systems, reduce manual intervention. However, breakthroughs in digital twin technology have significantly improved this issue: Nova Innovation in Canada reduced annual maintenance from 6 to 2 times using digital mirror predictions (Halifax case data). Blockchain technology has also shown promise, with the Perpetuus Tidal Energy Centre in the UK reducing spare parts inventory costs by 34% through smart contract systems.

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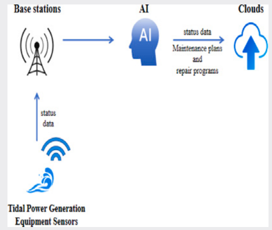
Table 4. Future trends in tidal energy technology

	Efficient energy conversion	Intelligent monitoring and operation & maintenance	Integrated Utilization of Marine Energy	Tidal Energy Storage System
				
Technical	Combination with Materials Science: New high-strength, corrosion-resistant, and wear-resistant materials are used for the key components of turbines and generators. The application of these materials can reduce the weight of the equipment, improve its operating efficiency and reliability, and lower the maintenance costs.	Combination with Internet of Things, big data, and artificial intelligence technologies: Real-time collection of the operating data of equipment. Utilize big data technology to analyze massive amounts of operating data and provide decision-making support for the operation and maintenance management of equipment. Meanwhile, achieve equipment failure prediction and intelligent diagnosis, detect potential problems of equipment in advance, and automatically generate maintenance plans and repair solutions.	Combination with wave energy, ocean thermal energy, offshore wind energy, solar energy, etc.: Jointly arrange and operate in a coordinated manner tidal energy power generation devices with other marine energy or renewable energy power generation devices such as wave energy power generation devices, ocean thermal energy power generation devices, offshore wind turbines, and solar photovoltaic panels.	Combination with battery energy storage, pumped storage, etc.: During the peak period of tidal energy power generation, store the surplus electric energy in batteries. During the peak period of electricity consumption or the trough period of tidal energy power generation, release the electric energy in the batteries to meet the power demand. The same principle applies when combined with pumped storage technology.
Advantages	Improve the conversion efficiency of tidal energy, increase power generation, and reduce power generation costs. In the case of limited tidal energy resources, high-efficiency energy conversion technologies can make full use of the energy of tidal energy, boost energy output, and enhance the competitiveness of tidal energy in the energy market.	Realize the remote monitoring and intelligent management of tidal energy power stations, improve the operational stability and reliability of the power stations, and reduce the operation and maintenance costs. Timely detecting equipment failures and handling them can reduce the downtime of equipment, and improve the power generation efficiency and economic benefits of the power stations.	Through the comprehensive utilization of multiple energy sources in a complementary manner, make up for the instability and intermittence of a single energy source, and improve the stability and reliability of energy supply. Meanwhile, the comprehensive utilization of multiple energy sources can make full use of marine space and resources, and enhance the development efficiency and economic benefits of energy.	Solve the problems of intermittence and instability in tidal energy power generation, and improve the quality and reliability of power supply. The energy storage system can flexibly adjust the output of electrical energy according to the changes in power demand, realize peak shaving and valley filling of electrical energy, and improve the utilization efficiency of energy.

