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Is Technological Innovation Effective for Energy Saving and Carbon Emissions Reduction? Evidence From China

MEILI ZHANG[1], BAIZHOU LI[1], AND SHI YIN[1,2]
[1]School of Economics and Management, Harbin Engineering University, Harbin 150001, China
[2]School of Business Administration, Liaoning Technical University, Huludao 125105, China

Corresponding author: Baizhou Li (hagdlk@yeah.net)

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ABSTRACT Technological innovation is increasingly becoming an important way to develop a low-carbon economy. Recently, exploring the driving path of low-carbon development has become the hot topic, however, the role of energy consumption in the carbon-reduction effect of technological innovation has been ignored. Based on China's provincial-level panel data from 2005 to 2016, this paper investigates the effect of technological innovation on energy saving and carbon emissions reduction and the role of energy consumption in the influencing process by using linear regression model, mediating effect model and threshold regression model. The results show that technological innovation has effectively promoted energy saving and carbon emissions reduction in China, with different effect coefficients between the three areas of China. Moreover, energy consumption plays a significant partial mediating role in the effect of technological innovation on carbon emissions reduction. Finally, the effect of technological innovation on carbon emissions is limited by energy consumption. Low energy consumption significantly promotes a reduction in carbon emissions through technological innovation. Once energy consumption exceeds a critical level, the promoting effect of technological innovation on carbon emissions reduction will turn into the inhibiting effect. Based on these findings, some policy recommendations are put forward to accelerate the low-carbon transformation of the economy.

INDEX TERMS Technological innovation, energy saving, carbon emissions reduction, threshold regression model, China.

I. INTRODUCTION

Energy saving and carbon emissions reduction, as the indispensable ways to deal with climate challenge and promote sustainable development of economy, have been paid great attention by every countries in the world [1]–[3]. Severe climate change has posed a serious threat to human life and economic development. The latest findings suggest that continued greenhouse gas emissions will expose people to multiple risks, including stunted economic growth, impaired health, food and water shortages, frequent extreme weather events, and rising sea levels, especially in less developed and more vulnerable regions [4]. The greenhouse gas emissions are considered to be the main cause of climate change [5], [6]. In order to reduce the impact of climate change on people, many countries have signed the Paris Agreement, whose goal is to keep the global average temperature rise within 2 ° this century and within 1.5 ° above pre-industrial levels. China, as the world's largest country in primary energy consumption and carbon emissions, faces enormous pressure to save energy and reduce carbon emissions to achieve the goal of temperature control [3]. Technological innovation and low-carbon transformation of energy structure are prerequisites for the realization of temperature control goals [7]. Faced with the pressure of energy saving and carbon emissions reduction, China is actively implementing the strategy of innovation-driven development. Accordingly, the effects of technological innovation on energy saving and carbon emissions reduction in China are worth discussing.

China's economic development model has entered a transition period, from factor-driven and investment-driven development to innovation-driven development [8]. Technological

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innovation, an important factor for the development of an innovation-driven country, contributes to the development and application of green technologies for making low-carbon transition in industrial enterprises, optimization of traditional industries, and progress of emerging industries [9]. In addition, technological innovation will help develop new sources of energy such as wind, solar and tidal power to replace high-emission fossil fuels. However, if the goal of technological innovation is not to save energy and reduce carbon emissions, but to improve production efficiency and expand production scale, which will increase energy consumption and carbon emissions [10]. Existing studies mainly focus on the impact of renewable energy technological innovation on climate change [6], [11], and neglect the effect of the technological innovation level of the whole region on energy consumption and carbon emissions in China. For an innovation-driven country, it is very valuable to explore the role of technological innovation throughout the region in reducing carbon emissions and energy consumption, which is conductive to determining the effect of the strategy of innovation-driven development on economic low-carbon transformation. Moreover, the amount of energy consumption, as the main source of carbon emissions, may play an important role in the influence mechanism of technological innovation on carbon emissions, which has been ignored by the existing literatures.

Therefore, based on above analysis, this study will attempt to answer the following questions: Is technological innovation of China's provincial-level regions biased toward energy saving and carbon emissions reduction? Does the effect of technological innovation on energy saving and carbon emissions reduction vary across different regions considering the disparities of resource endowment in different regions of China? What role does energy consumption play in reducing carbon emissions through technological innovation? Is the effect of technological innovation on carbon emissions heterogeneous at different energy consumption level? To answer these questions effectively, this study uses the China's provincial-level panel data from 2005 to 2016 as the sample of empirical analysis and adopts linear regression model, mediating effect model and threshold regression model to carry out these tests. Linear regression model contributes to determine the main effect of one variable on another. The advantage of mediating effect model and threshold regression model is that they can confirm the role of the third variable in the relationship between two variables, namely, mediating role and threshold role. The answers to these questions will provide theoretical value and practical significance to achieve the goal of energy saving and carbon emissions reduction through technological innovation. Meanwhile, it has reference significance for other developing countries to achieve low-carbon transformation of economic development driven by innovation.

This study has several contributions as follows. First, this study identifies whether or not technological innovation of China's provincial-level regions is biased toward energy saving and carbon emissions reduction. Second, this study examines different effects of technological innovation on energy saving and carbon emissions reduction between three economic areas in China. Third, against the background of the lack of the role of energy consumption in the relationship between technological innovation and carbon emissions in the existing literature, this study confirms the mediating role of energy consumption in the process of technological innovation affecting carbon emissions by using the mediation effect model for the first time, which complements existing theories. Finally, based the threshold regression model, this study determines how different levels of energy consumption influence the relationship between technological innovation and carbon emissions, and whether there is thresholds or tipping points in the relationship, which will shed light on the role of energy consumption in driving green development through innovation.

This paper is arranged as follows. Following the introduction in section 1, the next section summarizes the related literatures. Section 3 presents relevant materials for empirical analysis, including variables selection, data sources and model setting. Section 4 discusses the research results. Section 5 concludes this study and puts forward some policy recommendations.

II. LITERATURE REVIEW

A. THE EFFECT OF TECHNOLOGICAL INNOVATION ON CARBON EMISSIONS

There have been many literatures exploring the driving force of carbon emissions at the industry and regions level through quantitative methods, such as threshold regression model [2], [12], autoregressive distributed lag modeling [13], quantile estimates [14], [15], and generalized divisia index model [16]. The factors involved in these studies include economic development, urbanization, trade openness, technological innovation, industrial structure, energy structure, and industrial green transformation, *et al.* [2], [12]–[16]. As for technological innovation, which is also called technological progress, scholars have conducted many studies about its impact on carbon emissions from different aspects. For example, Kang *et al.* [17] explored the various impacts of different sources of technological progress (including R&D, FDI and international trade) on the low-carbon development based on the panel data of 50 cities across the year of 2005-2014 in China's three urban agglomerations. Wang *et al.* [18] employed patent data to measure technological progress and identified its heterogeneous influence on carbon emissions in different economic sectors of China using the panel data of 289 Chinese cities. Chen *et al.* [19] adopts patent application quantity to measure technological innovation and concludes that technological innovation significantly reduces CO_2 emissions in countries which have relatively higher CO_2 emissions. Salman *et al.* [15] uses total patent applications count to measure technological innovation and concludes technology innovation significantly reduces carbon emissions by improving energy efficiency in 7 ASEAN countries. Mensah *et al.* [20] finds that innovation (measured by patent application) plays a key role towards mitigation of CO_2 emissions in most OECD countries. Based on time series data in China, Liu, Song and Chen [13] consider the number of patents granted as the proxy variable of technological innovation, and find that in the short term, the impact of technological innovation on carbon emissions per capita is not significant, while in the long term, technological innovation helps reduce carbon emissions per capita.

