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Has Digital Finance Made Marine Energy Carbon Emission More Efficient in Coastal Areas of China?

Sheng Xu [1,2,*] and Liang Liang [1]

[1] School of Economic, Ocean University of China, Qingdao 266100, China
[2] Marine Development Research Institute, Ocean University of China, Qingdao 266100, China
* Correspondence: xusheng@ouc.edu.cn

Abstract: Energy is an essential material foundation for ensuring economic sustainability and national security. With the development of digitalization, the importance of digital finance in promoting the green and low-carbon transformation of the economy has emerged. The ocean is a national energy treasure house. In order to explore whether digital finance improves the carbon emission efficiency of marine energy, this paper selects panel data from 11 coastal areas from 2011 to 2019 in China and uses the panel fixed effect model, mediation, and moderation model to analyze the mechanism between them empirically. The results show that: (1) digital finance improves marine energy carbon emission efficiency, and the depth of use has the most obvious effect; (2) the incentive effect is heterogeneous due to different geographical locations, resource endowment degree, and digitalization degree; (3) the marine energy consumption structure plays a mediating effect, and marine industrial structure and technological innovation can enhance the impact of the digital finance on marine energy carbon emission efficiency. Therefore, optimizing the energy consumption structure and giving full play to the effect of digital finance in promoting the efficiency of marine energy carbon emission to help accelerate the low-carbon development of China's economy and the realization of carbon emission reduction.

Keywords: digital finance; marine energy carbon emission efficiency; marine energy consumption structure; industrial structure; technological innovation; low-carbon development

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1. Introduction

Energy security is a global and strategic issue related to national economic and social development [1]. With the development of the economy and society, environmental problems such as excessive discharge of pollutants, depletion of energy, rising sea levels, and frequent extreme weather caused by the massive burning of fossil fuels are becoming more severe. They have systematic, long-term, and irreversible negative impacts on human survival and development. It is a global problem. As the world's largest carbon emitter, China's long-established crude economic development has resulted in high energy consumption and low energy utilization efficiency, while higher energy consumption means more carbon emissions, which has had an irreversible impact on the environment [2], and the energy consumption structure is in urgent need of transformation. At this stage, the improvement of energy utilization efficiency in China faces the double constraints of energy supply structure and ecological environment [3]. Energy carbon emission efficiency is a multi-dimensional indicator compatible with energy efficiency, economic benefits, and environmental factors. It is a production ratio relationship that minimizes carbon emissions and maximizes economic output when the input of energy, capital, and labor remains unchanged. Optimizing energy consumption structure and improving energy carbon emission efficiency is essential in promoting carbon emission reduction and low carbon development of the economy. Existing studies have analyzed the crucial factors affecting energy efficiency from various perspectives, including technological progress [4], structural adjustment [5], market segmentation [6], economic agglomeration [7], and government intervention [8], which provide valuable references for the formulation of energy policy and transformation of energy consumption structure in key industries and different regions.

Finance is the lifeblood of economic development [9], and a stable source of finance is a core issue for developing a low-carbon economy [10]. Small and medium-sized enterprises are limited by the mismatch in financing maturity, information asymmetry, and lack of products and analytical tools, making it difficult to obtain sufficient financing from traditional financial markets [11]. In turn, enterprises are an essential vehicle for green economic development [12], and the green financing difficulties of small and medium-sized enterprises will seriously constrain the achievement of carbon emission reduction targets and green and low-carbon circular economic development. Existing studies generally confirm the positive role of financial support in optimizing the energy structure [13], curbing CO2 emissions [14], and promoting green economic development [15] and green economic transformation [16]. Digital finance is a new financial model that integrates digital technology and traditional finance, which can improve the possibility and convenience of micro individuals to obtain financial services, alleviate information asymmetry of enterprises [17], reduce the cost of information search and resource matching [18], alleviate financing constraints [19] and guide enterprises to green production and micro individuals to green consumption and green investment patterns [20] by expanding the reach of financial services, innovating financial products and services, guiding green capital orientation and green financial resource allocation [21]. Most of the existing studies start from the economic performance of digital finance, studying the role of digital finance in driving innovation [22,23], promoting industrial structure [24], alleviating financing constraints [25], promoting inclusive growth and high-quality economic development [26]; a few scholars start from the environmental performance of digital finance, finding that digital finance integrates financial resources through digital platforms [26], forms a long-term mechanism for managing long-term mechanism of pollution [27], promoting pollution reduction [28], green total factor productivity [29] and energy efficiency [30], effectively accelerating the process of economic ecologization and promoting the synergistic development of economy and ecological environment [31].

With the strategic goal of building maritime power, China has taken a new step in understanding the ocean. The ocean is a vast energy treasure trove, and marine resources provide a reliable guarantee for national energy security, and the ocean is a vital resource replacement zone for the long-term development of national energy and a sustainable economy [28], thus studying the utilization of marine energy is of great importance for carbon emission reduction. From the above analysis, there is a relative lack of literature examining the impact of digital finance from the perspective of environmental energy efficiency, among which the literature examining the impact of digital finance on marine energy and environment efficiency is even scarcer. Based on the existing studies, this paper explores the impact of digital finance on the carbon emission efficiency of marine energy from 11 coastal provinces in China, examining the differences in the impact of digital finance indices in different dimensions, discussing the heterogeneous mechanism in terms of geographical location, endowment effects and the degree of development of digitalization, analyzing the mechanism of the role of energy consumption structure, and finally exploring the transmission mechanism from the perspective of marine industrial structure and technological innovation. In conclusion, this paper will provide more precise development guidance for optimizing the energy consumption structure and harnessing digital finance to improve marine energy and environment efficiency in coastal areas of China.

The rest of this paper is arranged as follows: Section 2 sorts out the theory development. Section 3 states the econometric model, variables, data, and its source. Section 4 presents the empirical analysis and test results. Section 5 analyzes further discussion. Section 6 shows the conclusions and implications of this paper.