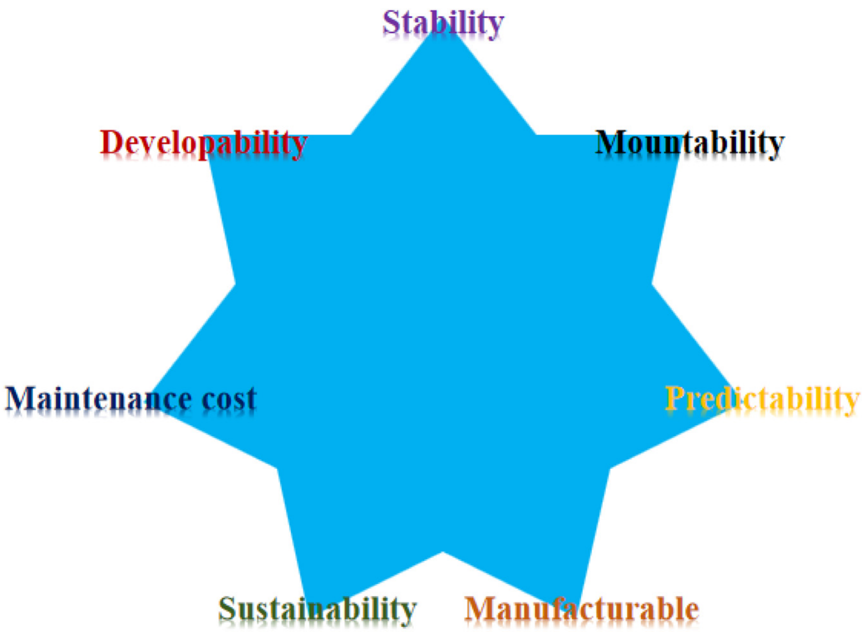


Figure 22. Challenges ahead for tidal energy

(7) Tidal energy presents developmental opportunities such as high energy production, low pollution, and relief of the energy crisis. Nevertheless, it is necessary to raise public awareness so that the government pays more attention to tidal energy power generation projects. Through assistance in the form of incentives, publicity, and stable policies, the sustainable development of tidal energy projects can be promoted to compete with other renewable energy sources.

Collaborative development of multiple energy sources

Comparative analysis of tidal energy, wind energy, and photovoltaic power generation

To clarify the position of tidal energy in the multi - energy system, a systematic comparison with wind energy and photovoltaic power generation is required from three aspects: technical characteristics, economic performance, and environmental impacts (Table 5).

Complementary nature and necessity of multi-Energy synergy

Tidal energy, wind energy, and photovoltaics have natural complementarity in terms of spatiotemporal distribution and output characteristics. At the EMEC in the Orkney Islands, Scotland, a hybrid tidal-wind energy storage system has reduced grid volatility by 42%.[193] Therefore, this section will discuss their complementarity and necessity.

(1) Temporal complementarity

1) Tidal energy generates electricity on a semi - diurnal cycle, and the tidal peaks at night can compensate for the insufficiency of photovoltaics.

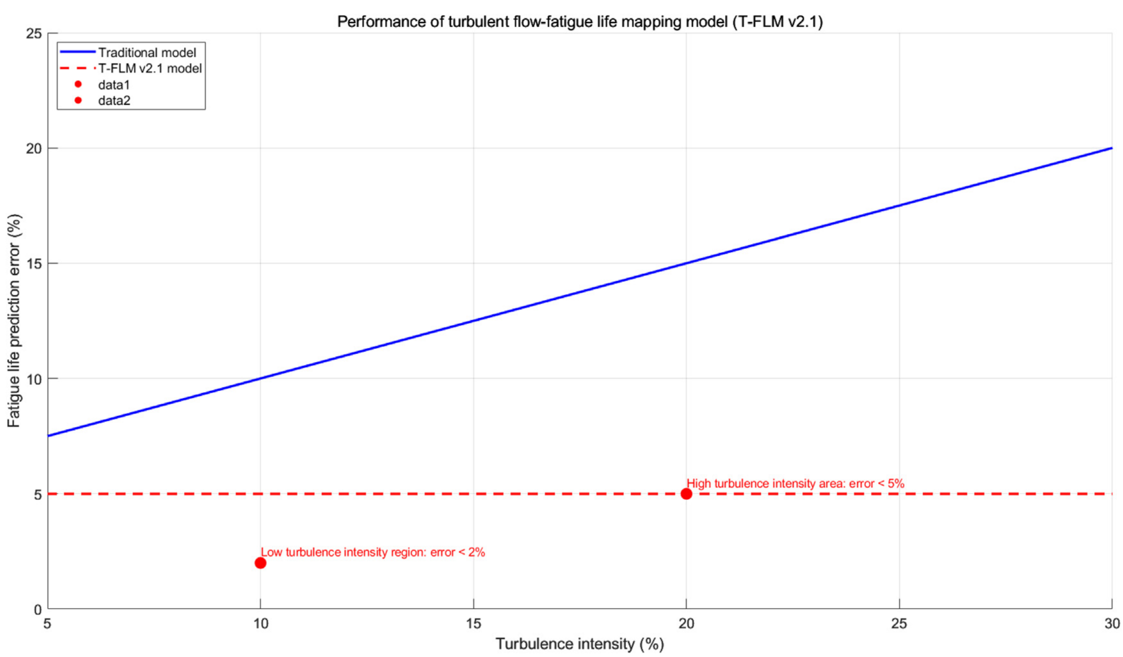


Figure 23. Performance of turbulent flow-fatigue life mapping model (T-FLM v2.1)