In China's three urban agglomerations, namely, ''Beijing-Tianjin-Hebei'', ''Yangtze River Delta'', and ''Pearl River Delta'', technological change (measured by the relative marginal output of two factors) is conducive to electricity saving, but it does not present an emission-reduction effect [21]. The study of Samargandi [22] showed that technological innovation (measured by total number of patent application) is insignificant in helping to reduce CO_2 emissions in the case of Saudi Arabia. It is possible that the carbon-reduction effect of technological innovation will be shown under certain conditions. Kang *et al.* [17] concluded that the path of technological progress is highly related to the level of economy, when GDP per capita is higher than 37000 yuan, indigenous innovation is the main driver for low-carbon development. Gu *et al.* [11] claimed that only when energy technology develops to a certain extent, will the effect of technical progress (measured by energy technological patent data) on carbon emissions reduction be reflected in China, otherwise, energy technological progress will bring about an increase in carbon emissions. Lin and Zhu [6] held that the effect of renewable energy technological innovation on curbing CO_2 emissions reduces with the rising of coal-dominated energy consumption structure but in contrast, this effect promotes with the growing proportion of renewable energy generation.

In a word, it is appropriate to measure technological innovation by using the number of patent application or patent granted. However, compared with total number of patents, invention patents can better represent the level of technological innovation for the reason that invention patents are more technically difficult than other kinds of patents. It has not been investigated in the existing studies whether technological innovation measured by invention patents is effective for reducing CO_2 emissions in China's provincial-level regions. Additionally, it has been proved that the carbon-reduction effect of technological innovation is limited by energy structure and energy technology level, however, it is uncertain whether the effect of technological innovation on carbon emissions reduction is limited by the amount of energy consumption.

B. THE EFFECT OF TECHNOLOGICAL INNOVATION ON ENERGY CONSUMPTION

Sohag *et al.* [23] concluded that technological innovation can reduce energy consumption by improving the energy efficiency of production processes in Malaysia. Kang and Li found [17] that FDI shows electricity-saving and carbon reduction effects, but R&D activities do not show the electricity-saving effect in China's three urban agglomerations. Li *et al.* [24] held that technical progress does not reduce energy consumption across industrial enterprises in the Beijing-Tianjin-Hebei region. The study of Jin *et al.* [25] showed that in the short run, technological innovation (measured by total factor productivity) help increase energy consumption, in the long run, energy consumption growth is positively and bilaterally related to technological innovation in China' provincial-level regions.

In short, due to the difference of research objects and measurement indicators of technological innovation, the effect of technological innovation on energy consumption in China' provincial-level regions and the difference of influence in three economic areas have not been confirmed.

C. THE ROLE OF ENERGY CONSUMPTION IN THE IMPACT OF TECHNOLOGICAL INNOVATION ON CARBON EMISSIONS

Energy consumption is considered to be a major contributor to carbon emissions [26]. The study of Ahmad *et al.* [27] found that energy consumption including gas, oil, electricity and coal, has a positive effect on carbon emissions. Technological innovation will contribute to reduce carbon emissions under certain conditions, for example, GDP per capita higher than 37000 yuan [17], or energy technology develops to a certain extent [11]. Under different energy structure, the impact of renewable energy technological innovation on CO_2 emissions is distinct [6]. Whether the amount of energy consumption will play a role in the carbon-reduction effect of technological innovation, which has not been determined in existent studies. Energy intensity plays a mediating role in the effect of economic agglomeration on carbon emissions in China, economic agglomeration can directly affect carbon emissions through its positive externalities and indirectly affect carbon emissions through energy intensity [3]. Accordingly, are there the mediating or threshold roles for energy consumption in the impact of technological innovation on carbon emissions?

To fill the gaps in existing researches and provide a better understanding of the relationship between technological innovation, energy consumption and carbon emissions, this paper makes some beneficial attempts as follows. First, we investigate the main effect of technological innovation on energy consumption and carbon emissions using linear regression model based on the data of 30 provincial-level regions in China for the period 2005-2016. Moreover, we determine the difference between the whole China and the three regions of China in the effect of technological innovation on energy consumption and carbon emissions. Third, by taking the mediating effect into consideration, we verify the mediating role of energy consumption in the impact of technological innovation on carbon emissions by adopting the mediating effect model. Finally, based on threshold regression model, we examine whether the relationship between technological innovation and carbon emissions is affected by

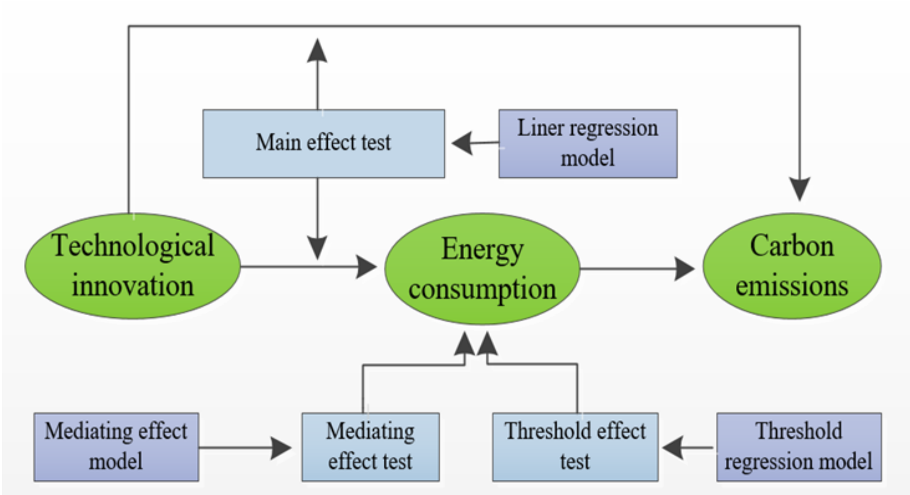

FIGURE 1. The conceptual framework.

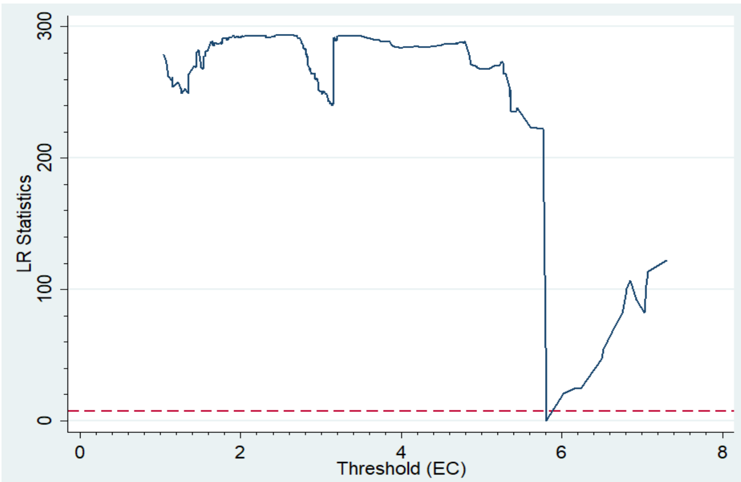

FIGURE 2. The construction of confidence interval.

energy consumption. The conceptual framework in this study is shown in Figure 1.