2. Theory Development

2.1. Effects of Digital Finance on Marine Energy Carbon Emission Efficiency

Digital finance has the advantages of digitalization and capital financing functions that traditional finance doesn't have, which may directly impact energy carbon emission efficiency. On the one hand, the digital industry is environmentally friendly and has a less negative impact on the environment. On the one hand, the digital platform provided by digital finance enables online transactions and financial services [32] and improves the information efficiency of the capital market through information disclosure [33], which all help to encourage green consumption and green investment in the marine sector [34], guide green production and green transformation of enterprises related to the marine sector [20], promote the large-scale use of marine clean energy, reduce wasting of resources and environmental pollution, thus improving marine energy carbon emission efficiency. On the other hand, the capital financing function of digital finance promotes the innovation of financial products, improves the efficiency of financial services, and optimizes the allocation of green resources assets [35], which in turn provides financing channels for enterprises in the marine sector, directs green financial resources to environment-friendly enterprises [26], facilitates the clean transformation of industrial structure [36], and effectively leads the marine economic growth from the traditional high energy-consuming and high-emissions extensive development model to a green and low-carbon intensive model [37], thus positively promoting intelligence and green development of marine industry, increasing the added value of the industry and reducing energy consumption and carbon emissions. All of these will ultimately have a positive impact on the improvement of marine energy carbon emission efficiency. Based on this, Hypothesis 1 is given as follows:

Hypothesis 1. *The development of digital finance can improve the marine energy carbon emission efficiency in coastal provinces of China.*

Due to the obvious differences in geographical location, economic base, and natural resource endowment among China's three major marine economic circles, there is a serious regional development imbalance in the development of the marine economy. The problem of unbalanced, uncoordinated, and unsustainable development of the marine economy is restricting the high-quality development of the marine economy [38]. Firstly, from the perspective of geographical location and economic foundation, the northern marine economic circle has a developed manufacturing industry and outstanding advantages in marine scientific research and education; the eastern marine economic circle has a complete port and shipping system and a high degree of the export-oriented marine economy; the southern marine economic circle has vast sea areas, rich resources, and a prominent strategic marine position. Secondly, from the perspective of resource endowment, great resource advantage means a significant advantage for industrial development, which in turn has a positive impact on energy and environmental efficiency [3]. However, according to the "Resource Curse" effect, the abundant resource also means "cost advantage " and "industrial extrusion" [39], leading to an over-reliance on a single marine energy industry, which in turn increases energy consumption. Finally, with the development of digital finance, the "Matthew effect" in the field of digital finance platforms has exacerbated the monopoly position of digital finance companies [40], accompanied by higher industry barriers and stagnant technological development, which in turn increased carbon emissions and reduced energy efficiency [41]. In this way, the improvement effect of digital finance on energy carbon emission efficiency may vary with the degree of digitization. Therefore, Hypothesis 2 is given as follows:

Hypothesis 2. *Digital finance is limited by differences in geographical location, resource endowment, and the degree of digitalization. There is heterogeneity in the extent of its impact on improving marine energy carbon emission efficiency.*

2.2. Mechanisms of Digital Finance to Marine Energy Carbon Emission Efficiency

The theoretical analysis of the impact of digital finance on marine energy consumption structure can be carried out from the following aspects. First of all, digital finance empowers the transformation of traditional finance with digital technology, providing diversified and targeted financing needs and financial services and driving the optimization of energy structure under the guidance of new energy policies [42]. Through the transmission of technological and financial elements, digital finance can help marine industries optimize energy consumption and reduce traditional energy consumption and carbon emissions. In addition, the embedding of digital technology allows more renewable energy to replace the traditional fossil energy. While by reducing the proportion of traditional fossil energy consumption, such as coal, can effectively reduce carbon emissions [43] and promote the formation of a low-carbon and carbon-free energy consumption structure, which in turn has a positive impact on marine energy carbon emission efficiency.

Industrial restructuring and green technological progress are the "twin engines" driving China's energy-saving and low-carbon economic transformation. By tapping into the "structural dividend" and "technological dividend" in the green transformation of the economy, digital finance can overcome energy and environmental constraints [44] and promote the improvement of marine energy efficiency. On the one hand, digitalization promotes the overall improvement of energy utilization and production technologies and gradually promotes the intelligent transformation and integration of resource utilization and energy-saving technologies in marine industrial enterprises [45], reducing the energy consumption and carbon emissions of marine enterprises at source, which is a critical way to improve energy and environment efficiency [46]. On the other hand, the penetration of digital technology has comprehensively promoted the optimization and upgrading of industrial structures. The progress of industrial structure can gradually reduce the dependence of the secondary industry on energy consumption, making factors of production transferring from inefficient sectors to high-efficiency sectors and promoting the rapid flow of factors as well as the optimal integration and efficient distribution of energy resources [30], thereby improving the production efficiency of marine enterprises and accelerating the green transformation of the marine industry. This ultimately leads to improved energy efficiency and reduced carbon emissions. Therefore, accelerating the elimination of outdated production capacities, controlling the development of marine industries with high pollution and high energy consumption, optimizing marine industrial structures, improving financial investment and capacity for green technological innovation, and developing marine green technologies will improve marine energy carbon emission efficiency. Based on this, Hypothesis 3 is given as follows:

Hypothesis 3. *The structure of marine energy consumption is a mediating variable in the impact of digital finance on marine energy carbon emission efficiency. The upgrading of marine industry structure and the processing of marine innovation can improve marine energy carbon emission efficiency through digital finance.*

In order to describe the main research contents and research ideas of this study in detail, a theoretical framework is drawn, as shown in Figure 1, which can provide the logic of the theory hypothesis clearly.

