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Research on the environmental benefits of marine tidal energy and its impact on regional economic structure

Kuan [a], Jing Zhang [b,*], Tao Liu [b]

[a] School of Economics and Management, Xinjiang University, Urumqi, Xinjiang 830000, China
[b] Economics and Management Department, Ningde Normal University, Ningde 352100, China

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ABSTRACT

Tidal power generation, being one of the earliest and largest developed new energy technologies, has evolved into a mature and increasingly competitive source of energy. This article delves into the evaluation of tidal energy's socioeconomic impact, establishing a connection between its environmental benefits and regional economic development. The focus is on marine economic efficiency, and the super-efficiency DEA model is employed to gauge this efficiency. The study conducts a thorough analysis of the green ocean economic efficiency in three major regions, introducing the Malmquist efficiency index for a comprehensive understanding of changing trends. Utilizing an economic effect model, the research explores the contribution of tidal energy development to regional economic growth, delving into industry-related effects. Through these analyses, we aim to provide a clearer and more comprehensive insight into the positive influence of tidal energy on regional socioeconomics. This understanding is pivotal for guiding sustainable tidal energy development and formulating relevant policies.

1. Introduction

In the face of escalating resource scarcity, intensifying environmental issues, and a growing strain on the relationship between humanity and nature, the significance of environmental value concerns has been heightened (Rees, 2008; McMichael, 1993; United Nations Environment Programme. International Resource Panel, 2011). A pivotal moment in human history occurred with the United Nations' 1992 Conference on Environmental Development, marking a shift from a sole focus on economic development or environmental protection to the coordinated development of the economy, society, and environment t (Conca, 1995). Approaching natural environment protection merely from a moral standpoint lacks pragmatic appeal; indeed, environmental preservation is integral to achieving sustainable economic development (*Merely approaching natural environment protection from a moral standpoint lacks pragmatic appeal; indeed, environmental preservation is integral to achieving sustainable economic development*, n.d.). The resource and environmental crisis can be explained economically as the externality of economic activities, where environmental costs are not factored into economic growth (Ahmad et al., 2021). Emphasizing sustainable development does not negate economic growth; instead, it necessitates a change in the approach to align economic growth with environmental carrying capacity (Tenaw and Beyene, 2021; Lorek and Spangenberg, 2014). The crux of this transformation lies in understanding the economic value of resources and the environment (Harich, 2010).

Under the influence of celestial bodies, primarily the moon and the sun, seawater experiences periodic rises and falls, resulting in tidal phenomena (Pugh, 1996). Tidal energy encompasses the potential and kinetic energy associated with these tidal fluctuations, constituting an inexhaustible and renewable energy source with substantial reserves (Charlier and Finkl, 2009; Polagye et al., 2010).

The primary application of tidal energy is power generation, akin to hydropower principles. Typically, a dam with an opening is constructed to create a natural reservoir by separating the seaward estuary or bay from the open sea (Ferreira et al., 2020). A hydroelectric generator is positioned at the dam's opening (Nasir, 2013). As the tide rises, seawater enters the reservoir through the opening, converting kinetic and potential energy into the mechanical energy of a water turbine, which, in turn, drives a generator to produce electricity (Salter et al., 2002). During the ebbing tide, the reverse process occurs, allowing continuous electricity generation. Distinctions between tidal and hydropower generation arise mainly due to the smaller water level difference in tidal

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* Corresponding author.
E-mail address: Jing_Zhang23@126.com (J. Zhang).

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power, necessitating hydraulic turbine units suitable for small water level differences and high flow rates.

Tidal energy represents a clean, renewable source with the advantage of daily tidal fluctuations, rendering it perpetual and virtually inexhaustible (Bansal, 2014). Utilizing tidal energy for electricity generation not only addresses energy scarcity but also emerges as a crucial supplementary energy source for production, life, and national defense in coastal regions (Kothari et al., 2021; Andrews and Shabani, 2012). Tidal energy is a stable and reliable source, minimally impacted by natural factors like climate and hydrology (Andrews and Shabani, 2012). The periodic nature of tidal phenomena ensures a consistent energy supply, distinguishing it from conventional hydropower with wet and dry periods (Rahman et al., 2022a; Clark, 2007). Electricity generation from tidal energy obviates the need for additional fuels and transportation costs, rendering it an economical energy source (Wagner and Mathur, 2011; Jacobson and Delucchi, 2011). However, construction investment is considerable compared to traditional thermal power plants (Ruiz et al., 2022). Despite the substantial initial investment, tidal power generation offers favorable long-term social and economic benefits, reducing dependence on conventional energy sources (Blackman and Wu, 1999).

This article holds profound theoretical significance and practical urgency. Theoretical importance lies in the fact that marine renewable energy constitutes a part of natural resources, aligning with the research scope of the regional economy when studying marine renewable energy in a specific area. Practically, the environmental benefit assessment of marine renewable energy, coupled with the analysis of regional marine resources, facilitates an understanding of the current status, stock scale, and development potential of marine renewable energy. This analysis enables an in-depth examination of the challenges and threats faced by marine renewable energy under the path of sustainable utilization, offering guidance for policy development and providing insights for regional economic and industrial planning. Moreover, by evaluating the environmental benefits of marine renewable energy, the research positively influences the economic impact on the region, contributing valuable references and policy suggestions for regional economic development studies.

This study uniquely addresses the integration of tidal energy into the broader context of environmental value concerns and regional economic development. It not only explores the theoretical underpinnings of the economic value of resources and the environment but also delves into the practical application of tidal energy as a clean and sustainable energy source. The article's focus on the socioeconomic impact of tidal energy development, utilizing advanced evaluation models, provides novel insights into the potential contributions of tidal energy to both environmental conservation and regional economic growth. The article, therefore, stands out as a comprehensive exploration that bridges the gap between renewable energy, environmental considerations, and sustainable regional development.

The primary issue tackled by this article is the need for a holistic understanding of the economic and environmental implications of tidal energy development. It addresses the challenge of integrating environmental value concerns into the assessment of marine renewable energy, providing a framework for evaluating its impact on regional economies. By doing so, the study contributes to the ongoing discourse on sustainable development, offering practical guidance for policymakers and regional planners in harnessing tidal energy's potential while ensuring environmental preservation and economic growth. Fig. 1 is a graphical summary of this article.