III. RESEARCH DESIGN

A. VARIABLE SELECTION

1) CORE EXPLANATORY VARIABLE: TECHNOLOGICAL INNOVATION (TI)

With respect to the measurement of technological innovation, patents and new product sales are commonly considered to be the proxy variables in existing studies. Generally, patents are better than new product sales from a regional perspective for the reason that patents come from companies, universities, research institutes and individuals in one region and new product sales only come from companies. In addition, patents provide a fairly reliable measure of innovative activity [28]. There are three types of patents in China: invention patent, utility model patent and design patent. Among them, the innovation quality and innovation difficulty of invention patent is the highest [29], which is more representative of regional technological innovation than the other two. Meanwhile, to eliminate the positive correlation between the total of inhabitants and the total of patents, the number of invention patents granted per capita is chosen as the proxy variable of technological innovation in this study [30].

2) EXPLAINED VARIABLE: CARBON EMISSIONS (CE)

Since carbon emissions are not published directly in the statistical yearbook in China, we need to estimate carbon emissions adopting the calculation method of CO_2 emissions provided by the IPCC (2006). The burning of fossil fuel is the main source of CO_2 emissions, and previous studies tend to be based on energy consumption to calculate CO_2 emissions [12], [31]. Therefore, seven major fossil fuels including coal, coke, gasoline, kerosene, diesel, fuel oil and natural gas, are considered in this study to measure CO_2 emissions. In addition, non-fossil fuels such as cement, lime, calcium carbide and steel also emit CO_2 due to physical and chemical reactions in industrial production [31]. In total emission of

CO_2 from industrial production processes, cement accounts for about 56.8%, lime for about 33.7%, and calcium carbide and steel production for less than 10% [12], [31]. Data on consumption of lime, calcium carbide and steel are not available, and the share of CO_2 emissions is relatively small. Therefore, for the non-fossil fuels, we only consider CO_2 emissions produced by cement production process and not include lime, calcium carbide and steel production processes. The calculation formula of CO_2 emissions from fossil fuel burning is as follows:

$$CF = \sum_{i=1}^{7} (CO_2)_i = \frac{44}{12} \sum_{i=1}^{7} C_i \times NCV_i \times CC_i \times COF_i \tag{1}$$

where CF denotes the amount of CO_2 emissions from seven kinds of fossil fuel consumption; i denotes the fossil fuel kind; C represents the amount of fossil fuel consumption; NCV represents the net calorific value of the fossil fuel provided by Chinese government; CC represents the carbon content from the IPCC; COF represents the carbon oxidation factor provided by Chinese government.

The calculation formula of CO_2 emissions from cement production is as follows:

$$CP = A \times EE \tag{2}$$

where CP represents the amount of CO_2 emissions from cement production, A denotes the amount of cement production; EE denotes the CO_2 emissions coefficient of cement production process, whose value is 0.527 t CO_2/t referring to the study of Du [31]. In this study, the total amount of CO_2 emissions (CE) is the sum of CF and CP. To keep up with the scale of measurement of technological innovation, CO_2 emission per capita is adopted as a proxy variable of CO_2 emissions.

3) ENERGY CONSUMPTION (EC)

In this study, energy consumption plays several roles, such as explained variable, mediating variable and threshold variable. With respect to the quantity of energy consumption (EC), we choose total energy consumption from China Energy Statistical Yearbook. The quantity of energy consumption per capita is used to represent the level of energy consumption in a region, which is consistent with the scale of technological innovation.

4) CONTROL VARIABLES

The purpose of this paper is to explore the relationship between technological innovation, energy consumption and carbon emissions, the three variables are considered as the core variables. In order to have a better empirical effect, the other factors influencing energy consumption and carbon emissions should be set as control variables. Referring to existing studies, industrial structure (IS), environment regulation (ER), economic development (ED), urbanization (UR), trade openness (TO), marketization (MA), and energy structure (ES) are chosen as control variables. First, industrial structure is measured by the proportion of secondary industry in GDP in our study, secondary industry is the main industry of carbon emissions [32], increasing the proportion of secondary industry is not conducive to energy saving and carbon emissions reduction. Second, higher environmental regulation will force enterprises to choose emissions reduction or relocation, which will be conducive to energy saving and carbon emissions reduction in local area [3], [33]. We use comprehensive utilization rate of solid waste to measure environmental regulation, referring to the study of Lin [34]. When the comprehensive utilization rate of solid waste is high, the level of environmental regulation in this region tends to be high. Third, the relationship between economic development and environment pollution is complex. According to the classical environmental kuznets curve (EKC) hypothesis, the relationship between economic development and environmental pollution shows an "inverted U" curve [35]. And there may be a complex nonlinear relationship between carbon emissions and economic development [3], [36]. The GDP per capita is considered to be as the proxy variable of economic development. Fourth, urbanization is measured by the proportion of urban population in the total population, which has a nonlinear effect on energy consumption and carbon emissions, for the reason that urbanization will lead to a large amount of energy consumption demand, but on the other hand, when the urbanization rate exceeds a certain level, citizens' demand for green urban development will curb energy consumption and carbon emissions [3], [37], [38]. Fifth, marketization is measured by the proportion of non-state employees in total employees, the improvement of marketization will optimize the allocation of resources and improve the energy efficiency, which has a positive effect on energy consumption and carbon emissions [32]. Sixth, regional energy consumption is closely related to the global value chain system, and trade openness is an important indicator of regional participation in global value chain system [2]. We adopt the proportion of total imports and exports in GDP as the proxy variable of trade openness [39]. Finally, we use the proportion of coal consumption in total energy consumption to measure energy structure [3], which has a positive effect on carbon emissions for the reason that fossil fuels, mainly coal, are the main source of carbon dioxide [40], and carbon emissions depend heavily on energy consumption structure. The abbreviation, measurement and source of each variable in this study are shown in Table 1.

B. DATA SOURCES AND DESCRIPTION

This paper chooses 30 provinces, municipalities and autonomous regions in China as empirical object (excluding the Tibet Autonomous Regions, Taiwan Province and Special Administrative Regions of Hong Kong and Macau, because of data shortage). Descriptive statistics of the variables are shown in Table 2. We can see that the dispersion degree of the original data of economic development is quite different from that of other variables from Table 2. Therefore, the original data of economic development are processed logarithmically

TABLE 1. Variables and measurement.