Table 5. Comparison of tidal energy, wind energy, and photovoltaic power generation

Contrast dimension	Tidal energy	Wind energy	Solar power
Technical characteristics			
Energy density	High (sea water density 1025 kg/m^3)	Medium (Air density 1.25 kg/m^3)	Low (dependent on light intensity)
Stability	High predictability (daily/semi-daily cycle)	Strong indirectness (dependent on wind speed fluctuations)	The periodicity of day and night is strong, and it is significantly affected by weather
Equipment life	25-30 years (corrosion resistant material required)	20-25 years (gear box easy to wear)	25-30 years (component decay rate about 0.5%/year)
Economics			
LCOE(US$/kWh)	0.1–0.3	0.053–0.156	0.068–0.378
CAPEX(US$/kWh)	8000-12,000(Underwater construction costs are high)	4000-5000(Offshore wind power)	1000-1500(Surface power station)
Recovery cycle	15-20 years	8-12 years	5-10 years
Environmental impact			
Ecological impact	It may interfere with fish migration and sediment migration	Bird strike risk, noise pollution	Land use, carbon emissions from manufacturing processes
Carbon footprint (gCO_2/kwh)	15-20 (Full life cycle)	10–15	30-50 (Silicon based components)

2) Wind energy is stronger in winter, while photovoltaics reach their peak output in summer. Combined with the stable base load of tidal energy, it can achieve balanced power supply throughout the year.

(2) Spatial synergy

1) Ocean space can integrate tidal turbines, floating photovoltaics, and offshore wind turbines (such as the "Ocean Ranch" project in the Netherlands).
2) Near-shore tidal power stations and onshore wind farms can share transmission infrastructure, reducing grid - connection costs.

Innovative approaches to multi-Energy synergy

To break through the limitations of single-energy sources, the following synergy strategies and technical paths are proposed.

(1) Intelligent multi-energy scheduling system

- AI-driven prediction – optimization model

By integrating tidal astronomical forecasts, meteorological models, and historical power generation data, an LSTM neural network is utilized to predict the output of multiple energy sources (with an accuracy of >90%). The charging and discharging strategies of energy storage are optimized through a dynamic programming algorithm. The formulas are as follows:

$$\text{Objective function : } \min \sum_{t=1}^{T} \left(C_{\text{grid}}\left(P_{\text{grid},t}\right) + C_{\text{storage}}\left(P_{\text{bat},t}\right) \right)$$

where C_{grid} is the cost of purchasing electricity from the grid and C_{storage} is the cost of energy storage loss.

(2) Hybrid ocean energy platform

- Modular design

Develop an integrated platform of "tidal turbine + floating photovoltaic + vertical-axis wind turbine", which shares the mooring system and power transformation equipment, reducing the capital expenditure (CAPEX) by 30%.

- Eco-integration Design

Artificial coral reefs are implanted on the base of tidal turbines to attract fish communities and offset ecological impacts (for example, the fish survival rate in the Sihwa Lake project in South Korea has increased by 18%).

(3) New ocean – adapted energy storage technologies

- Seawater pumped hydro energy storage (Seawater PHES)

Utilize the near-shore topography to construct two-way reservoirs. The surplus power generated by tidal energy drives water pumps to store water, and the stored water is released for power generation during low-tide periods (with an efficiency of >75%).

- Ocean-adapted liquid air energy storage (LAES)

Combine tidal energy to compress air, liquefy it, and store it in pressure-resistant tanks on the seabed. When releasing energy, the liquid air drives a turbine to generate electricity (the feasibility has been verified by the Tidal Siren project in Norway).