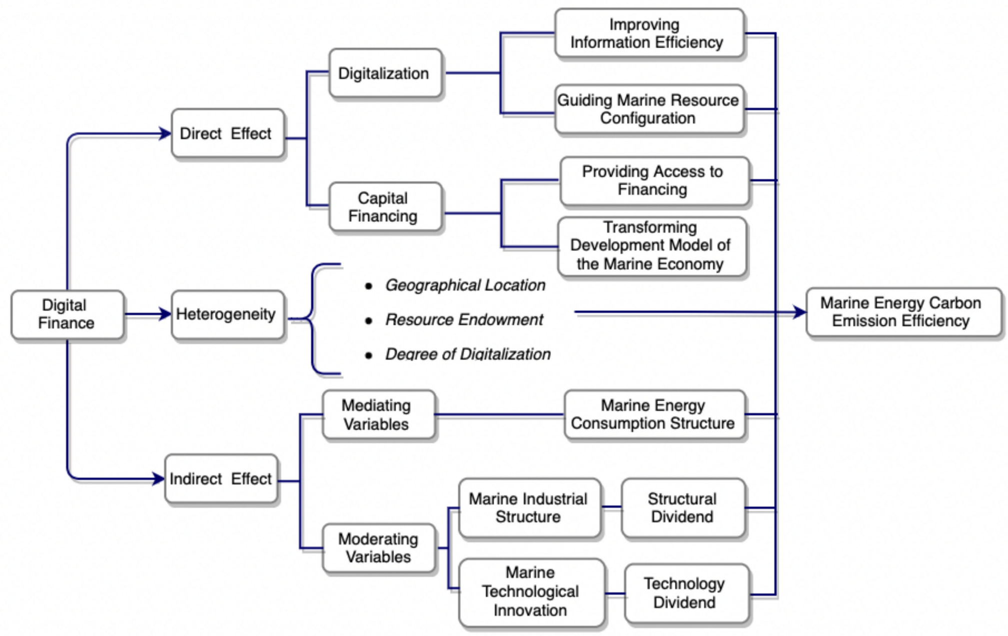

Figure 1. Theoretical framework.

3. Materials and Methods

We divide the verification into three stages. First, we will test Hypotheses 1 to verify whether digital finance will improve marine energy carbon emission efficiency. Second, Hypothesis 2 will test the heterogeneity in this mechanism. Third, Hypothesis 3 will be tested to verify whether marine energy consumption structure is a significant mediator of digital finance's impact on marine energy carbon emission efficiency and to examine the moderating role of industrial structure and technological innovation in the process of digital finance affecting marine energy carbon emission efficiency.

3.1. Empirical Model

To test Hypotheses 1 and 2 and consider the possible lagged effect between digital finance and marine energy carbon emission efficiency, we constructed the following econometric model:

$$ee_{i,t} = \alpha + \beta L.diff_{i,t} + \sum \gamma_j Control^j_{i,t} + \theta_i + \mu_t + \varepsilon_{i,t} \quad (1)$$

where *i* refers to the observation province, and *t* refers to the observation year. *ee* is marine energy carbon emission efficiency. *L.diff* denotes the degree of digital finance with one period lag. *Control* is a series of control variables. Additionally, θ_i is the province-fixed effect, μ_t is the time-fixed effect, and $\varepsilon_{i,t}$ is the error term. β is the coefficient for *diff*. If the results show that β is significantly positive, digital finance can improve marine energy carbon emission efficiency. If β is negative, Hypothesis 1 and 2 are overturned, meaning Hypothesis 3 remains true.

Further, Hypothesis 3 is examined according to the mediation models. We chose a two-step model to test the intermediary mechanism effect of digital finance on marine energy emission efficiency. The first step replace explained variable with mediating variable on the basis of Equation (1) to test the effect of digital finance on optimized marine energy consumption structure. The second step analyses the effect of optimized marine energy consumption structure on marine energy carbon emission efficiency theoretically. We constructed the mediation model of the first step as follows:

$$energy_{i,t} = \alpha_0 + \beta_0 L.diff_{i,t} + \sum \gamma_j Control^j_{i,t} + \theta_i + \mu_t + \varepsilon_{i,t} \quad (2)$$

where *energy* represents the mediating variable, namely, marine energy consumption structure, and the other variables have the same meanings as Equation (1).

Finally, Hypothesis 3 is also tested using the moderation model. Based on Equation (1), this paper introduces the industrial structure and technological innovation to test the moderating effect. The moderation model was constructed as follows:

$$ee_{i,t} = \alpha_1 L.diff_{i,t} + \alpha_2 Mod_{i,t} + \alpha_3 L.diff_{i,t} \times Mod_{i,t} + \sum \gamma_j Control^{j}_{i,t} + \theta_i + \mu_t + \varepsilon_{i,t} \quad (3)$$

where *Mod* represents the mediating variable, namely, industrial structure and technological innovation, and $L.diff \times Mod$ is the variable we are interested in. The other variables have the same meanings as Equation (1).

3.2. Variables and Data Selection

3.2.1. Explained Variable

The explained variable is marine energy carbon emission efficiency (*ee*). Current research on energy efficiency measurement is mainly based on the ratio method (the ratio of real *GDP* to total energy consumption) and the output method as the hotspot. When measuring marine energy carbon emission efficiency, issues such as economic benefits (desired output) and negative environmental effects (undesired output) need to be considered simultaneously. Namely, on the one hand, economic benefits and energy use efficiency need to be improved, while on the other hand, pollution emissions and environmental damage need to be reduced. In contrast to the ratio approach, an output-based approach is a comprehensive approach to measuring energy carbon emission efficiency that considers both energy utilization efficiency and environmental energy efficiency and is based on a tripartite weighing of inputs, desired outputs, and undesired outputs under the background of the coordination of "economy-resource-environment." The paper draws on the approach of Tone [47] to construct a non-radial, non-angular SBM-Undesirable model by putting the slack variables directly into the objective function and to measure the carbon efficiency of marine energy more accurately under both energy and environmental constraints in a variable payoff of scale (BCC). The specific equation is as follows:

$$\rho^* = \min \frac{1 - \frac{1}{m}\sum_{i=1}^{m} S_i^- / x_{i0}}{1 + \frac{1}{S_1 + S_2}\left(\sum_{r=1}^{S_1} S_r^g / y_{r0}^g + \sum_{r=1}^{S_2} S_r^b / y_{r0}^b\right)}$$
$$s.t. \begin{cases} X_0 = X\lambda + S^-; y_0^g = Y^g\lambda + S^g; y_0^b = Y^b\lambda + S^b \\ S^- \geq 0, S^g \geq 0, S^b \geq 0, \lambda \geq 0 \end{cases} \quad (4)$$

where S represents Input-output slack variables, λ represents the weight vector, r is output, S_1 is a consensual output, and S_2 is a non-consensual output.