2. Tidal energy environmental benefit assessment technical means

2.1. Analysis of resource and environmental impact of tidal power station

The construction of tidal power stations will have an impact on the ecological environment of the site, including the natural environment, hydrology, biology, aquaculture, cultural landscape, navigation, etc. (Rahman et al., 2022b). Based on the research on relevant literature, this article summarizes the environmental impacts as shown in Table 1.

As a clean renewable energy source, tidal energy itself does not harm

Table 1
Environmental impact of tidal power stations.

Impact classification	Specific impact
Natural environment	Reduce pollutant emissions, adverse effects on groundwater and drainage, sedimentation, climate change
Hydrology	Change tidal range, tidal current, water temperature, water flow pattern, and some physical and chemical parameters
Biology	Affects the growth environment and population survival of birds, affects fish migration, and changes species
Aquaculture	Promote siltation and reclamation and optimize the breeding environment
Cultural attractions	A new cultural landscape is formed, and the original facilities are affected.
Floods and tsunamis	Mitigating flood and tsunami losses
Navigation	Convenient transportation in the reservoir area affects navigation capabilities

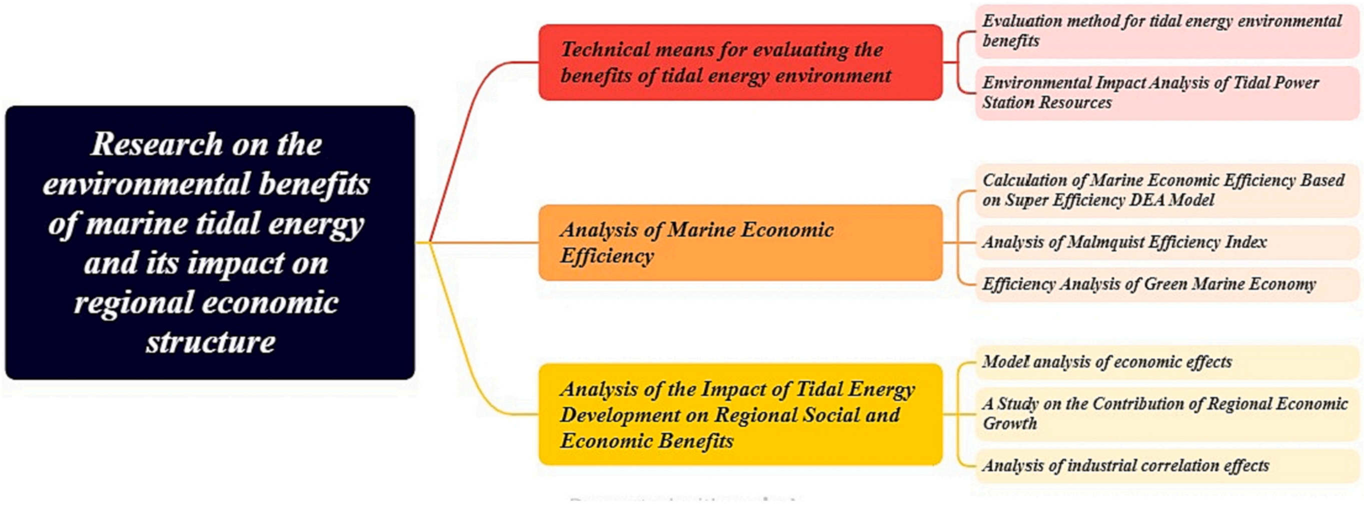

Fig. 1. The graphical summary.

the environment. It can reduce the emission of carbon dioxide, sulfur dioxide, nitrogen dioxide, and dust. At the same time, compared with nuclear power, it has the advantage of no potential pollution from radioactive substances.

Whether the impact is controlled or relatively unimportant. The first step is to determine whether the impact is an internal cost or benefit. If an impact is internal, that is, only the party causing the impact is expected to be affected, then it is double counted in the analysis of environmental value. Secondly, it is necessary to determine whether the impact can be controlled in whole or in part, that is, whether the party causing the impact takes some measures to eliminate or minimize the impact on others. If the impacts are controlled, then the control costs incurred (such as pollution control) should be included in the economic analysis, and no environmental impact analysis is required. Finally, if the impact is small, only a qualitative description will suffice.

2.2. *Tidal energy environmental benefit assessment method*

Tidal energy environmental benefit assessment is a quantitative assessment of the goods or services provided by environmental assets through certain means and is usually expressed in monetary terms (Elliott et al., 2019). The reason why it is necessary to conduct a monetary evaluation of environmental goods or services is that the costs and benefits of social and economic activities can be measured in the form of currency. The evaluation methods suitable for this article mainly include alternative market development, protection cost method, opportunity cost method, willingness survey method, achievement reference method, etc., as shown in Fig. 2.

Faced with environmental changes, people may take protective measures, purchase environmental substitutes, and migrate. In the process of calculating the benefits of pollutant reduction, this method needs to be used to determine the environmental value standards of relevant pollutants. When evaluating the market price of natural resources, the potential benefits that may be obtained from using the resource for other purposes, namely opportunity cost, can be used to characterize the value of the natural resource. In general, people estimate the opportunity cost of resource conservation and then let decision-makers or the public decide whether natural resources have such value or whether it is worth sacrificing these benefits to protect them. The estimated tidal energy environmental value in this article to some extent belongs to the opportunity cost of thermal power generation. The contingent valuation method, also known as CVM, is the most widely used standard method for evaluating the value of public goods in ecological and environmental economics abroad in recent years. The economic foundation of CVM is utility value theory, which uses the principle of maximizing utility to derive the public's Willingness to Pay (WTP) for environmental resources, to obtain the economic value of environmental resources without market value.

The achievement reference method takes the actual evaluation results of the travel cost method, survey evaluation method, etc. as the reference object, and is used to evaluate a new environmental item. This method is equivalent to the analogy analysis method.

There are three types of achievement reference methods:

1. Directly refer to unit value.
2. Referring to the evaluation function of existing case studies, substitute the variables of the project area to be evaluated to obtain the environmental value of the project.
3. Perform a meta-analysis with environmental value as the dependent variable and environmental quality characteristics (E), population characteristics (P), research model (M), etc. as independent variables to obtain the calculation function of environmental value (V):

$$V = f(E, P, M\ldots) \tag{1}$$

In the process of calculating the benefits of reducing tidal energy pollutants, the following text refers to the research results of wind power generation.