Variables	Abbreviations	Measurement	Units	Data source
Energy consumption	EC	Energy consumption per capita	Ton standard coal /capita	China Energy Statistical Yearbook
Carbon emissions	CE	CO_2 emission per capita	Ton / capita	China Energy Statistical Yearbook
Technological innovation	TI	Invention patents granted per capita	Item / per ten thousand capita	China Statistical Yearbook
Industrial structure	IS	Proportion of secondary industry in GDP	Percentage	China Statistical Yearbook
Environment regulation	ER	Comprehensive utilization rate of solid waste	Percentage	China Statistics Yearbook on Environment
Economic development	ED	GDP per capita	Yuan (RMB) / capita	China Statistical Yearbook
Urbanization	UR	Proportion of urban population in the total population	Percentage	China Population & Employment Statistics Yearbook
Trade openness	TO	Proportion of total imports and exports in GDP	Percentage	China Statistical Yearbook
Marketization	MA	Proportion of non-state employees in total employees	Percentage	China Labor Statistical Yearbook
Energy structure	ES	Proportion of coal consumption in total energy consumption	Percentage	China Energy Statistical Yearbook

in empirical analysis to reduce the dispersion degree of sample data.

C. MODEL SETTING

1) MODEL FOR EXAMINING MAIN EFFECT

We investigate the main effect of technological innovation on energy consumption and carbon emissions using China's 30 provinces data during 2005-2016. Considering that the dispersion degree of the proxy variable of economic development is quite different from that of other variables, we perform logarithmic treatment on the proxy variables of economic development and other variables remain unchanged. Based on C-D production function, we build the linear regression models as follows.

$$CE_{it} = \alpha_0 + \alpha_1 TI_{it} + \alpha_2 IS_{it} + \alpha_3 ER_{it} + \alpha_4 \ln ED_{it} + \alpha_5 UR_{it} + \alpha_6 TO_{it} + \alpha_7 MA_{it} + \alpha_8 ES_{it} + \varepsilon_{it} \quad (3)$$

$$EC_{it} = \beta_0 + \beta_1 TI_{it} + \beta_2 IS_{it} + \beta_3 ER_{it} + \beta_4 \ln ED_{it} + \beta_5 UR_{it} + \beta_6 TO_{it} + \beta_7 MA_{it} + \beta_8 ES_{it} + \mathrm{e}_{it} \quad (4)$$

where α_0 and β_0 refer to the constants, $\alpha_1 - \alpha_8$ and $\beta_1 - \beta_8$ denote regression coefficient of each variable in two models, respectively, ε_{it} and e_{it} are error terms, the subscripts i represents province and t represents year.

2) MODEL FOR EXAMINING MEDIATING EFFECT

To examine whether energy consumption plays a mediating role in the impact of technological innovation on carbon emissions, we build a mediating effect model. The indirect effect of explanatory variable (X) on explained variable (Y) through mediating variable (M) is called mediating effect [41], the process can be described as follows [3], [42].

$$Y = cX + e_1 \quad (5)$$

$$M = aX + e_2 \quad (6)$$

$$Y = c'X + bM + e_3 \quad (7)$$

where c is the main effect coefficient of explanatory variable X on explained variable Y, a represents the effect coefficient of explanatory variable X on mediating variable M, b is the effect coefficient of mediating variable M on explained variable Y after controlling the influence of explanatory variable X, c' is the direct effect coefficient of explanatory variable X on explained variable Y after controlling the influence of mediating variable M, $e_1 - e_3$ are error terms. The mediating effect is the indirect effect, which is equal to the coefficient product ab. According to the significance of coefficient c', the mediating effect is divided into partial mediating effect and complete mediating effect. If the coefficient c' is significant, it is the partial mediating effect, otherwise, it is the complete mediating effect [3]. The significance of coefficient c is the prerequisite for the existence of mediating effect, and the test of coefficient product ab is the core of mediating effect test [42]. Stepwise test of regression coefficient is the most commonly used method to test the mediating effect [43], which test the significance of coefficients in three equations (5), (6) and (7) above, respectively. However, the stepwise test of regression coefficients has certain risks, for the reason that the coefficient product ab is actually significant while stepwise test is easier to get the conclusion that it is not significant [44]. Therefore, some tests have been proposed to directly test the significance of the coefficient product ab, such as Sobel method, bootstrap method, product distribution method, and Markov Chain Monte Carlo (MCMC) method [45]. Due to higher power of bootstrap method [45], [46], bootstrap method was used to test the significance of mediating effect in this study. The mediating effect model is shown as follows

$$CE_{it} = \delta_0 + \delta_1 EC_{it} + \delta_2 TI_{it} + \delta_3 IS_{it} + \delta_4 ER_{it} + \delta_5 \ln ED_{it} + \delta_6 UR_{it} + \delta_7 TO_{it} + \delta_8 MA_{it} + \delta_9 ES_{it} + \eta_{it} \quad (8)$$

TABLE 2. Descriptive statistics of variables.

Variables	Mean	P50	Std. Dev.	Min	Max
CE	7.6616	6.1423	5.0643	1.5769	28.6500
EC	3.2132	2.8639	1.5056	0.9927	8.2844
TI	0.9210	0.3101	1.9021	0.0300	18.6848
IS	0.4685	0.4845	0.0790	0.1926	0.5904
ER	0.6709	0.6640	0.1933	0.2150	0.9983
ED	36820.61	33066.5	22790.81	5052	118198
UR	0.5238	0.5008	0.1403	0.2687	0.8960
TO	0.3201	0.1396	0.3914	0.0321	1.7215
MA	0.6841	0.6855	0.1221	0.3562	0.9166
ES	0.9586	0.8968	0.3767	0.1217	2.0292

where δ_0 denotes a constant, $\delta_1 - \delta_9$ denote regression coefficient of each variable, respectively, η_{it} is an error term.

Obviously, model (8) corresponds to model (7) in the mediating effect test model, models (3) and (4) correspond to models (5) and (6) in the mediating effect test model, respectively. Models (3), (4) and (8) constitute a complete testing process of the mediation effect model.

3) MODEL FOR EXAMINING THRESHOLD EFFECT

The threshold role of energy consumption in the influence process of technological innovation on carbon emission is explored by adopting the threshold regression model which was developed by Hansen [47]. This model can determine the threshold value according to the characteristics of sample data, and carry out significance and authenticity tests, so as to objectively analyze the nonlinear impact of technological innovation on carbon emissions under the influence of energy consumption. The threshold regression model is divided into single-threshold and multiple-threshold models, according to the number of threshold. The single threshold model in this study is set as follows.

$$\begin{aligned} CE_{it} &= \lambda_0 + \lambda_1 IS_{it} + \lambda_2 ER_{it} + \lambda_3 \ln ED_{it} + \lambda_4 UR_{it} \\ &\quad + \lambda_5 TO_{it} + \lambda_6 MA_{it} + \lambda_7 ES_{it} + \rho_1 TI_{it} I(EC_{it} \leq \mu) \\ &\quad + \rho_2 TI_{it} I(EC_{it} > \mu) + \tau_{it} \end{aligned} \tag{9}$$

where λ_0 denotes a constant, $\lambda_1 - \lambda_7$ denote regression coefficients of control variables, respectively, τ_{it} is an error term, I($\cdot$) is the indicator function, μ is the value of threshold variable EC, ρ_1 and ρ_2 represent the influence coefficients of technological innovation on carbon emissions at different energy consumption levels (EC is lower than μ, or EC is higher than μ).