The paper integrates the measurement of theories and data availability in the marine field. It draws on the energy carbon emission efficiency index system constructed by Shi and Li [3] to construct an innovative value of marine energy carbon emission efficiency based on coastal areas. The index system constructed in the article contains two parts: input and output. The input elements include labor, capital, and resource, among which labor input is expressed as the number of sea-related employment; capital input is expressed as the marine capital stock, and the fixed capital stock in coastal areas is firstly calculated by using the perpetual inventory method following the practice of Zhang et al. [48]:

$$K_{it} = (1 - \delta)K_{it} - 1 + I_{it}/P_{it} \quad (5)$$

where K_{it} represents fixed capital stock, I represents fixed asset investment (current year price), P represents fixed investment price index (2000-based), δ is the depreciation rate of fixed assets and takes the value of 9.6%, while marine capital stock is substituted by the product of gross ocean product as a share of regional GDP and fixed capital stock; resource input is expressed as the product of total energy consumption in coastal areas and the share of gross ocean product in regional GDP; outputs include both desired and undesired outputs, the desired output is expressed by gross ocean product and deflated to the base year of 2011; the undesired output is expressed in terms of marine carbon emissions, and CO_2 emissions are measured in terms of carbon emission factor method [49] by converting coal, coke, crude oil, gasoline, paraffin, diesel, fuel oil, natural gas, and electricity into the standard coal, meanwhile, multiply the share of gross ocean product in regional GDP. The CO_2 emission factor method is based on the following formula:

$$Q_{CO_2} = \sum_{i=1}^{n} K_i \cdot E_i \quad (6)$$

where E_i represents energy usage of the ith energy variety, which can be converted into standard coal; the coefficient K_i is the CO_2 emission coefficient of the ith energy source. The specific indicators are characterized in Table 1.

Table 1. The evaluation system of marine energy carbon emission efficiency.

Variable Classification	Criterion Level	Index Level
Input variables	labor input	the number of sea-related employment/10,000
	capital input	marine capital stock/100 million
	resource input	marine energy consumption/10,000 tons of standard coal
Output variables	desired output	gross ocean product/100 million
	undesired output	marine carbon emissions/10,000 tons

Further, this paper uses MAX-DEA software to calculate the marine energy carbon emission efficiency of 11 provinces in China's coastal areas from 2011 to 2019. Moreover, in recent years, comprehensive analysis and ranking have been conducted to analyze the situation of marine energy utilization efficiency and marine environment ecology.

Based on Table 2, the overall trend of marine energy carbon emission efficiency values from 2011 to 2019 is decreasing, which may be explained by the fact that with the increasing awareness of the public about marine energy, the development and use of marine energy has caused environmental pollution than economic benefits. The level of marine energy and environmental efficiency has been decreasing year by year. Analysis by area shows that the eastern marine economic circle has the highest marine energy carbon emission efficiency, the southern marine economic circle is the next, and the northern marine economic circle is the least efficient. Analyzing the provinces individually, Shanghai ranked first, and its efficiency value has changed steadily, while Tianjin and Guangdong Province have seen the most significant decline in marine energy efficiency rankings over the past nine years, which should be taken seriously by the relevant authorities.

3.2.2. Explaining Variables

The paper uses the China Digital Inclusive Finance Development Index [50] published by the Digital Finance Research Center of Peking University to indicate the level of digital finance development (*diff*). This index measures the development of digital finance in China in three dimensions: breadth of coverage (*cover*), depth of use (*usage*), and degree of digitization (*dig*), while logarithmically processing the index.

3.2.3. Mediating Variable

Coal has long been the primary source of energy consumption for production and living in China. The carbon emissions per unit of coal consumption are 1.73 times higher than those of clean energy sources such as natural gas. China's energy endowment is "rich in coal but poor in oil and gas." Coal consumption is mainly responsible for environmental pollution and greenhouse gas emissions [39]. Changing the high carbon consumption tendency and carbon preference, reducing fossil energy consumption, and increasing the proportion of clean energy such as electricity and natural gas are the key means to accelerate the upgrading of energy consumption structure and promote the reduction in greenhouse gas emission [51]. Using clean energy can significantly reduce regional carbon emissions and thus optimize energy carbon emission efficiency [52]. This paper takes optimized marine energy consumption structure (*energy*) as mediating variable, which is calculated by the share of natural gas and electricity consumption in total energy consumption, while by the product of gross ocean product as a share of regional GDP and expressed in logarithmic form.

Table 2. Marine energy carbon emission efficiency rankings.

Area	Province	Value of 2011	Ranking	Value of 2019	Ranking
Northern Marine Circle	Liaoning	0.4966	11	0.3150	11
	Hebei	0.5253	10	0.3555	10
	Tianjin	0.7712	5	0.3718	8
	Shandong	0.6328	7	0.3953	7
Eastern Marine Circle	Shanghai	1.0000	3	1.0000	1
	Jiangsu	1.0000	2	0.7178	2
	Zhejiang	0.8371	4	0.5869	4
Southern Marine Circle	Fujian	0.7259	6	0.5497	5
	Guangdong	1.0000	1	0.6823	3
	Guangxi	0.5346	9	0.3716	9
	Hainan	0.5945	8	0.4110	6

3.2.4. Moderating Variable

This paper adopts the marine industrial structure index (*sdu*) and marine technological innovation (*inn*) as moderating variables.

Firstly, According to China Marine Economic Statistical Yearbook, the primary marine industry mainly includes marine fishery; the secondary marine industry includes the marine oil and gas industry, coastal sand mining industry, marine salt industry, marine chemical industry, marine biological medicine industry, marine power and seawater utilization industry, marine shipbuilding industry, marine engineering construction industry, etc.; the marine tertiary industry includes marine transportation, coastal tourism, marine scientific research, education and management, and other service industries. Further, as one of the main features of the highly upgraded industrial structure is the increasing prominence of the marine tertiary industry and the decreasing importance of primary marine industry, this paper thus adopts the industrial structure measurement method conducted by Xu [53] to measure the marine industrial structure index of coastal areas. The specific formula is as follows.

$$CY = \sum_{i=1}^{3} iC_i = 1 \times C_1 + 2 \times C_2 + 3 \times C_3 \quad (7)$$

where CY indicates the measured industrial structure index; Ci (i = 1, 2, 3) indicates the proportion of marine industry i to the gross marine product.