3. Analysis of marine economic efficiency

3.1. *Calculation of marine economic efficiency based on super efficiency DEA model*

Data Envelopment Analysis (DEA) was proposed by Charnes et al. (Dalton et al., 2015) in 1978 to evaluate the relative effectiveness between decision units with the same input and output indicators and similar properties. The DEA method uses linear programming to construct nonparametric front surfaces of observation data and determines the efficiency of each DMU based on the distance between each decision-making unit (DMU) and the effective production front surface.

In the traditional DEA model proposed by Charnes, Banker et al. (Charnes et al., 1978), if there is more than one effective DMU with an efficiency value of 1, this method cannot further evaluate the relative advantages and disadvantages of these effective decision units. To compensate for the shortcomings of traditional DEA, Anderson et al.

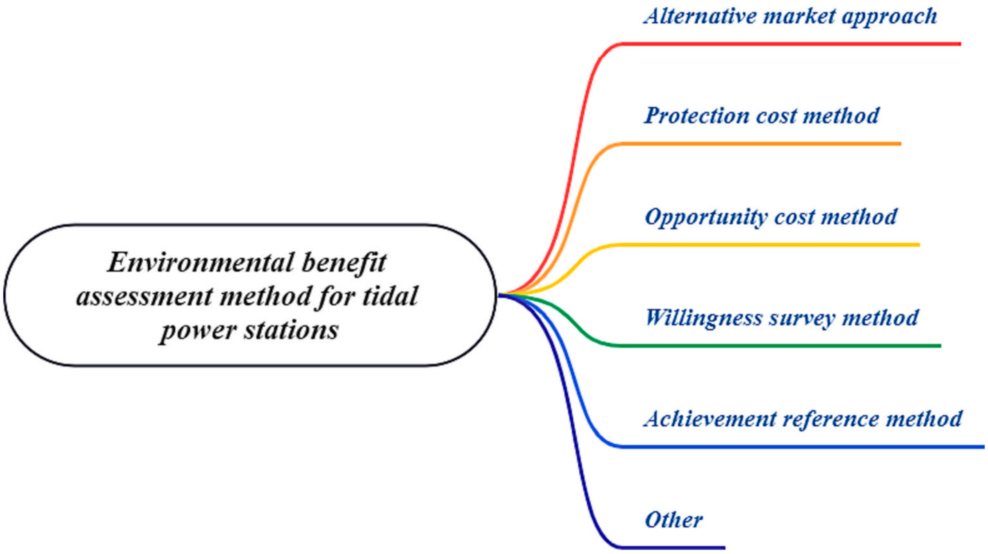

Fig. 2. Environmental value assessment technical methods.

proposed a super-efficient DEA model (Banker, 1984), which can further evaluate the decision units on the effective frontier and distinguish the differences between effective DEA decision units. The super-efficient Output DEA model can be described by the following linear programming:

$$max_{\phi,\lambda}\phi$$

$$s.t.$$

$$\begin{cases} \sum_{\substack{i=1 \\ i\neq k}}^{n} Y_i\lambda_i - S^{+} = \phi Y_k \\ \sum_{\substack{i=1 \\ i\neq k}}^{n} X_i\lambda_i + S^{-} \geq X_k \\ \lambda_i \geq 0 \\ S^{+} \geq 0, S^{-} \geq 0 \end{cases} \tag{2}$$

The main difference between this model and the traditional Output DEA model is that when evaluating the k-th decision unit, it is excluded from the production possibility set. For decision units with ineffective technical efficiency, because they are located below the production frontier, even if they are excluded from the production possibility set when calculating efficiency values, their production frontier remains unchanged. Therefore, their final efficiency value is the same as measured using traditional DEA models. However, when evaluating effective decision units on the frontier, the production frontier changes due to the disappearance of that point, Therefore, the final efficiency value will also change. The dual output model can be used to illustrate the meaning of super-efficient Output DEA, as shown in Fig. 3.

It can be seen from the model that in the traditional output-oriented model, ACB represents the boundary of the frontier production function. The inefficient point D falls below the frontier surface, and its technical efficiency value is the ratio of the distance from the origin O to the actual output point D (OD) to the distance from the origin O to its projection point D′ on the front surface ACB (OD'), that is $TE = OD/OD' = 1/\phi_D < 1$.

The efficiency effective point C falls exactly on the boundary represented by the frontier production function, so its technical efficiency value $TE = OC/OC = 1/\phi_C = 1$. In the super-efficiency DEA model, when evaluating the efficiency value of the ineffective point D, due to its being outside the production frontier, its frontier is still ACB, and the efficiency value does not change. When evaluating the efficiency of decision unit C, it is necessary to exclude it from the set of participating decision units. Consequently, for decision unit C, the efficient frontier changes from the original ACB to AB. The projection of C onto the efficient frontier becomes C′, resulting in the efficiency value for point C being “$TE = OC/OC' = 1/\phi_C > 1$”. At this point, “$\phi < 1$, $\phi\text{-}1 < 0$”, implying that an effective decision unit, without altering inputs, can increase its output by a proportion of $|\phi\text{-}1|$ without compromising its efficiency.

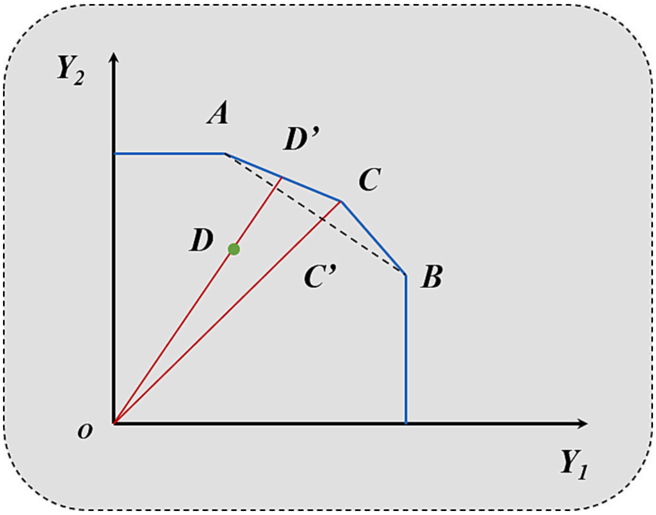

Fig. 3. Supper efficiency DEA model.