We introduce the multiple-threshold model with the double-threshold model as an example, which has been built as follows.

$$\begin{aligned} CE_{it} &= \lambda_0 + \lambda_1 IS_{it} + \lambda_2 ER_{it} + \lambda_3 \ln ED_{it} + \lambda_4 UR_{it} \\ &\quad + \lambda_5 TO_{it} + \lambda_6 MA_{it} + \lambda_7 ES_{it} + \rho_1 TI_{it} I(EC_{it} \leq \mu) \\ &\quad + \rho_2 TI_{it} I(\mu < EC_{it} \leq \upsilon) + \rho_3 TI_{it} I(EC_{it} > \upsilon) + \tau_{it} \end{aligned} \tag{10}$$

where μ and υ are the two threshold values, $\rho_1 - \rho_3$ are the influence coefficients of technological innovation on carbon emissions at different energy consumption levels (EC is lower than μ, or EC is higher than μ and EC is lower than υ, or EC is higher than υ).

IV. EMPIRICAL RESULTS AND ANALYSIS

A. MAIN EFFECT TEST RESULT AND ANALYSIS

Linear regression model has three main models, including mixed effect model, fixed effect model and random effect model. Before analyzing the main effect of technological innovation on carbon emissions and energy consumption, it is needed to choose an appropriate model to carry out empirical analysis to ensure the accuracy of the results. We adopted F test and hausman test to determine scientific regression results.

In order to further investigate the effect of technological innovation on carbon emissions and energy consumption in different regions, we categorized China as the eastern region, central region and western region according to the classification standard of Chinese bureau of statistics. The results of linear regression model exploring main effect of technological innovation on carbon emissions and energy consumption in the whole China, eastern China, central China, and western China, are presented in Table 3 and Table 4, respectively. As shown in Table 3 and Table 4, the p-values of F tests are all zero, which indicates the samples in this study have an individual effect, and therefore it is not suitable to adopt mixed effect model. For the whole China in Table 3, the statistic of hausman test is 14.19, with corresponding p-value of 0.115, which supports the null hypothesis of random effect. Consequently, we consider the regression result of random effect as the estimation coefficient in our linear regression model for the whole China in Table 3. Besides, the other

TABLE 3. Main effect of technological innovation on carbon emissions.

CE	Whole China		Eastern China		Central China		Western China	
	Fixed effect	Random effect	Fixed effect	Random effect	Fixed effect	Random effect	Fixed effect	Random effect
TI	-0.1789***	-0.1803***	-0.1576***	-0.1602***	-1.3076***	-3.2624***	-2.0986***	-8.2268***
	(0.007)	(0.004)	(0.000)	(0.000)	(0.009)	(0.000)	(0.004)	(0.000)
IS	1.6548	1.6592	5.4247***	6.7937***	2.2921	1.9926	-9.6479**	-11.3811**
	(0.343)	(0.326)	(0.001)	(0.000)	(0.399)	(0.630)	(0.021)	(0.024)
ER	0.4536	0.0869	-1.1145*	-1.9781***	2.3657	-2.3797	-5.6943***	-12.1971***
	(0.555)	(0.908)	(0.091)	(0.001)	(0.211)	(0.105)	(0.000)	(0.000)
ED	2.8506***	2.8116***	1.4234***	1.7401***	2.4131***	2.4227***	4.5454***	3.9044***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.006)	(0.001)	(0.000)
UR	8.4018**	9.1419***	12.6936***	10.5038***	19.0213***	29.6485***	8.4527	51.7554***
	(0.035)	(0.006)	(0.000)	(0.000)	(0.005)	(0.000)	(0.557)	(0.000)
TO	-0.9903	-0.9347	-0.4150	-1.3541***	-11.0340**	-42.4667***	-2.7442	-1.4368
	(0.146)	(0.127)	(0.294)	(0.000)	(0.029)	(0.000)	(0.319)	(0.676)
MA	-2.1867**	-2.1894**	-0.6609	-2.2939***	-1.0239	1.0115	-1.5321	2.0907
	(0.017)	(0.016)	(0.448)	(0.000)	(0.549)	(0.675)	(0.383)	(0.429)
ES	11.6154***	11.4290***	4.2512***	5.9220***	12.0492***	12.2248***	13.3237***	10.9014***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
_cons	-36.4141***	-35.9910***	-20.0191***	-21.3624***	-40.0462***	-39.4862***	-45.0784***	-50.8785***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Obs	360	360	144	144	108	108	108	108
F test	68.98***		32.92***		23.56***		46.72***	
	(0.000)		(0.000)		(0.000)		(0.000)	
Hausman test		14.19		34.31***		66.77***		79.61***
		(0.115)		(0.000)		(0.000)		(0.000)

Note: p-values in parenthesis, ***p < 1%, **p < 5%, *p < 10%.

TABLE 4. Main effect of technological innovation on energy consumption.

EC	Whole China		Eastern China		Central China		Western China	
	Fixed effect	Random effect	Fixed effect	Random effect	Fixed effect	Random effect	Fixed effect	Random effect
TI	-0.1259***	-0.1075***	-0.1106***	-0.0617***	-0.4168***	-1.0681***	-0.4945	-3.5404***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)	(0.000)	(0.124)	(0.000)
IS	-0.5243	-0.2533	1.2243**	3.0181***	0.0249	0.3091	-3.9573**	-2.2893
	(0.387)	(0.672)	(0.031)	(0.000)	(0.972)	(0.785)	(0.036)	(0.289)
ER	0.5582**	0.4766*	-0.3432	-0.6125**	0.6939	0.2370	-0.4034	-4.1707***
	(0.038)	(0.072)	(0.147)	(0.014)	(0.161)	(0.557)	(0.568)	(0.000)
ED	1.3438***	1.1721***	1.0533***	0.5500***	1.0351***	0.7644***	1.9718***	1.7212***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)	(0.001)	(0.000)
UR	-0.3628	1.5539	0.8065	6.6445***	2.1579	10.7171***	-2.5562	20.4883***
	(0.792)	(0.202)	(0.461)	(0.000)	(0.216)	(0.000)	(0.695)	(0.000)
TO	-0.8664***	-0.7185***	-0.5772***	-0.8218***	-3.9505***	-13.2176***	-2.2084*	-2.3146
	(0.000)	(0.001)	(0.000)	(0.000)	(0.003)	(0.000)	(0.079)	(0.115)
MA	-1.0511***	-1.0356***	-0.4047	-0.6599*	-0.3839	-1.0261	-1.0835	-1.4607
	(0.001)	(0.001)	(0.197)	(0.086)	(0.391)	(0.122)	(0.175)	(0.196)
ES	1.4733***	1.4715***	-0.5189*	0.4678	1.3033***	2.2506***	1.6799***	1.4111***
	(0.000)	(0.000)	(0.063)	(0.110)	(0.000)	(0.000)	(0.000)	(0.000)
_cons	-10.9030***	-10.2788***	-7.4932***	-6.8095***	-9.8294***	-10.5669***	-13.7875***	-18.4022***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Obs	360	360	144	144	108	108	108	108
F test	90.44***		39.72***		27.14***		40.19***	
	(0.000)		(0.000)		(0.000)		(0.000)	
Hausman test		18.50***		66.45***		69.76***		77.16***
		(0.029)		(0.000)		(0.000)		(0.000)

Note: p-values in parenthesis, ***p < 1%, **p < 5%, *p < 10%.

p-values of hausman test in Table 3 and Table 4 are all lower than 0.05, which indicates that the results strongly reject the null hypothesis of random effect at the 5% significance levels. Therefore, fixed effect model was used to estimate the main effect of technological innovation on carbon emissions for the three regions, and the main effect of technological innovation on energy consumption for the whole China and the three regions.