And then, while improving energy carbon emission efficiency, technological innovation also reduces the cost and price of unit products, which may eventually lead to further growth of energy consumption and carbon emissions, thus counteracting the energy saving brought by technological progress and producing “energy rebound effect” [39]. Therefore, it is uncertain whether marine technological innovation can actually play a positive role in marine energy carbon emission efficiency. So it is necessary to discuss the moderating effect of marine technological innovation. The existing literature for measuring technological innovation mainly includes indicators such as the number of patents and R&D investment. As the number of patent applications from marine research institutions is available, this paper chooses the number of marine patent applications to measure marine technological innovation capacity in coastal areas and divides it by 100 to eliminate the difference in magnitude.

3.2.5. Control Variables

In order to eliminate omitting variable bias, this study controls a series of other variables that might influence marine energy carbon emission efficiency. The control variables include: (1) the level of regional economic development (*pgdp*), measured by the logarithmic form of GDP per capita in coastal areas; (2) the level of regional fiscal support (*gov*), measured by the logarithmic form of regional fiscal; (3) regional port activity (*pa*), measuring by the logarithmic form of port's cargo throughput; (4) the level of marine scientific research development (*rdl*), measuring by the proportion of marine scientific and technological activities personnel in the number of employees.

3.3. Sources of Data

This study used a panel dataset of 11 coastal provinces of China from 2011 to 2019 as a sample. The data were obtained from China Statistical Yearbook and China Marine Statistical Yearbook; the digital finance index was obtained from the Peking University Digital Inclusive Finance Index (2011–2019) published by the Internet Finance Research Centre of Peking University. For some missing data, linear interpolation was used to fill in the gaps. Table 3 is a summary of descriptive statistics for the main variables.

Table 3. The statistical description of main variables.

Variables	N	Mean	Sd	Min	Max
ee	99	0.6461	0.2071	0.3150	1.0000
diff	99	5.2602	0.5815	3.4788	6.0168
cover	99	5.1535	0.6261	2.9156	5.9356
usage	99	5.2842	0.5360	3.7856	6.0866
dig	99	5.4348	0.7822	2.0255	6.1361
pgdp	99	11.0718	0.4093	10.1396	11.9658
gov	99	10.9673	0.7612	9.2970	12.0726
pa	99	8.4756	0.6497	6.6585	9.7593
rdl	99	0.8375	0.1002	0.5229	0.9904
energy	99	1.0259	0.6153	−0.2970	1.8886
sdu	99	5.5020	0.0433	5.3991	5.5951
inn	99	3.2248	4.1975	0.0200	21.4900

4. Results

4.1. Results for the Benchmark Model

The article uses a panel double fixed-effects model to explore the impact of digital finance on the efficiency of marine energy carbon emissions in coastal areas. The first column of Table 4 reports the results of the baseline regression of digital finance on marine energy carbon emission efficiency, while the following three columns report the impact of the breadth of coverage, depth of use, and digitization of digital finance on marine energy carbon emission efficiency, respectively. The benchmark regression results show that digital finance development can significantly improve marine energy carbon emission efficiency in coastal areas. Further, in terms of the three dimensions of digital finance, the breadth of coverage and depth of use of digital finance have significant positive effects on marine energy carbon emission efficiency, and the depth of use has a more significant effect than the breadth of coverage. In contrast, the positive incentive effect of digitalization is not significant. This indicates that the development of digital finance can promote the improvement of marine energy environmental efficiency in coastal areas, mainly due to the reaching scope of digital finance and the use of utility to support green energy, while the degree of digitization has not yet played its value benefit in the coastal energy and environmental efficiency.

Table 4. Results of the baseline model.

Variables	Diff	Cover	Usage	Dig
	(1)	(2)	(3)	(4)
L.diff	0.169 *** (0.061)			
L.cover		0.069 ** (0.033)		
L.usage			0.157 ** (0.068)	
L.dig				0.018 (0.021)
pgdp	0.235 *** (0.060)	0.221 *** (0.061)	0.227 *** (0.061)	0.182 *** (0.061)
gov	−0.040 (0.046)	−0.051 (0.046)	−0.047 (0.046)	−0.062 (0.047)
pa	−0.294 *** (0.080)	−0.274 *** (0.081)	−0.235 *** (0.077)	−0.206 ** (0.080)
rdl	−0.126 * (0.073)	−0.121 (0.076)	−0.134 * (0.074)	−0.182 ** (0.077)
Constant	1.110 (0.834)	1.539 * (0.832)	0.649 (0.930)	1.561 * (0.857)
Observations	88	88	88	88
Year Effects	YES	YES	YES	YES
Province Effects	YES	YES	YES	YES
Adjusted R-squared	0.753	0.741	0.745	0.727

Note: ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively. Cluster robustness standard error in parenthesis.

4.2. Heterogeneity Analysis

Considering the heterogeneity of 11 coastal provinces in China in terms of geographic location, resource endowment, and the degree of digital development, there may be heterogeneity in the impact of the level of digital finance on the efficiency of the marine energy carbon emissions in coastal areas. The article analyses the heterogeneity in terms of geographical location, resource endowment, and the degree of digitalization to explore the differences in the impact of digital finance on marine energy carbon emission efficiency.

4.2.1. Heterogeneity Analysis Based on Geographic Location

The paper divides the total sample into three sub-samples, namely the northern, eastern and southern marine economic circles, and uses group regression methods to conduct regional heterogeneity analysis. The empirical results are shown in Table 5. The enhancement coefficient of digital finance on marine energy carbon emission efficiency shows that the northern marine economic circle has the most potent enhancement effect, followed by the southern marine economic circle. The eastern marine economic circle has the weakest enhancement effect. The possible reasons are that the northern region is a manufacturing hub. Digital finance has digital support and effective allocation of resources, which can support the green transformation of the industry in the northern marine economic circle more efficiently, thus, in turn, has a more significant marginal enhancement effect of marine energy carbon emission efficiency; the southern region has vast sea areas, rich resources, mature development of the digital economy and a good base of talent, technology and location, which can promote the rapid development of regional digital finance and the realization of the process of digital finance on marine energy carbon emission efficiency; the eastern region has leading talent and location advantages, a high degree of openness, a well-developed financial base, and coordinated regional green development, thus the effect of digital finance on the improvement of marine energy carbon emission efficiency is relatively mature.