Based on the above analysis of the super-efficiency Output-DEA model, the practical guiding function of using this model to evaluate the efficiency of the marine economy is demonstrated. For inefficient evaluation units, it is possible to increase the outputs in terms of marine economy and environment without additional resource or labor inputs by improving their technical efficiency. For efficient decision units, outputs can be increased to some extent without affecting their efficiency. In the presence of slack variables, adjustments to the structure of inputs and outputs are needed to optimize resource allocation. It should be noted that since the efficiency values calculated by both DEA models and super-efficiency DEA models are relative efficiency values, the marine economic efficiency values calculated in this paper are only suitable for comparative analysis between units. This includes both horizontal and vertical comparative analyses and is not suitable for absolute value analysis.

First, the correlation between input variables and output variables is determined by calculating the Pearson correlation coefficient to verify the “same direction”. As shown in Table 2, there is a positive correlation between all input variables and output variables in the sample, and except for the insignificant relationship between human input and environmental output, all other input variables and output variables are different It is significant at the significance level and satisfies the condition of “same direction”, indicating that the DEA efficiency assessment using the selected input-output variables is reliable.

The super-efficiency DEA model is used to separately measure the traditional marine economic efficiency values and green marine economic efficiency values of 8 provinces and cities in China's three major marine economic zones with an output orientation from 2016 to 2020, and through the input of non-DEA effective decision-making units Analyzing the output slack can provide targeted improvement suggestions and countermeasures for each province and city to improve marine economic efficiency. The measurement process is implemented through EMS (Efficiency Measurement System) version 1.3.0 software. For the input-oriented DEA model, the calculation results of this software directly display the efficiency value of each DMU, while for the output-oriented DEA model, the output results are parameters, and the efficiency value $TE = 1/\phi$. G represents the green ocean economic efficiency value, and T represents the traditional ocean economic efficiency value. The calculation results are shown in Table 3, and Fig. 4 is the five-year average value of each region.

Although compared as a whole, from traditional marine economic efficiency to green marine economic efficiency, the average efficiency ranking of my country's three major marine economic zones remains unchanged. The average efficiency value of the Yangtze River Delta is the highest, followed by the Bohai Rim region, and the marine economic efficiency of Guangdong Province. The value is the lowest, but through comparison it is easy to find that the rankings of half of the provinces and cities have changed, confirming the necessity of measuring marine economic efficiency including environmental variables.

3.2. Green ocean economic efficiency analysis

This study conducts a comparative analysis from the perspectives of maritime economic development factors and the status of maritime industry development in three key regions of China: The Bohai Rim

Table 2
Pearson's correlation coefficient.

	Human input - economic output	Human input - environmental output	Resource input - economic output	Resource input - environmental output	Technology investment - economic output	Technology investment - environmental output
Correlation coefficient	0.763***	0.171	0.721***	0.361**	0.742***	0.153*
P-value	0	0.326	0	0.044	0	0.079

Note: *, * *, and * * * respectively indicate significant at the 10%, 5%, and 1% significance levels (two tailed).

Table 3
Supper efficiency value of three marine economic regions during 2006–2010.

Region	2016		2017		2018		2019		2020	
	G	T	G	T	G	T	G	T	G	T
Tianjin	0.55	0.47	0.56	0.49	0.64	0.64	0.78	0.78	1.10	1.10
Hebei	1.07	0.95	1.20	1.03	1.30	1.30	1.09	1.09	1.33	1.04
Liaoning	0.61	0.60	0.70	0.70	1.19	1.19	0.46	0.46	0.53	0.53
Shandong	0.45	0.45	0.54	0.54	0.65	0.65	0.72	0.72	0.87	0.87
Bohai rim region	0.67	0.62	0.75	0.69	0.95	0.95	0.76	0.76	0.96	0.89
Shanghai	1.23	1.09	1.21	1.21	1.12	1.12	0.96	0.96	1.21	1.18
Jiangsu	0.68	0.41	0.64	0.57	0.71	0.71	0.82	0.82	0.99	0.99
Zhejiang	0.43	0.43	0.50	0.51	0.58	0.58	0.74	0.74	0.86	0.86
Yangtze River Delta region	0.78	0.64	0.79	0.76	0.80	0.80	0.84	0.84	1.02	1.01
Gangdong	0.39	0.39	0.43	0.43	0.51	0.51	0.60	0.60	0.74	0.74

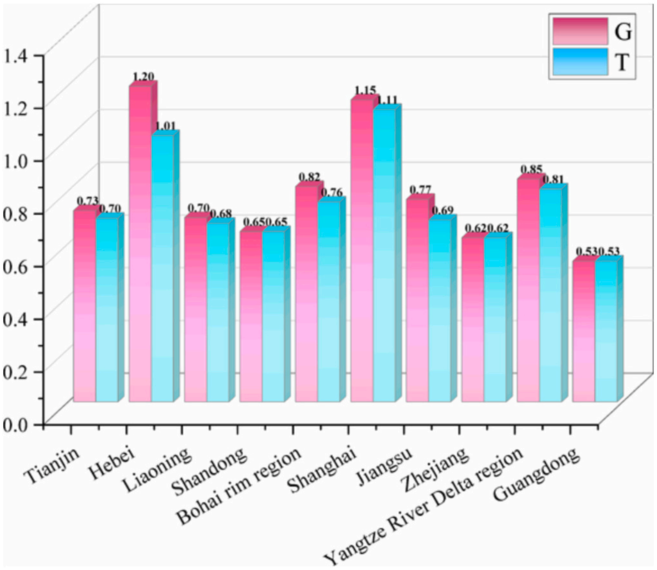

Fig. 4. Supper efficiency value of three marine economic regions during 2016–2020.