TABLE 5. Mediating effect of energy consumption.

Path	Direct effect	P	95% Conf. Interval		Indirect effect	P	95% Conf. Interval	
			Lower bound	Upper bound			Lower bound	Upper bound
TI→EC→CE	-0.2049**	0.024	-0.3834	-0.0264	-0.2365	0.004***	-0.3954	-0.0776

Note: ***p < 1%, **p < 5%, *p < 10%.

As shown in Table 3, technological innovation has a significant negative effect on carbon emissions at the 1% level in the whole China and the three regions of China, which manifests that technological innovation significantly reduce carbon emissions in China. Technological innovation help enterprises improve the production processes, develop alternative technologies and promote carbon recycling technologies, so as to reduce regional carbon emissions. The influence coefficients of technological innovation on carbon emissions for the whole China, eastern China, central China and western China are −0.1803, −0.1576, −1.3076, and −2.0986, respectively, which indicates the carbon-reduction effect of technological innovation is best in the western region, followed by the central region and the worst in the eastern region. This may be because that high emissions industries are shifting from the eastern to the central and western regions due to low environment regulation in the central and western regions of China according to pollution haven hypothesis, thus leading to high carbon emissions per capita in the central and western regions. Once the technology of these regions is improved, it will bring about great carbon emissions reduction effect.

In terms of control variables, the result in Table 3 shows that economic development, urbanization and energy structure have positive relationship with carbon emissions for the whole China and the three regions of China, which indicates that instead of reducing carbon emissions, economic development, urbanization and energy structure have increased them in China during the observation period. Moreover, trade openness and marketization have negative effect on carbon emissions, which indicates that trade openness and marketization are conducive to reducing carbon emissions. Besides, industrial structure and environment regulation show different effect on carbon emissions in different regions of China.

Table 4 reports the effect of technological innovation on energy consumption in the whole China and the three regions of China, the results show that technological innovation has significant negative effect on energy consumption for the whole China, the eastern region and the central region, with the effect coefficients of −0.1259, −0.1106, and −0.4168 at the 1% level, which manifests that technological innovation is conducive to saving energy consumption in China, especially the eastern and central regions of China. Technological innovation helps the regions improve energy efficiency and find alternatives to conventional energy sources, thereby significantly reducing energy consumption. The energy-saving effect coefficient in the eastern region is lower than that in the central region, showing that the energy-saving effect of technological innovation in the eastern region is worse than that in the central region, which shows the same effect as the carbon-reduction effect of technological innovation in the central and eastern regions. However, technological innovation has non-significant effect on energy consumption in the western region of China, which is clearly different from the significant carbon-reduction effect of that technological innovation in the western region. It indicate there is disconnect between technological innovation and energy conservation in the western region, the direction of technological innovation should be taken seriously.

For control variables in this study, Table 4 shows that economic development has a significant positive effect on energy consumption for the whole China and the three regions of China, which is in line with the effect of economic development on carbon emissions. It suggests that China's economy is based on industries that consume a lot of energy and emit a lot of CO_2 in the period 2005-2016, which deserves the attention of the Chinese government. In addition, trade openness and marketization have negative relationship with energy consumption for the whole China and the three regions of China, which indicates that trade openness and marketization contribute to saving energy, consistent with the effect of trade openness and marketization on carbon emissions. Finally, industrial structure, environment regulation, urbanization and energy structure have different effect on energy consumption in different regions of China.

B. MEDIATING EFFECT TEST RESULT AND ANALYSIS

Based on the significant negative effect of technological innovation on carbon emissions above, we investigate the mediating role of energy consumption in the effect of technological innovation on carbon emissions adopting bootstrap method with 1000 repeat sampling. The results are shown in Table 5. We can see from Table 5 that the indirect effect coefficient of technological innovation on carbon emissions is −0.2365 at the 1% level and the confidence interval does not contain zero, which indicates the mediating effect of energy consumption is significant. Besides, the direct effect coefficient of technological innovation on carbon emissions is −0.2049 at the 5% level. It suggests that energy consumption plays a significant partial mediating role in the effect of technological innovation on carbon emissions

TABLE 6. Threshold significance test.

			Critical value		
	F-value	P-value	1%	5%	10%
Single threshold	301.26***	0.0000	50.9625	41.1746	32.2176
Double threshold	24.49	0.2467	60.4789	41.0729	32.3353
Triple threshold	23.06	0.5233	71.5952	52.7763	45.6414

Note: The p-value and the critical value are obtained from 300 bootstrap replications, ***p < 1%, **p < 5%, *p < 10%.

TABLE 7. Results of threshold estimators and confidence intervals.

Model	Threshold estimators	95% Confidence intervals
Single threshold	5.8089	[5.7692, 5.8152]
Double threshold	5.8089	[5.7692, 5.8152]
	1.2650	[1.1659, 1.3116]
Triple threshold	3.1425	[3.0520, 3.1504]

reduction. Technological innovation can reduce carbon emissions through two ways, one is to directly promote carbon recycling by improving production process. Another is to indirectly reduce carbon emissions by promoting energy efficiency or developing clean energy.

C. THRESHOLD EFFECT TEST RESULT AND ANALYSIS

Stata14 software was used to estimate and test the nonlinear impact of technological innovation on carbon emissions by selecting the threshold estimate that minimizes the sum of squares of the residual errors of the model using bootstrap method, and testing the significance and authenticity of the threshold estimate. The F test was used to test the significance of the threshold estimate and determine the number of the threshold estimate. The results of single threshold model, double threshold model and triple threshold model are shown in Table 6. We can see from Table 6 that single threshold model is significant at the 1% level, and double threshold model and triple threshold model have not passed the significance test. Therefore, based on Hansen threshold theory, there exists one threshold of energy consumption in the relationship between technological innovation and carbon emissions.

Then, with energy consumption as threshold variable, the single threshold estimator is 5.8089 in the effect path of technological innovation on carbon emissions. Besides, the threshold estimate values in the 95% confidence intervals are [5.7692, 5.8152]. The results are shown in Table 7.

After testing the significance of threshold estimate, the likelihood ratio statistic $LR = -2\ln(1-\sqrt{1-\alpha})$ is used to verify the authenticity of threshold estimate, which is the consistency between the threshold estimate and the true threshold value [48]. The significance level α in this study has been set 5%, and the likelihood ratio statistic LR equals to 7.3523. The likelihood ratio function graph is shown in Figure 1, in which the horizontal dotted line is the value of LR. At the significance level of 5%, all values less than LR(7.3523) constitute the confidence interval. The confidence interval estimated by the threshold values of 5.8089 is [5.7692, 5.8152], which falls within the confidence interval of the likelihood ratio graph. It suggests that the threshold estimate of energy consumption is consistent with the true value. Therefore, threshold estimate has passed the authenticity test.