Table 5. Heterogeneity analysis based on geographic location.

Variables	Northern	Eastern	Southern
L.diff	0.262 ** (0.117)	0.132 (0.414)	0.193 (0.133)
Control variables	YES	YES	YES
Observations	32	24	32
Year Effects	YES	YES	YES
Province Effects	YES	YES	YES
Adjusted R-squared	0.844	0.900	0.634

Note: ** represent significance at 5% levels. Cluster robustness standard error in parenthesis.

4.2.2. Heterogeneity Analysis Based on Resource Endowment

According to the "resource curse" effect, regions with richer energy endowments may have negative impacts on the environment through "cost advantages" and "industrial crowding out" [39]. Thus, this paper divides 11 coastal provinces into marine resource-rich and marine resource-poor areas based on the length of their coastlines to verify the role of resource endowments in digital finance on marine energy carbon emission efficiency. The resource-rich areas include Liaoning, Shandong, Zhejiang, Fujian, and Guangdong, while the resource-poor areas include Hebei, Tianjin, Shanghai, Jiangsu, Guangxi, and Hainan. Based on the empirical results in Table 6, it is concluded that the effect of digital finance on marine energy carbon emission efficiency is more significant in resource-poor areas than in resource-rich areas. This is explained by the fact that resource-rich areas rely on their resource endowments to attract investment and production and have long been dependent on resource-driven economic growth, thus falling into the disadvantageous situation of the 'resource curse'. The incentive effect of digital technology and rational allocation of resources brought by digital finance to reform the energy consumption structure and promote green transformation is insignificant. At the same time, the resource-poor areas are less endowed with resources, and the energy consumption structure still needs to be determined. Thus, digital finance can play a significant positive role in the local energy transformation, improving energy and environment efficiency and reducing carbon emissions.

Table 6. Heterogeneity analysis based on resource endowment.

Variables	All	Rich	Poor
L.diff	0.169 *** (0.061)	0.124 (0.106)	0.154 ** (0.067)
Control variables	YES	YES	YES
Observations	88	40	48
Year Effects	YES	YES	YES
Province Effects	YES	YES	YES
Adjusted R-squared	0.753	0.764	0.838

Note: ***and ** represent significance at 1% and 5% levels, respectively. Cluster robustness standard error in parenthesis.

4.2.3. Heterogeneity Analysis Based on the Degree of Digital Finance Development

In order to further investigate the sustainability and incentive intensity of digital finance on the efficiency of marine energy carbon emissions in coastal areas, this paper divides 11 coastal provinces into developed digital finance regions and developing regions based on the median of the digital finance index. Developed digital finance regions include Jiangsu, Shanghai, Zhejiang, Fujian, and Guangdong; developing regions include Liaoning, Hebei, Tianjin, Shandong, Guangxi, and Hainan. The empirical results in Table 7 show that digital finance in developing regions can significantly improve marine energy carbon emission efficiency. In contrast, digitalization in the developed regions of digital finance shows a non-significant negative effect on marine energy carbon emission efficiency. The possible reason is that digital finance can promote marine energy carbon emission efficiency in coastal areas. This performance is particularly evident in areas where digital finance still needs to mature, while as the digitalization process deepens, the universality of digital finance becomes apparent. The marginal benefit of its promotion of marine energy carbon emission efficiency decreases with the improvement of the digital industry, namely the sustainability of digital finance incentive for improving marine energy carbon emission efficiency is weak and needs to find a better mechanism to reduce energy consumption and improve energy carbon emission efficiency.

Table 7. Heterogeneity analysis based on the degree of digital finance development.

Variables	All	Developed	Developing
L.diff	0.169 *** (0.061)	0.203 ** (0.078)	−0.511 (0.308)
Control variables	YES	YES	YES
Observations	88	48	40
Year Effects	YES	YES	YES
Province Effects	YES	YES	YES
Adjusted R-squared	0.753	0.856	0.825

Note: *** and ** represent significance at 1% and 5% levels, respectively. Cluster robustness standard error in parenthesis.

4.3. Robustness Analysis of the Benchmark Model

This paper further conducts the robustness test, and the results are presented in Table 8. Firstly, to avoid the endogeneity problem, this paper uses a systematic GMM model to test the original model. The results in Column (1) show that the estimated coefficients of both the one-period lag of energy efficiency and the one-period lag of digital finance are significantly positive at the 10% level, which again verifies that digital finance has an enhancement effect on marine energy carbon emission efficiency. Secondly, the first and last year of the sample data were excluded, the sample data interval was shortened to 2012–2019, and regression tests in Columns (2) were conducted. Thirdly, considering that the value of marine energy carbon emission efficiency is a double-truncated tail between 0 and 1, there may be different years of data compressed at the point of 1, respectively. The panel Tobit model was thus selected for robustness testing, and the results in Columns (3) again confirmed the study's findings. Finally, to avoid the influence of extreme values on the test results, the model was subjected to a 1% quantile tail shrinkage in Columns (4), which proved that the findings were enormously robust. Therefore, we confirmed that digital finance exerts a significant positive effect on marine energy carbon emission efficiency, and the empirical results of this paper are robust and reliable.

4.4. Influence Mechanism Analysis

4.4.1. Results of the Mediation Model

The optimization of energy consumption structure is the key factor in reducing carbon emissions. The energy consumption structure is closely related to the quality of the environment. If coal, oil, and other fossil fuels account for too much in the energy consumption structure, it will cause higher carbon emissions, which is harmful to environmental security. Therefore, the optimization of energy consumption structure can effectively promote energy efficiency and carbon emission reduction. Financial support can optimize energy consumption structure and thus contribute to energy and environment efficiency. In order to verify the pathway mechanism that digital finance can optimize energy consumption structure and thus improve energy carbon emission efficiency, the paper uses the consumption of two representative clean energy sources, natural gas and electricity, as a share of total energy consumption and multiplies the ratio of marine GDP to regional output to measure the optimized marine energy consumption structure. Table 9 shows the impact of the digital finance index and the sub-dimensional digital finance indicators on the structure of marine energy consumption, respectively. Results show that the development of digital finance can significantly optimize and improve the structure of marine energy consumption.

