Does renewable energy consumption contribute to the development of low-carbon economy? Evidence from China

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Abstract
Stimulating renewable energy consumption has become a major strategic choice for China to both fulfill the international commitment to reduce carbon emissions and realize the high-quality growth of the domestic economy. On account of the provincial data during the period of 2000 to 2017, we creatively incorporate the ecological footprint into the measurement of low-carbon economy development level through super-efficient SBM model, so as to infer the coordinated development level of 3E system more precisely. Based on the factor substitution effect, energy path dependence effect, and scale effect, the complex nonlinear relationship between the two core research objects is further probed by constructing the threshold regressive model. On the foundation of theoretical research, the consumption of renewable energy, the intensity of energy use, and the level of regional economic development are respectively selected as the moderating variables of the model. Further, we divide different intervals of threshold values to distinguish the differences in the effects caused by regional heterogeneity. The following conclusions are drawn ultimately: There is an apparent threshold effect between renewable consumption and the advancement of the low-carbon economy. Only when renewable itself reaches a higher level of consumption can it show a significant advantage in green economic development. In addition, to make full use of renewable resources to boost the low-carbon and green economy, it is necessary to reduce the economy’s dependence on energy, that is, to decrease the intensity of energy use while maintaining the process of improving coordination of regional economy.

Keywords Renewable energy consumption · Low-carbon economy development · Threshold effect · Regional heterogeneity · Ecological footprint

Introduction
With the intensified contradiction between economic growth and ecological preservation, the green economy has attracted more and more attention from various countries (regions). The idea of the “low-carbon economy” (LC economy), which is closely linked with technological innovation and energy transition, was first introduced in the “Energy White Paper” promulgated by the UK in 2003. Guided by the practice of sustainable development, it contains an economic development model that aims to achieve mutual benefit and win-win outcome on both sides of economy and ecology with minimum consumption of dirty energy (coal, oil, etc.) and greenhouse gases. Featured with low energy use and less pollution, the development pattern of the LC economy is not merely a major innovation for social progress, but also a critical social reform to carry forward a series of technologies in energy-saving and pollution control.

In the course of pursuing low-carbon economic development, the externalities of energy and the environment have also been paid attention to (Marshall 1999). Energy is the material guarantee of social production and living consumption. However, in the overall system of energy, economy, and environment, both the development and utilization of energy will produce certain externalities. Such an external diseconomy is mainly the destruction of the ecological environment, which is not only a generational externality, but also an inter-generational externality related to sustainable development. Currently, global energy consumption, which is typified by fossil fuels, has caused a whole set of energy issues and
environmental problems, including ozone layer destruction, and greenhouse gas emissions (Zhu et al. 2020a, b). To varying degrees, countries in the world are faced with a common practical problem—ecological deterioration and serious environmental pollution, among which China’s predicament is more prominent. In the context of the accelerated pace of worldwide industrialization and urbanization, global energy consumption, especially the expense of traditional fossil energy, is expanding year by year, which further leads to the continuous rise of total carbon dioxide emissions (Yang et al. 2021). According to the IEA (International Energy Agency), the emissions of green gases related to energy use have reached unprecedented levels. Fatally, the utilization of energy resources and the emissions of carbon dioxide have risen by a third in 2020 and are set to double by 2050. The large amount of high energy consumption dominated by fossil fuels and the sharp increase of carbon dioxide emissions have brought severe challenges to sustainable economic growth, resulting in the energy structure adjustment being a vital issue of concern to all countries (Wang et al. 2020). The European Parliament has set the target of raising the share of clean power in the total energy use of the EU to 35% by 2030. And as the largest developing country, China also aims to enlarge the percentage of non-fossil fuels to twenty percent by the year 2030. At present, realizing the transformation of energy consumption structure has become one of the momentous development strategies of all countries, during when the topic of global clean energy governance has also been regarded as pivotal academic research since the 21st century (Zhu et al. 2020a, b; Xu et al. 2020). At the 75th session of the United Nations General Assembly in September 2020, Chinese President Xi stressed increasing China’s outstanding contribution in adopting more forceful policy measures to peak the CO₂ discharge by 2030 and determined to achieve carbon neutrality until 2060. Notably, the speech has been one of the most considerable climate commitments yet made by the world.