Table 8 shows the effect coefficients of technological innovation on carbon emissions under the different energy consumption (EC is lower than 5.8089, or EC is higher than 5.8089). When the energy consumption per capita in one region is lower than 5.8089, technological innovation has a significant negative effect on carbon emissions at the 1% level, which indicates technological innovation can significantly reduce carbon emissions. When the energy consumption per capita in one region is higher than 5.8089, the effect coefficient of technological innovation on carbon emissions changes from negative to positive, and its significance is also at the 1% level. However, the absolute value of the influence coefficient has increased significantly from 0.1647 to 2.1678. It suggests that once the energy consumption per capita exceeds 5.8089, the effect of technological innovation on carbon emissions will change from inhibition to promotion with a greater intensity. When technological innovation reduces carbon emissions by increasing energy efficiency, the carbon-reduction effect of technological innovation is limited by energy consumption. Energy consumption per capita exceeds a certain threshold, the carbon-reduction effect of technological innovation will be restrained, which indicates energy consumption per capita need to be kept within limits to achieve the target of carbon reduction as soon as possible.

In terms of the other influence factors of carbon emissions in Table 8, economic development still shows a significant positive effect on carbon emissions, which is consistent with the above findings. Moreover, urbanization and energy structure have a significant positive relationship with carbon emissions, which proves again that urbanization promotes carbon emissions and carbon emissions are positively correlated with the energy consumption structure, particularly, the proportion of coal fuels. Besides, marketization has a significant negative impact on carbon emissions, which

TABLE 8. Results of threshold regression.

CE	Coef.	Std. Err.	t	P>｜t｜	95% Conf. Interval	
IS	1.6701	1.6436	1.02	0.310	-1.5635	4.9036
ER	0.4807	0.7254	0.66	0.508	-0.9463	1.9077
ED	2.7485***	0.3969	6.92	0.000	1.9675	3.5294
UR	7.6132**	3.7418	2.03	0.043	0.2515	14.9748
TO	-0.6939	0.6436	-1.08	0.282	-1.9602	0.5722
MA	-1.6969**	0.8634	-1.97	0.050	-3.3956	0.0017
ES	11.1496***	0.5348	20.85	0.000	10.0975	12.2017
TI(EC≤5.8089)	-0.1647***	0.0625	-2.64	0.009	-0.2877	-0.0417
TI(EC > 5.8089)	2.1678***	0.3737	5.80	0.000	1.4326	2.9031
_cons	-35.0280***	2.1707	-16.14	0.000	-39.2986	-30.7574

suggests that marketization contributes to carbon emissions reduction due to the optimal allocation of energy resources under the market mechanism [32] and fierce competition for low-carbon technologies in the market. Finally, industrial structure, environment regulation, and trade openness show indistinctive impact on carbon emissions for the whole China during the period 2005-2016, which is consistent with the empirical results using panel random effect model in Table 3. It indicates industrial structure, environment regulation, and trade openness have not shown definite effect on carbon emissions during the study period.

D. DISCUSSION

The purpose of this study is to identify whether technological innovation is effective for reducing carbon emissions and saving energy consumption in China, and investigate the role of energy consumption in the effect of technological innovation on carbon emissions.

First, before analyzing the impact of technological innovation on carbon emissions and energy consumption, the appropriate linear regression models (mixed effect model, fixed effect model or random effect model) were chosen by F test and hausman test to obtain accurate results. By adopting linear regression models, it is verified that technological innovation effectively saves energy and reduces carbon emissions for the whole China, which proves again the important role of technological innovation in low-carbon transformation accepted by many scholars [6], [11], [17], [21]. Besides, this paper illustrates that the effect of China's innovation-driven development strategy on energy saving and carbon emissions are obvious and successful, and technological innovation tends to be environmentally friendly. Technological innovation helps exploit alternatives to conventional fossil fuels and discover new ways of living and producing which use less or no fossil fuels. Therefore, technological innovation can significantly reduce the consumption of traditional energy. In addition, technological innovation can optimize the production process, promote clean production and improve carbon recycling technologies, thus it contributes to reducing carbon emissions.

Second, in terms of the three regions of China, technological innovation has played a significant role in promoting the reduction of carbon emissions in the eastern, central and western regions shown in Table 3. Interestingly, the carbon-reduction effect coefficient of technological innovation is the highest in the western region, followed by the central region and the lowest in the eastern region. It probably because that high emissions industries are shifting from the eastern to the central and western regions due to low environment regulation in the central and western regions of China according to pollution haven hypothesis, thus leading to high carbon emissions per capita in the central and western regions. Technological innovation is more effective in reducing carbon emissions in the central and western regions than that in the eastern region. Moreover, the energy-saving effect of technological innovation has been proved in the eastern and central regions in China with the significance of 1% level. However, technological innovation has non-significant promoting effect on saving energy in the western region by adopting fixed effect model, which is obviously different from the significant carbon-reduction effect of technological innovation in the western region. It probably because that technological innovation is mainly aimed at reducing carbon emissions rather than saving energy in the western region.

Third, by adopting the mediating effect model, this study verifies the partial mediating role of energy consumption in the impact of technological innovation on carbon emissions, which fills a gap in existing research. Sources of carbon emissions include the burning of fossil fuels and the production of non-fossil fuels, such as cement, lime, calcium carbide and steel. On the one hand, technological innovation could directly reduce carbon emissions through the improvement in carbon release and recycling technology. On the other hand, technological innovation could indirectly reduce carbon emissions by improving the efficiency of energy consumption [19] and developing clean energy.

Fourth, the results in Table 8 show that the effect of technological innovation on carbon emissions is limited by energy consumption, which happens in the indirect impact of technological innovation on carbon emissions by changing energy consumption. Limited by the critical value (5.8089) of energy consumption, the impact of technological innovation on carbon emissions is different. When energy consumption per capita is lower than 5.8089, technological innovation is conducive to reducing carbon emissions with the effect coefficient of −0.1647. Once energy consumption per capita exceeds the critical value of 5.8089, technological innovation will no longer reduce carbon emissions, but increase them rapidly with the effect coefficient of 2.1678. It indicates that China's technological innovation has a limited capacity to reduce carbon emissions, which relies heavily on energy consumption. Therefore, energy consumption needs to be reduced to meet carbon reduction targets through technological innovation.

Finally, for the control variables used in this study, the results in Table 3, Table 4 and Table 8 show that economic development significantly increases carbon emissions and energy consumption in China, it probably because that China's economic growth mainly depends on industries that consume a lot of energy and emit a lot of CO_2, the Chinese government should take measures to speed up the readjustment of the industrial structure and realize the low-carbon transition of economic development. Urbanization contributes to increase carbon emissions, since urbanization stimulates demand for energy consumption [37], and during the study period, urbanization has not reached the critical level where citizens' demand for green urban development curbs energy consumption and carbon emissions [3]. Energy structure measured by the proportion of coal consumption in total energy consumption has a significant positive effect on carbon emissions, which because that carbon emissions come mainly from the burning of fuels, especially coal burning [40]. Besides, marketization is conducive to reducing carbon emissions and energy consumption since marketization improves the use efficiency of energy resources. Trade openness significantly reduces energy consumption, however, the carbon-reduction effect of trade openness is not significant for the whole China. It probably because that technology introduced by trade openness helps reduce energy consumption but does not help improve energy consumption structure, so as not to significantly reduce carbon emissions. Industry structure has non-significant effect on carbon emissions and energy consumption. Environment regulation is markedly conducive to increasing energy consumption in China, which should be taken seriously by the Chinese governments to improve the role of environmental regulation in energy saving and carbon emissions reduction.