Economic Zone, the Yangtze River Delta Economic Zone, and Guangdong Province, which is part of the Pearl River Delta. Fig. 5 shows the location of China's three major marine economic zones. Overall, the green maritime economic efficiency values in these three major maritime economic zones during the sample period are not high, with an average efficiency value consistently below 1, indicating a suboptimal state. There is a noticeable regional disparity in the level of green maritime economic efficiency among these three areas, with the Yangtze River Delta showing the highest average efficiency value of 0.755, distinguishing itself in regional maritime economic development, followed by the Bohai Rim region with an average efficiency value of 0.729. This phenomenon is understandable, considering that the Yangtze River Delta region comprises economically advanced provinces and a municipality, serving as focal points of high population density, industrial concentration, and wealth accumulation, with evident advantages in economic conditions, technological level, and policy environment. The infrastructure, including information technology, communication, and transportation, is well-developed, and the region has an ample supply of human capital, with a generally high level of education contributing to a high-quality workforce, providing favorable conditions for the development of the maritime economy. In contrast, the economic development in the Bohai Rim region started later, and although the momentum of maritime economic development has been established, regional disparities are more pronounced, manifesting in issues related to resource utilization, industrial structure, and regional cooperation. Regional collaboration has the potential to conserve resources and bring about more net benefits. The Bohai Rim region must swiftly break free from individualistic economic practices, proactively align itself with the Yangtze River Delta Economic Zone, absorb successful experiences from advanced maritime economic regions, facilitate broader maritime economic exchanges and cooperation, and expand market space.

Of particular concern is the fact that Guangdong Province has the lowest efficiency value, merely 0.477, suggesting a significant wastage of input resources. With the existing resource inputs, improving technological efficiency could lead to a substantial enhancement in the economic output and environmental conditions of the maritime industry.

To visually depict the changes in green maritime economic efficiency values across the three major regions from 2016 to 2020, the overall trends are illustrated in Fig. 6. The Yangtze River Delta, as a model for maritime economic development, should simultaneously leverage the “polarization effect” and “diffusion effect”—concentrating and creating high-end production factors compatible with maritime economic development, such as higher-tier talent, knowledge, and technology, to build the foundation for efficient, high-tech maritime industries. It should also disperse some production factors that are not conducive to maritime economic development, transfer industries that no longer have development advantages, and drive the development of the maritime economy in other regions. The Pearl River Delta, at the forefront of China's opening-up, has been a pioneer in regional maritime economic cooperation and maritime industry transformation, accumulating substantial achievements. It should actively share successful experiences and innovative capabilities, propelling the development of less-developed maritime economic areas in the vicinity. Simultaneously, it should integrate resources, adjust the layout of maritime economic development, and continually enhance the competitiveness of maritime industries. The Bohai Rim region, rich in maritime resources but with a

Fig. 5. China's three major marine economic zones.

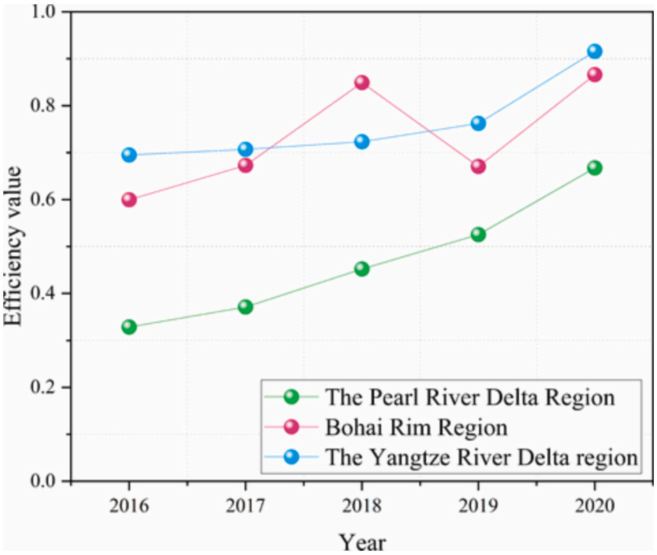

Fig. 6. The change trend of marine green economic efficiency of the three marine economic regions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

later economic start, holds considerable development potential. It should deeply learn and draw lessons from the successful practices and advanced experiences of the Yangtze River Delta and Pearl River Delta regions, conduct a comparative analysis of its gaps and deficiencies, strengthen inter-regional cooperation in maritime economic development, and ultimately achieve efficient and sustainable development of the green maritime economy.

3.3. *Malmquist efficiency index analysis*

This paper, starting from the perspective of green economy, constructs a more comprehensive input-output indicator system to assess the efficiency of marine economic development in the study area. On one hand, technological factors are introduced. On the other hand, considering green economic efficiency, the marine water quality compliance rate is selected as an environmental output, meaning this output indicator is only included in the calculation of green economic efficiency. Research data is sourced from the “China Ocean Statistical Yearbook” for the years 2017–2021, the “Bohai Sea Marine Environmental Quality Bulletin” for the years 2017–2021, and the environmental quality bulletins of various provinces and cities for the years 2016–2020.

Utilizing the Deap2.1 software, this study calculates the Malmquist efficiency indices for the years 2016–2020 across the eight provinces and municipalities in China's three major maritime economic zones. Based on the software computations, the paper compiles the Malmquist efficiency indices, technical efficiency indices, and technological progress indices for each year in the three major regions, as depicted in Table 4 and Fig. 6. To gain a better understanding and analysis of the maritime economic efficiency in each region, the paper presents a graphical representation (Fig. 7) that illustrates the Green Maritime Economic Efficiency (TE), Total Factor Productivity (tfpch), Technological Progress Variation (techch), Technical Efficiency Variation (effch), Pure Technical Efficiency Change (pech), and Scale Efficiency Change (sech) for each area. Subsequently, the following sections summarize the temporal changes in the overall factor productivity growth, regional characteristics, and structural changes in the maritime economy during the “Eleventh Five-Year Plan” period in the three major economic zones.

In a comprehensive analysis, the Bohai Rim, Yangtze River Delta, and Guangdong Province in the Pearl River Delta all achieved Total Factor Productivity (TFP) growth from 2016 to 2020, with average annual growth rates of 8.6%, 8.7%, and 16.7%, respectively. Notably,

Table 4
Malmquist index and decomposition of three economic regions.