However, on account of the significant diversities in the industrial structure, resource endowment, and technological level among different regions in China, there remain striking discrepancies in both energy consumption structure and economic development among various regions (Xiao et al. 2019). Whether it is scientific and appropriate to blindly set uniform standards for clean fuels or renewable energy still remains discussing. On this basis, this research argues that when discussing the impact of the utilization of the renewable on the LC economy, instead of simply studying a linear impact between the two, it is of vital significance to comprehensively consider the regional heterogeneity factors to explore whether the consumption of the renewable sources can contribute to the green development. Furthermore, does the magnitude or the effect of the influence differ from region to region? If so, what is the determining factor behind it? The specific detection of these doubts may well contain the practical implication of reshaping the industrial structure and adjusting the proportion of energy for China’s future, thus realizing the low-carbon economy development with minimal environmental loss. Therefore, from the perspective of regional heterogeneity, this paper selects China’s provincial data from 2000 to 2017 and adopts threshold regression to explore the nonlinear relationship between renewable energy consumption and low carbon economy.

In view of the above, this paper may have the following contribution margins. On the one hand, at the level of research methods, we may have two contributions: (1) in the measurement of total factor productivity, not only input factors such as labor, capital, and energy are taken into account, but also ecological footprint, which is an important variable affecting economic growth, and non-expected output variables such as carbon emissions are also included in the calculation system, so as to estimate the level of regional low-carbon economic development more accurately and comprehensively; (2) in the application of the model, the panel threshold method is introduced into the study of renewable energy consumption and the low-carbon economy, and the nonlinear relationship between the two is scientifically tested. On the other hand, in terms of research content, we may have enlightenment from the following three aspects: (1) by integrating the economy and the environment into the same framework, the complex impact of renewable energy consumption on the low-carbon economy is explored, thus providing guidance for China to achieve the dual benefits of “economy” and “environment”; (2) the threshold effect of renewable energy on the development of low-carbon economy has been deeply analyzed, such as factor substitution effect, path dependence effect of energy consumption and technological base effect of economic level on increasing renewable energy consumption, which has laid a theoretical foundation for the process of the low-carbon economy from the perspective of regional heterogeneity; (3) the regional heterogeneity of the impact of China’s renewable energy consumption on the development of the low-carbon economy is analyzed deeply. It will provide a scientific policy basis for China to develop non-fossil energy efficiently, optimize energy structure and achieve low-carbon economic development goals with minimum economic cost.

**Literature review**

Energy, as an important production factor, is included in the production function model along with capital, labor, and other factors (Ma et al. 2018). It is imperative to boost the green transition of the whole social and economic production in that both the finiteness and hazards of fossil energy are becoming an increasingly serious problem worldwide, and energy security issues such as the bottleneck of crude oil supply have
become prominent (Qi and Li 2018). Scholars have started studying the correlation between the energy structure and economic development, attaching increasing importance to the positive externality of adjusting energy consumption structure. Nevertheless, due to the diversity in sample selection, empirical methods, and research objects, there are striking differences in the research findings.