Policy and industrial collaboration suggestions and environmental mitigation strategies

(1) Policy and industrial collaboration suggestions

1. Cross-sector standard setting
   a) Establish unified interface standards for marine multi - energy sources (such as the EU Tide - EC agreement) to promote equipment compatibility.
   b) Set up a multi - energy data sharing platform to support the joint training and optimization of AI prediction models.

  c) Establish a marine ecological monitoring network to quantify the impacts of tidal power stations on fish migration and sediment transport.
2. Composite subsidy mechanism
  a) Provide additional per - kWh subsidies for "tidal + photovoltaic + energy storage" hybrid projects (for example, +0.03 USD/kWh in the Sihwa Lake project in South Korea).
  b) Offer a 50% tax reduction for research and development of innovative tidal energy materials and intelligent scheduling technologies.
3. Ecological compensation fund
  a) Extract 1% from the tidal power generation fees for coral reef restoration or fishery resource enhancement.

(2) Environmental mitigation strategies

1. Fish habitat interference
  a) Artificial coral reefs implanted on the turbine bases have increased fish abundance by 18% (Sihwa Lake project in South Korea).
  b) Optimize the blade design (such as bionic blades) to reduce the fish strike mortality rate (expected to decrease by 30%).
2. Sediment migration and coastal erosion
  a) Dynamic water level control technology to reduce the impact of tidal power stations on water flow (expected to restore sediment transport to 80% of the natural state).
  b) Regular dredging and ecological restoration to maintain the ecological balance of estuaries.
3. Noise pollution
  a) Use low-noise blade materials (such as carbon fiber composites) to reduce noise by 10–15 dB.
  b) Set up noise isolation zones and limit the operation time of equipment in sensitive areas.
4. Carbon emissions
  a) Based on the LCA model, quantify the carbon emissions throughout the life cycle of tidal energy. It is found that the main carbon emissions come from equipment manufacturing. Exploring new materials for equipment manufacturing is a promising direction.
  b) Combine new energy storage technologies such as flow batteries and hydrogen energy storage. Store the excess electricity generated by tidal energy and release it during peak demand or low-generation periods to avoid energy waste and indirect carbon emissions caused by power curtailment.
  c) Utilize carbon-finance tools to quantify and trade the carbon emission reductions of tidal power generation projects, obtain additional economic benefits, and use them to support the research and development of emission reduction technologies and project upgrades. Issue green bonds to attract social capital investment in low - carbon tidal energy projects and provide financial support for emission-reduction measures.

CONCLUSIONS AND PERSPECTIVES

As an important member in the field of renewable energy, tidal energy has huge potential and occupies a unique position in the process of energy development.

To help tidal energy technology gain a firm foothold in the commercialization process, further development of economic benefit indicators is needed to better understand the economic situation of tidal energy commercialization. Meanwhile, continuous research and development in tidal energy technology is required to overcome deficiencies such as stability, sustainability, and installation issues. Grid connection and array deployment also need to be taken into account. Stakeholders must consider multiple aspects economically, including high upfront costs, high LOCE values, long payback periods, grid connection risks, and equipment maintenance and operation. To ensure more stable clean power supply for the country, government departments should vigorously respond to the call for tidal energy commercialization, conduct educational publicity for the public, continuously optimize policies, and increase support. With joint efforts from all parties, tidal energy can better enter the market.

Looking ahead, tidal energy commercialization faces numerous challenges. It is necessary to continue innovating, seek predictable methods for tidal current energy, and improve equipment stability, manufacturability, and installability. Economically, manufacturing and maintenance costs should be reduced, project benefits optimized, and competitiveness enhanced to gradually improve the integration of the industrial chain and increase market share. That is to say, stakeholders need to address the aforementioned future challenges of tidal energy: stability, predictability, installability, manufacturability, maintenance cost, sustainability, and developability. Only in this way can tidal energy play a greater role in the energy transition and achieve sustainable development.

ACKNOWLEDGMENTS

This work was funded by the National Science Foundation of China (No. 42276070).

AUTHOR CONTRIBUTIONS

Conceptualization, D.Z. and K.Y.; methodology, D.Z., and H.Z.; investigation, K.Y., and S.Z.; writing—original draft, K.Y. and D.Z.; writing—review and editing, D.Z., Y.Z., and K.S.; funding acquisition, H.Z.; resources, K.S.; supervision, D.Z., and H.Z.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, there was no use of AI in the creative process.

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