Year	The Pearl River Delta Region			Bohai Rim Region			The Yangtze River Delta region		
	Effch	Techch	Tfpch	Effch	Techch	Tfpch	Effch	Techch	Tfpch
2016	1.306	0.926	1.081	1.350	0.951	1.146	2.033	0.693	1.258
2017	1.086	1.678	1.627	0.977	1.363	1.188	0.692	2.060	1.273
2018	1.242	0.783	0.868	1.521	0.905	1.229	1.940	0.765	1.324
2019	1.111	1.443	1.432	1.116	1.318	1.314	1.142	1.351	1.378
2010	1.183	1.151	1.216	1.223	1.116	1.217	1.328	1.102	1.307

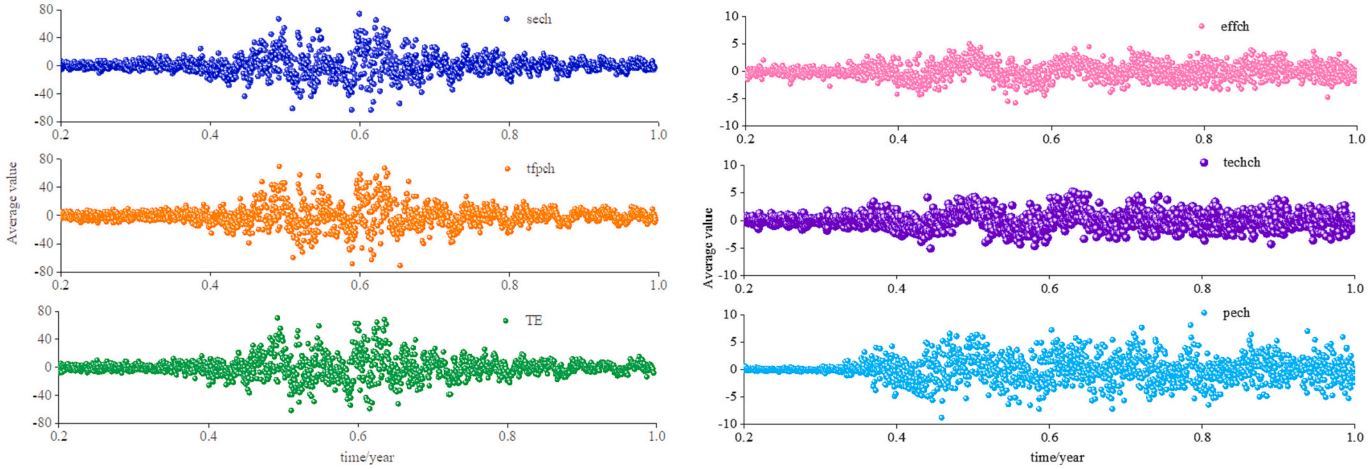

Fig. 7. The changing trend of marine green economic efficiency and total factor productivity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Guangdong Province exhibited a TFP growth rate significantly surpassing the other two regions. TFP is further decomposed into Technical Efficiency (effch) and Technological Progress (techch) indices. Technical efficiency reflects the distance between the decision-making unit and the boundary of the production function frontier, with a larger distance indicating a greater space for the decision unit to reach technical efficiency and thus lower technical efficiency. If the Technical Efficiency Index (effch) is >1, it signifies that the decision unit under consideration moved closer to the efficient frontier during the evaluation period, indicating improved technical efficiency. Technological progress refers to the "upward" movement of the technological boundary, manifested as increased output through technological progress or innovation without adding additional input factors. From 2016 to 2020, the growth rates of technical efficiency for the Bohai Rim, Yangtze River Delta, and Guangdong Province were 5.6%, 9.2%, and 18.6%, respectively. The technological progress variation shows that during the "Eleventh Five-Year Plan" period, the Bohai Rim region experienced a 2.8% increase in the technological progress index, while the Yangtze River Delta and Guangdong Province witnessed varying degrees of technological decline, with decreases of 0.4 and 1.6 percentage points, respectively. The increase in technical efficiency outweighed the decrease in technological progress, leading to an overall rise in TFP. This indicates that during the "Eleventh Five-Year Plan" period, the maritime industry in the three major economic zones made significant progress in operational management and optimizing production scale. Those falling behind within the production frontier demonstrated a noticeable catch-up effect toward the "best practices" at the production frontier, suggesting a trend of convergence between regions. However, there is room for improvement in areas such as the introduction of advanced technology, enhancement of technological capabilities, and product research and development.

4. Analysis of the impact of tidal energy development on regional social and economic benefits

4.1. Model analysis of economic effects

Tidal power projects not only meet the local demand for clean energy but also stimulate local economic development, fostering employment opportunities and tax contributions from the residents (Anderson and Peterson, 1993). To evaluate the economic benefits, it is imperative to consider the impact of tidal energy on regional economic development. In developed countries, the harmonious coexistence of economic development and ecological environmental protection has become a predominant trend, leading to rapid transformations in industrial production due to environmental considerations. The Harrod-Domar model is a widely employed economic growth forecasting model that regards savings and capital reserves as two major variables. Solow's economic development model posits that labor input, capital investment, and technological progress are pivotal aspects driving economic development, particularly the substantial impact of technological progress on productivity and capital efficiency improvement. Building on Solow's theory, Denison transforms the technological development element into the labor quality of employees and emphasizes its influence. Therefore, the models presented above qualitatively and semi-quantitatively analyze the impact of investments in different factors on the economy. The Cobb-Douglas equation is a widely recognized formula for quantifying economic development issues, as manifested in Eq. (3).

$$Y = A(t)K^{\alpha}L^{\beta}\mu \tag{3}$$

In the equation: K represents capital input, L denotes the quantity of labor input, α is the elasticity coefficient of capital output, β is the elasticity coefficient of labor output, and A(t) represents the overall technological level. Under general circumstances, it is assumed that this comprehensive level remains constant over a specific period.

Tidal energy represents a marine ecological resource and a significant investment in the emerging marine renewable energy industry. Leveraging its inherent ecological effects, tidal energy can influence the economic system of an entire region, contributing to the sustainable development of the entire economic system and providing clean energy for human development. In other words, within the entire cyclical system comprised of nature, economy, and society, tidal energy possesses all the elements of productivity, making it a productive input. Tidal energy serves as a direct or indirect contributor to regional economic development through its direct or indirect effects. Specifically, it integrates with other financial resources as a novel energy investment, providing power and other services to the entire economic system and, to some extent, promoting social development and welfare.