On the one side, some scholars apply renewable energy to the production function and regard it as a production factor, discovering that traditional highly polluting energy can be replaced by clean energy to some extent, which is conducive to energy diversification and energy diversification and climate mitigation, thus promoting economic growth together with other production factors. Most scholars have verified the positive economic benefits of renewable energy in Asian countries through empirical studies (Mohsin et al. 2021). For instance, based on Pakistan’s time-series data from 1995 to 2017, Shahzad et al. (2020) adopted ADRL and VECM to explore the dynamic linkages among health expenditure (HE), economic growth (EG), production function and regard it as a production factor, discovering that traditional highly polluting energy can be replaced by clean energy to some extent, which is conducive to energy diversification and energy diversification and climate mitigation, thus promoting economic growth together with other production factors. Most scholars have verified the positive economic benefits of renewable energy in Asian countries through empirical studies (Mohsin et al. 2021). For instance, based on Pakistan’s time-series data from 1995 to 2017, Shahzad et al. (2020) adopted ADRL and VECM to explore the dynamic linkages among health expenditure (HE), economic growth (EG), carbon dioxide emission reduction (COE), renewable energy consumption (REC) and information and communication technology (ICT). It was found that there is a one-way causal relationship between renewable energy consumption and economic growth, carbon dioxide emission reduction and health expenditure, and health expenditure can be reduced to a certain extent, which indicates that renewable energy plays a key role in improving environmental quality and economic growth. In addition, the beneficial impact of the cleaner energy transition on economic growth has also been confirmed in relevant studies in other countries and regions. Taking OECD countries as research samples, Inglesi-Lotz (2016) proposed that the utilization of renewables can significantly advance the sustainable economy, which was also verified by Armeanu et al. (2017) through empirical models of 28 countries in Europe. Similarly, by means of the ARDL method and the sample of G-7 countries, Cai et al. (2018) proved the favorable influence of energy consumption transition on the economy increase as well; based on the same empirical method, Sohag et al. (2021) changed the research object to 25 OECD countries and concluded that renewable energy consumption could significantly improve total factor productivity in both the short and long term, which is different from the non-significant impact of fossil energy on total factor productivity.

On the other hand, some scholars hold a neutral view that both fossil energy and renewable energy can play a positive economic benefit, but relatively speaking, renewable energy is at a disadvantage in promoting economic growth (Adams et al. 2018). Furthermore, parts of scholars still maintain on the sidelines for the clean transformation of energy consumption. Based on the empirical test of ADLM, Ocal and Aslan (2013) explored the causality between the renewables use and economic increase in Turkey, and the findings showed that renewable energy consumption is not beneficial to the economy; also, some scholars hold the point that in comparison with polluting energy sources, the present evolution of the renewable sources produces neither the technological superiority nor cost advantages. At this stage, the progress of renewables is primarily actuated by government policies, which hides a certain opportunity cost, causes quite a few economic losses, and goes against the productivity improvement (Qi and Li 2018); in the context of COP21, Doğan et al. (2020) discovered the regional variation in the effect of the utilization of renewables in different countries and regions. For one thing, when conducting research on a national scale, Omri et al. (2015) put forward that in advanced countries such as Netherlands and Japan, there is a one-way causal correlation between renewable sources utilization and economic gain; Sikder et al. (2019) pointed out that the renewables do not have the same impact on economic output in various countries by carrying out the data analysis concerning economic gain and energy consumption structure of G20 countries. For example, in countries such as the USA, Italy, and Argentina, the consumption of renewable energy can powerfully impel economic growth; through measuring the long-term elasticity coefficient of economic growth of 38 energy-consuming countries during 1990–2018, Shahbaz et al. (2020) proposed that renewable energy consumption has different effects on economic growth based on national heterogeneity. The coefficient results showed positive significance (Korea and other countries), positive non-significance (Romania), negative significance (Canada), and negative non-significance (Italy).

For another thing, there are also significant differences within the same country. Some scholars believed that in regions with relatively high or low carbon intensity in China, renewable energy can play a better role in the low-carbon economy, while in regions with moderate carbon intensity, its promoting role is very limited (Yu et al. 2020); similarly, under the assumption of limited resources constraints and diminishing returns from production scale, Zhu et al. (2020b) concluded that China’s overall economic growth did not change significantly during the transition from thermal power
generation to hydroelectric power generation. However, when the sample is divided, the eastern regions of China gain significant economic benefits, while the western regions suffer some economic losses.

Current studies related to renewable use and economic development authentically provide the theoretical basis for this paper. However, there remains some room for improvement in the previous literature. For one thing, the above kinds of literature mainly studied the influence of renewables on economic development and regional differences by means of linear methods and grouping methods. But in fact, since the application of non-fossil fuels affects economic advance through a variety of mechanisms, there is probably a nonlinear correlation between the two. Hence, the inaccuracy of traditional linear methods may well lead to inconsistency of conclusions; for another thing, the most serious exposure problem of the grouping method is that grouping criterion are determined arbitrarily rather than inferred through mathematical statistics, so it is impossible to test the significance of the difference of regression results of different samples, thus leading to the vulnerability and unavailability of model estimations which are easily challenged; additionally, most studies only study the relationship between renewable energy and economic growth from the perspective of economic aggregate, which is likely to lack a comprehensive investigation of the economy-environment-energy system. Consequently, as a supplement to the available literature, this study endeavors to explore nonlinear threshold effects of renewable energy consumption on the low-carbon economy of 30 regions in China and further dissects a variety of possible threshold effects.