V. CONCLUSION AND POLICY RECOMMENDATIONS

A. CONCLUSION

The driving factors and influence mechanism of low-carbon development are diverse and complex, which requires scholars to continuously explore for expanding the discovery and providing reference for policy makers. Based the panel data of 30 provinces, municipalities and autonomous regions in China for the years 2005-2016, by using linear regression model, mediating effect model, and threshold regression model, this paper systematically analyzes the effect of technological innovation on carbon emissions and energy consumption for the whole China and the three regions of China, and explores the mediating and threshold role of energy consumption in the impact of technological innovation on carbon emissions.

According to the analysis above, we obtain some meaningful findings as follows. First, technological innovation is effective for reducing energy consumption and carbon emissions in China, with different effects between the three regions of China. Second, energy consumption plays a significant partial mediating role in the effect of technological innovation on carbon emissions. Third, the effect of technological innovation on carbon emissions is limited by energy consumption, which happens in the indirect impact of technological innovation on carbon emissions by changing energy consumption. Low energy consumption per capita, which is lower than 5.8089, significantly promotes a reduction in carbon emissions through technological innovation. Once energy consumption per capita exceeds a critical level of 5.8089, the promoting effect of technological innovation on carbon emissions reduction will turn into the inhibiting effect. Finally, in terms of the other influence factors of energy consumption and carbon emissions, economic development and energy structure have a significant positive effect on energy consumption and carbon emissions, urbanization has a significant positive effect on carbon emissions and the effect of urbanization on energy consumption is not significant for the whole China. Marketization is conducive to reducing energy consumption and carbon emissions, trade openness significantly reduces energy consumption, but the effect of trade openness on carbon emissions is not significant. Industry structure has non-significant effect on carbon emissions and energy consumption. Environment regulation is markedly conducive to increasing energy consumption and the effect of environment regulation on carbon emissions is not significant.

B. POLICY RECOMMENDATIONS

Based on these findings, the following recommendations on economic low-carbon development for China are proposed.

First, the strategy of innovation-driven development is effective for saving energy and reducing carbon emissions in China. Therefore, the government should continue to promote technological innovation in both breadth and depth. Not only does the technology of energy industry need to be improved, but also the technology of some related industries needs to be optimized and improved. Moreover, the core technology on reducing carbon emissions should be overcome through the original innovation of enterprises. Besides, through policy encouragement and financial support, government should optimize the technological innovation atmosphere and improve the technological innovation conditions, so as to stimulate the motivation of enterprises or individuals to innovate. In addition, all provinces should enhance their abilities to realize the economic and ecological value of technological innovation. Given the greater impact of technological innovation on carbon emissions reduction in the central and western regions of China than that of eastern region, the central and western regions should pay more attention to the promotion of technological innovation through talent introduction, technology introduction, technology imitation innovation and original innovation. For the eastern region with massive populations and advanced economy, in order to realize the target of low-carbon development, only depending technological innovation is not enough, but the government's policy restraint and the citizen's self-consciousness about the resource-efficient, environmentally-friendly growth also needs to be improved.

Second, the above study shows that energy consumption plays a significant partial mediating and threshold role in the effect of technological innovation on carbon emissions. For the sake of achieving the carbon-reduction effect of technological innovation, traditional energy consumption should be reduced according to the above findings. Therefore, all regions should take measures to reduce the use of traditional fossil energy by developing and utilizing the clean energy in personal life and industrial production, for example, promoting the application of solar street lamps and strengthening the use of 3D printing technology in the construction industry. Besides, governments should encourage citizens to purchase and use new energy vehicles through financial subsidies and to take public transportation to work in order to reduce the use of private cars. Moreover, energy efficiency should be improved by increasing energy reuse and improving energy recovery technologies.

Finally, other influence factors should be considered to achieve the goal of low-carbon transition. At first, environmental regulation is an essential tool to solve environmental problems, and carbon emissions should be considered as an important part of environmental regulation to achieve the goal of temperature control quickly. Government should assign carbon emission rights to each region according to its characteristics, and establish a fair carbon emission trading market. What's more, the energy consumption structure should be optimized to reduce the proportion of fossil fuels and increase the proportion of clean energy. Besides, Chinese governments should make efforts to increase the degree of marketization so that the market really plays a decisive role in the allocation of resources for the reason that marketization can strongly promote energy saving and carbon emissions reduction.

C. LIMITATIONS AND FUTURE RESEARCH

This study verifies the effect of the strategy of innovation-driven development on economic low-carbon transformation and determine the mediating and threshold role of energy consumption in the influencing process of technological innovation on carbon emissions for the first time, which extends existing research and provides a solid theoretical basis for policy making. Although this study has acquired some valuable findings, it also has several limitations that should be solved by future research. First, this study has explored the static effect of technological innovation on energy consumption and carbon emissions, but it ignores lag effect and dynamic factors, which will be concerned in the future research. Besides, the influencing mechanism of technological innovation on carbon emissions may be limited by other factors, such as economic development and environment regulation, which will be proved by future research. Finally, this study has identified the effect of technological innovation on carbon emissions across energy consumption, however, the effect of energy consumption on carbon emissions across technological innovation is worth discussing in the future study.

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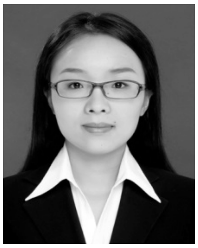

MEILI ZHANG was born in Shandong, China, in 1991. She received the B.S. degree in engineering cost from Qingdao Technological University, in 2015, and the M.S. degree in management science and engineering from Harbin Engineering University, China, in 2017, where she is currently pursuing the Ph.D. degree with the School of Economics and Management. During her studies, she has participated in research work with National Social Science Fund Projects and the Provincial Social Science Fund Project of China. Her research interests include innovation management, technology management, regional green development, and innovation economics.

BAIZHOU LI was born in Liaoning, China, in 1964. He received the Ph.D. degree in management science from Harbin Engineering University, in 2003. He is currently a Professor and a Ph.D. Supervisor with Harbin Engineering University. He is also the Director of the Academic Committee, School of Economics and Management, Harbin Engineering University, and also the Chairman of the Heilongjiang Management Association. He enjoys a special allowance from the State Council of China and is awarded the honorary title of "Longjiang Scholar." His research interest includes innovation management, technology management, and innovation economics.

SHI YIN was born in Hebei, China, in 1988. He received the bachelor's degree in management from the Hebei University of Economics and Business, in 2012, the master's degree in accounting from Heilongjiang Bayi Agricultural University, in 2015, and the Ph.D. degree in economic management from Harbin Engineering University, in 2020. He is committed to scientific and technological innovation, scientific decision-making, and green development research. He published about 20 articles in SSCI, SCI, and CSSCI.