The expansion of the depth of use has the most significant effect on the improvement of the marine energy consumption structure; the expansion of the breadth of coverage also has a significant optimization effect; and the increase in the degree of digitalization has a non-significant dampening effect, but to a lesser extent, namely for every 1% increase in the degree of digitalization, the marine energy consumption structure deteriorates by 0.07%.

Table 8. Results of robustness test.

Variables	Systematic GMM Model	Shorten Time Interval	Panel Tobit Model	1% Quantile Tail Shrinkage
	(1)	(2)	(3)	(4)
ee_{t-1}	0.792 ***			
	(0.100)			
L.diff	0.252 *	0.232 *	0.234 ***	0.169 ***
	(0.134)	(0.134)	(0.055)	(0.062)
pgdp	0.023	0.111	0.141 **	0.235 ***
	(0.032)	(0.082)	(0.054)	(0.061)
gov	0.034	−0.019	−0.065 *	−0.040
	(0.033)	(0.046)	(0.038)	(0.046)
pa	−0.024	−0.314 ***	−0.091	−0.290 ***
	(0.015)	(0.111)	(0.080)	(0.089)
rdl	0.038	−0.088	−0.064	−0.127 *
	(0.058)	(0.074)	(0.062)	(0.074)
Constant	−1.588 ***	2.060	−0.300	1.076
	(0.609)	(1.274)	(0.769)	(0.928)
Observations	88	66	88	87
Year Effects	YES	YES	YES	YES
Province Effects	YES	YES	YES	YES
Adjusted R-squared		0.649		0.748
AR (1)	0.025			
AR (2)	0.464			
Sargan	0.181			

Note: ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively. Cluster robustness standard error in parenthesis. AR (2) and Sargan represent the values of the residual sequence autocorrelation and the Sargan tests, respectively.

In summary, the development of digital finance has eased the financing problems of enterprises in coastal areas and guided the green production and consumption of relevant enterprises in the marine sector, urged polluting enterprises to accelerate the upgrading of carbon-emitting equipment and technology, and enhanced the substitution of clean energy for fossil energy consumption, thus promoting the large-scale use of clean energy and clean low-carbon consumption structure, and improving the consumption structure of marine energy. Optimizing the energy consumption structure helps restructure the energy industry, reduce greenhouse gas emissions and improve energy carbon emission efficiency. Existing studies have primarily confirmed the relationship between the optimization of energy consumption structure and energy and environment efficiency, with Han et al. [54] indicating that changes in China's energy structure have positively improved energy utilization efficiency. Zhao et al. [55] argued that actively reducing the share of coal consumption can obtain a more reasonable energy consumption pattern and structure, improving energy and environment efficiency. From the perspective of environmental regulation, Tao et al. [56] argue that there is a significant fitness relationship between the evolution of energy consumption structure and the level of environmental regulation on energy and environment efficiency and that as the energy structure evolves, the substitution effect of non-fossil energy sources gradually emerges and energy efficiency can be improved. The estimation results in Table 9 imply that the development of digital finance optimizes the structure of marine energy consumption, which in turn contributes to the improvement of marine energy carbon emission efficiency.

Table 9. Results of mediation test.

Variables	Energy	Energy	Energy	Energy
	Diff	**Cover**	**Usage**	**Dig**
L.diff	0.353 ** (0.136)			
L.cover		0.152 ** (0.073)		
L.usage			0.310 ** (0.152)	
L.dig				−0.070 (0.045)
pgdp	−0.185 (0.133)	−0.209 (0.134)	−0.204 (0.135)	−0.244 * (0.134)
gov	−0.034 (0.101)	−0.055 (0.102)	−0.049 (0.103)	−0.070 (0.103)
pa	0.213 (0.177)	0.246 (0.180)	0.337 * (0.170)	0.331 * (0.174)
rdl	−0.132 (0.161)	−0.114 (0.168)	−0.151 (0.164)	−0.149 (0.168)
Constant	−0.434 (1.854)	0.447 (1.838)	−1.290 (2.071)	0.908 (1.871)
Observations	88	88	88	88
Year Effects	YES	YES	YES	YES
Province Effects	YES	YES	YES	YES
Adjusted R-squared	0.563	0.549	0.547	0.536

Note: **, and * represent significance at 5%, and 10% levels, respectively. Cluster robustness standard error in parenthesis.

4.4.2. Results of the Moderation Model

In order to investigate the moderating role of industrial structure and technological innovation in the promotion of marine energy carbon emission efficiency by digital finance, the independent and moderating variables were first standardized, and the standardized independent variables, moderating variables, and interaction terms were included in a two-way fixed effects model for regression. Columns (1) of Table 10 show the moderating effect of industrial structure, while Columns (2) show the moderating effect of technological innovation. The results show that the interaction term between industrial structure and digital finance has a significant positive effect on the efficiency of marine energy carbon emission, indicating that upgrading marine industrial structure positively moderates the relationship between digital finance and marine energy carbon emission efficiency; similarly, the interaction term between technological innovation and digital finance also has a significant positive effect on the efficiency of the marine energy carbon emission, meaning that technological innovation also plays a positive moderating role in the promotion of the efficiency of the marine energy carbon emission efficiency by digital finance. Therefore, the more rational the marine industrial structure, the more substantial technological innovation capability and the more significant the effect of digital finance on the local marine energy carbon emission efficiency.

Table 10. Results of Moderation test.

Variables	Sdu	Inn
	(1)	**(2)**
L.diff	0.278 *** (0.080)	0.124 ** (0.047)
sdu	−0.221 (0.359)	

Table 10. *Cont.*

Variables	Sdu	Inn
	(1)	**(2)**
*L.diff*sdu*	0.522 * (0.272)	
inn		−0.011 *** (0.002)
*L.diff*inn*		0.005 ** (0.002)
Constant	2.230 *** (0.829)	−0.028 (0.684)
Control variables	YES	YES
Observations	88	88
Year Effects	YES	YES
Province Effects	YES	YES
Adjusted R-squared	0.762	0.863

Note: ***, **, and * represent significance at 1%, 5%, and 10% levels, respectively. Cluster robustness standard error in parenthesis.