In the Cobb-Douglas eq. (5.1), capital input is assumed to represent the total assets of a capital item. Due to the inability to ascertain and obtain essential data, fixed asset investment (IN) is used as a substitute for capital investment, and the Cobb-Douglas eq. (3) is modified to formula (4).

$$Y = C + aln(1N) + \beta ln(L) + \mu \tag{4}$$

In the formula: Y is the regional GDP, IN is the annual fixed asset investment in the region, L is the number of employees on the job at the end of the year, α is when the growth rate of IN is 1%, the added value of Y is α%, β is the current When the growth rate of L is 1%, the increased value of Y is β%.

To reduce the volatility of the data, we take logarithmic values of the amount of investment in fixed assets (IN) and labor input (L).

We used the data from 2020 to 2021 where the tidal power station is located to perform regression calculations on the model. Y takes the gross national product of the region (100 million yuan), IN takes the fixed asset investment in the region (100 million yuan), and L takes the current employment of the location. The number of employees (10,000 people) (relevant data comes from the statistical yearbook of the local municipal government). The regression results after calculation using statistical software are shown in Table 5.

As can be seen from Table 5 to some significant extent, each variable included in each model meets the test criteria, and the overall regression fit shows a good level. With fixed labor investment and a 1% increase, the region's GNP will correspondingly increase by 376.72%. According to the annual statistical report, the total investment in the entire region is 24.262 billion yuan. The total investment in this project is about 800 million yuan. If calculated based on local fixed asset investment, it will increase fixed asset investment by 3.297%. Then the increase in local GDP from this tidal power station is 1.242 billion yuan.

4.2. Research on contribution to regional economic growth

Among them, energy consumption elasticity and electric energy consumption elasticity are the main indicators to measure a country's regional economic development (Sen et al., 2016). The energy consumption elasticity factor en is a measure of the ratio between energy consumption and economic development rate, expressed by formula (5). At an annual energy consumption growth rate of 1% per year, the country's development rate is the relationship between this factor and energy consumption. Economic value is affected by many aspects such as industrial structure, process equipment, production technology, energy efficiency, overall regional management level, and residents' quality of life.

Table 5
Regression results.

Variable	Coefficient	Std.Error	T-Statistic	Prob.
C	−6803.725	2127.098	−3.359	0.011
LOG(IN)	395.561	107.421	3.866	0.005
LOG(L)	1539.503	698.246	2.315	0.058

$$\text{Annual average growth rate of energy consumption} = \frac{\text{Energy consumption elasticity coefficient}}{\text{The average annual growth rate of the national economy}} \tag{5}$$

The electric energy consumption elasticity index ed. is used to express the ratio between electric energy consumption and economic development rate, expressed by formula (6). That is, the product of the electricity consumption rate and this factor is the economic development rate of that year. When economic development reaches a certain level, its energy consumption is low, such as electricity, etc., and its energy consumption is low.

$$\text{Annual average growth rate of electricity consumption} = \frac{\text{Elastic coefficient of electricity consumption}}{\text{The average annual growth rate of the national economy}} \tag{6}$$

A certain region of the Yangtze River Delta in China was selected as the assessment area, and the values of the above two coefficients from 2011 to 2021 were compiled, as shown in Fig. 8. As can be seen from Fig. 6, the overall energy consumption and elasticity index indicators of electric energy consumption in each region have not changed significantly in history. However, as my country's energy conservation and emission reduction indicators are gradually determined, various measures are gradually implemented, especially After 2016, this number has dropped significantly. According to the different situations of each province, the energy consumption elasticity index of each province is 0.60, and the electricity consumption elasticity index is 0.89. The total annual energy consumption of this project in this area is 9.105*10°TW, the electricity consumption is 9.393*109kWh, and the city's annual GDP is 211.095 billion yuan. The power generation capacity of the tidal power station is 7.968 × 107 kilowatt hours, which is equivalent to 26693tec of standard coal. All electric energy can be used by local users, which is equivalent to an increase in energy consumption by 0.293317% and an increase in electric energy consumption by 0.8483%. In terms of energy consumption, the total regional GDP increased by 0.4729%, equivalent to a GDP of 998 million yuan. From the perspective of energy consumption, the total regional GDP increased by 0.9024%, approximately 1.905 billion yuan.

4.3. Analysis of industry-related effects

The construction of this power station is of decisive significance in promoting the development and development of the entire region's industrial chain, especially in the process of investment and construction, power development and operation, involving equipment purchase,

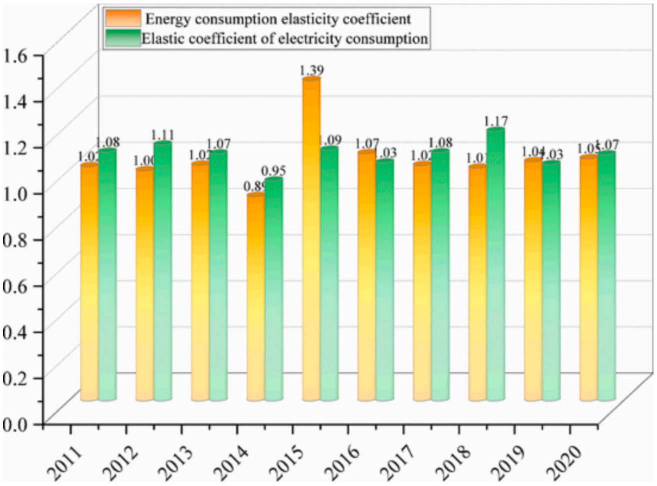

Fig. 8. Energy consumption elasticity coefficient and electricity consumption elasticity coefficient of the province where the project is located.

construction, and maintenance. From the perspective of industry relevance, it can be divided into three different types. The main structure is shown in Fig. 9. Among them, the backward correlation effect: refers to the correlation between the industries with various production factors that provide services for the tidal power station project; the forward correlation: refers to the correlation between the power supply, the power supply, and the industry where the supplier is located after the project is completed., aquaculture and other industries, indirect correlation effect: that is, the driving effect of the construction and operation of tidal power plants on the development of other finance, logistics, and other related industries. Here is a specific breakdown:

As an important pillar of the national economy, its business involves all walks of life, but the levels of energy consumption are different. For the primary industry, it directly increases the fishery production of the primary industry and adds power to fishery production, thereby enabling the fishery to continue to increase income and promoting the sustainable development of the fishery. Secondly, it can promote the adjustment of local industrial structures, improve traditional industrial production methods, and achieve the goals of energy conservation, emission reduction, green development, cost reduction, and production efficiency improvement. At the same time, the completion of this tidal power plant has also created opportunities for the development of its service industry and other tertiary industries. It can not only create business opportunities for the traditional service industry but also create more jobs for the local tertiary industry. Chance.