5. Discussion

Since the industrial revolution, while the large-scale use of fossil energy has dramatically improved production efficiency, the CO2 produced by its combustion is subtly affecting global climate security. It has become the greatest non-traditional security challenge to human development. Energy consumption is an essential source of carbon emissions, and an irrational energy consumption structure will seriously affect climate security and economic sustainability. A profound transformation of the energy and economic system is urgently needed to optimize the energy structure further and improve energy and environment efficiency on top of controlling total carbon emissions [57]. By expanding the reach of financial services and innovating financial products and services, digital finance can lead enterprises to green production and green transformation, thereby promoting carbon emission reduction and improving energy carbon emission efficiency.

China is a vast country, and its coastal areas have a high degree of green economic development due to their superior geographical location and rich marine energy reserves, while the impact of unreasonable consumption of energy structures on the marine environment is irreversible. Marine resources are essential for guaranteeing national energy security and achieving long-term national energy development. The rational use of marine energy is conducive to protecting the marine environment and promoting carbon emission reduction. In this context, exploring the impact of digital finance on the efficiency of marine energy carbon emissions in coastal areas can provide not only new evidence to promote the rational transformation of the marine energy consumption structure and improve the utilization efficiency of marine energy in coastal areas but also provides corresponding policy references to promote carbon emission reduction and marine environmental protection in coastal areas. Therefore, this paper empirically tests the relationship between digital finance and marine energy carbon emission efficiency, the mediating role of optimized marine energy consumption structure, and the moderating effect of marine industrial structure and technological innovation. This paper also discusses the heterogeneity mechanism regarding geographical location, the endowment effect, and the degree of digital finance development.

Through analysis and discussion, it is concluded that digital finance plays an important role in promoting marine energy carbon emission efficiency. The impact of digital finance on marine energy carbon emission efficiency is different due to geographical locations, resource endowments, and digital degrees; digital finance can promote the improvement of marine energy carbon emission efficiency by optimizing and upgrading the consumption structure of marine energy; the upgrading of marine industrial structure and marine technological innovation play a positive role in the effect of digital finance on marine energy carbon emission efficiency. Unlike previous studies that focused on the measurement of single energy efficiency or total factor carbon emission efficiency, this paper creatively discussed from the ocean perspective deeply analyzed the impact mechanism and heterogeneity characteristics of digital finance on marine energy carbon emission efficiency and concluded the important role of digital finance in promoting energy utilization and environmental efficiency, and carbon emission reduction in coastal areas from both theoretical and empirical perspectives. From an empirical perspective, it is verified that optimizing the marine energy consumption structure is an important intermediary mechanism, and upgrading the marine industrial structure and encouraging marine technology innovation will help digital finance to further improve marine energy carbon emission efficiency, which provides important reference and suggestions for improving marine energy efficiency and promoting carbon emission reduction in coastal areas.

6. Conclusions and Policy Implications

6.1. Main Conclusions

Based on the relative theory, we used the panel data of 11 coastal provinces from 2011 to 2019 to empirically tests the relationship between digital finance and marine energy carbon emission efficiency. The main conclusions are as follows:

1. The development of digital finance can significantly improve marine energy carbon emission efficiency and expanding the breadth of coverage and depth of use can significantly contribute to improving marine energy carbon emission efficiency, with the depth of use having a more substantial effect. The degree of digitalization has an insignificant effect on statistics.
2. From the perspective of geographical location, digital finance in the northern marine economic circle has the most obvious effect on the improvement of marine energy carbon emission efficiency, followed by the southern marine economic circle and finally, the eastern marine economic circle; from the perspective of resource endowment, the incentive effect is stronger in resource-poor areas than resource-rich areas; from the perspective of the development degree of digital finance, the incentive effect is stronger in developing areas than in developed areas, which can also be explained as that with the development of digital finance, its effect on improving marine energy carbon emission efficiency has weakened.
3. Energy consumption structure plays a partial mediating role in the influence of digital finance on marine energy carbon emission efficiency. Upgrading marine industrial structure and encouraging ocean technological innovation can strengthen the incentive effects of digital finance on marine energy carbon emission efficiency.

6.2. Policy Implications

The following policy implications are put forward as follows:

1. Digital transformation is an important driving force for reforming the financial industry. We should comprehensively promote the coverage of digital financial infrastructure construction, improve the innovation of financial products and services, continue to promote the integrated and coordinated development of digital finance, and give full play to the driving force of digital finance to lead enterprises in low-carbon transformation, optimize the energy consumption structure, and improve energy carbon emission efficiency.
2. The government should fully consider the differences between geographical differences, endowment effects, and digital degrees, then take targeted measures, such as increasing policy support for the low-carbon transformation of the manufacturing industry in the northern marine circle, accelerating the popularization of financial digitalization in coastal resource-poor areas, and continuing to encourage marine scientific innovation to enable digital financial developed areas to break through energy carbon emission efficiency bottlenecks as soon as possible.

3. Optimizing the marine energy consumption structure, promoting the upgrading of the marine industrial structure, and encouraging ocean technological innovation had a positive impact on digital finance to improve the marine energy carbon emission efficiency. This means reducing the consumption of traditional coal energy and increasing the consumption proportion of clean energy, encouraging the development of marine emerging service industries, and increasing support for marine research and development institutions and marine technological innovation, which provides a reference for the rational use of energy and environmental protection in coastal areas in the future, and helps to achieve the carbon emission reduction goal and build a maritime power as scheduled.

6.3. Limitations and Future Directions

In conclusion, although this paper provides new insights into the influence of digital finance on marine energy carbon emission efficiency in coastal areas, some limitations deserve further investigation. First, this paper only uses coastal provinces as a study sample, ignoring the critical role of coastal enterprises in digital finance and carbon emissions. The next step is to examine the environmental effects of enterprise from a microscopic point of view. Secondly, other mediating and moderating factors may need further study.

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