Table 6 shows the electricity consumption and composition of the whole society. It can be seen that during the construction and operation of tidal power stations, it is necessary to establish indirect connections with the financial industry, insurance industry, catering service industry, third-party management industry, consulting industry, and other industries. Connect. The tidal power station is a project under construction, and its operation and operation cannot be separated from huge financial support and services, these employment opportunities will promote the development of logistics, transportation, catering, and other industries. Therefore, the construction and operation of tidal power stations involve many industries. As the mainstay of the entire industrial chain, its function is not only to stimulate upstream industries but also to adjust and innovate the entire regional industry.

5. Discussion

This study employs advanced models, including the super-efficiency Output-DEA model and the Malmquist index, to comprehensively evaluate the efficiency of the maritime economy across three major regions. The evaluation indicator system constructed encompasses key variables such as technological input and environmental output, providing a holistic view of green maritime economic efficiency. The use of EMS software facilitates a detailed assessment of each province and municipality, enabling both horizontal and vertical comparative analyses.

Our analysis reveals that the rapid development of the maritime economy in recent years has been heavily reliant on significant inputs of marine natural resources and labor resources, resulting in a relatively low production efficiency. To ensure sustainable growth, the future development of the maritime economy must prioritize efficiency and quality alongside speed. This necessitates a careful balance in the utilization of marine resources and increased investments in technology.

6. Conclusions

Over the years, the maritime economy's rapid development has highlighted the need for enhanced efficiency. The study recommends a shift toward emphasizing efficiency and quality in addition to speed, advocating for prudent utilization of marine resources and increased investments in technology. This approach is crucial for ensuring the sustainable and responsible growth of the maritime economy.

In alignment with a focus on economic growth and industrial structure adjustment, we propose a secondary indicator system for economic impact evaluation. Centered around overall improvements in people's living standards, industrial structure, and the economic system, this system considers indicators such as regional economic growth, the contribution rate of green GDP, optimization of industrial structure adjustment, industrial cluster effects, and the sustainable development of the regional economy.

Utilizing the modified Cobb-Douglas equation as an economic evaluation model, our predictions indicate significant potential for economic growth associated with tidal power station development. Under fixed labor investment and a 1% increase, the region's GNP is predicted to increase by 376.72%. Moreover, calculations based on local fixed asset investment project a 3.297% increase, resulting in a substantial growth of 12.42 billion yuan in the local GDP attributable to the tidal power station in the research area. These predictions underscore the positive economic impact and potential returns on investment in tidal energy development.

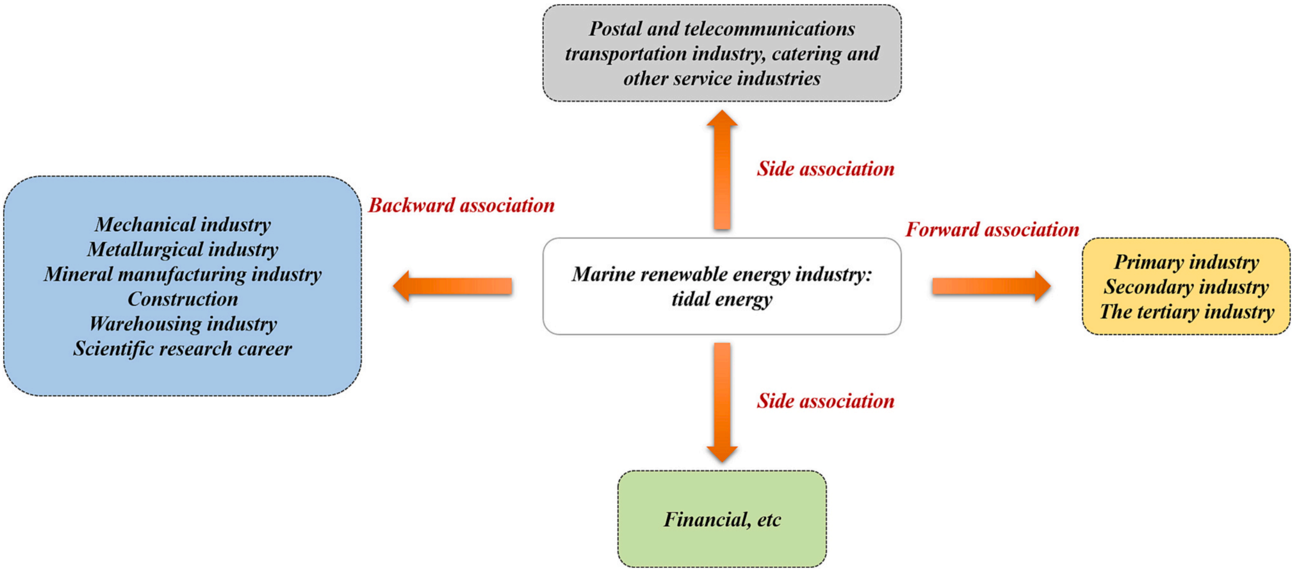

Fig. 9. Tidal energy industry related effects.

Table 6
Forecast of electricity consumption and composition of the whole society.

Year	Total electricity consumption	Industry wide	Primary industry	Secondary industry	The tertiary industry	Resident life
2015	99,908	79	6	64	8	26
2016	113,996	78	6	63	8	27
2017	132,327	76	5	61	9	29
2018	153,402	72	5	59	9	33
2019	176,841	69	4	56	8	36
2020	283,710	68	3	58	7	37

CRediT authorship contribution statement

Kuan: Writing – original draft, Writing – review & editing. **Jing Zhang:** Writing – review & editing, Writing – original draft. **Tao Liu:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The author declares that there is no conflict of interest.

Data availability

Data will be made available on request.

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