Theoretical analysis

As the major features of the transition of economy mode, the allocation structure adjustment of the three basic elements of capital, labor, and energy plays a fundamental role on economic advance (Liu et al. 2018). In the context of “restructuring for transformation”, it is increasingly urgent to adjust the configuration structure of energy elements and promote the clean transformation of the energy system dominated by fossil energy for low-carbon development. Yet, we have to realize that as non-fossil energy has developed rapidly, the adjustment of energy structure, which is characterized by renewable energy consumption, is definitely possible to have more than a purely positive impact on the economy (Lin 2017). In other words, under the action of some regulatory mechanisms, the relationship between the two may present a structural evolution. What is noteworthy is that the panel threshold regression model is a nonlinear econometric model, whose connotation is to incorporate the regulated index as an unknown factor into the model equation, establish the piecewise regression function based on the core independent variable, thereby estimating both the inflection point value of threshold mechanism and its related parameters. Therefore, we apply the conventional nonlinear model, namely the threshold regression model, to the study of the impact relations between renewable consumption and green development. Furthermore, based on the following theoretical analysis and mechanism research, this paper attempts to raise three hypotheses.

(1) The consumption of renewable energy. In the process of increasing the utilization of renewable energy, the overall energy structure is also facing slow evolution, which is embodied in the transformation of the energy system from fossil fuels to clean energy (Koak and Aykutarkgünei 2017). However, the impact of the two energy systems on the economic and social system is bound to be different, especially on the economic growth. More precisely, when fossil energy is dominant in the energy system, the economic cost of energy use is small, but its negative externality to the ecological environment is more obvious, which is reflected in the enhancement of the greenhouse effect, thus leading to global warming (Omri and Belaïd 2021; Naqvi et al. 2020). At the same time, because of the unproducible essence of fossil energy and the overexploitation of fossil fuels by human beings, the traditional energy sources are running out, which also makes economies that have long relied on fossil energy consumption face uncertainty in energy security (Li and Cheng 2020). On the contrary, when the energy system is dominated by non-fossil energy, the economic cost of energy use will be large, and the negative externalities brought by energy use will be greatly weakened, which will impose a correspondingly large influence on the economic systems, significantly strengthening the socially sustainable development ability (Xie et al. 2018). However, boosting non-fossil energy consumption does not happen overnight at all. In the preliminary stage of the increase of non-fossil energy consumption, the production process and equipment need to be updated in time, the clean production capacity of enterprises needs to be improved, and the relevant market of products also needs to be redefined. Consequently, renewable energy consumption may impose huge economic costs on the economic growth of enterprises, thereby inhibiting the advancement of the green economy (Teng and Rong 2020; Li and Yi 2020). When the cleanliness of the energy system is continuously improved, the driving effect of non-fossil energy consumption on ecological environmental protection and economic
development is gradually highlighted, and thus it will exert a favorable influence on the green economic development. Therefore, this study considers that in the process of renewable energy consumption, there must be a special point through which the renewable energy consumption breaks. Its impact on the evaluation of the LC economy will change from negative to positive, displaying an obvious “J” curve effect.

On such a basis, this article comes to formulate Hypothesis 1: Renewable energy consumption does not linearly affect the green economy. Accompanied by the continuous advancement of renewable consumption, its influence on the development of the low-carbon economy may well undergo a structural mutation, with the effect direction changing from suppressive to stimulative.

(2) The intensity of energy consumption. The energy intensity refers to the energy use per unit of real GDP, reflecting the degree of the energy dependence of an economy (Luan et al. 2021). As the energy consumption intensity reaches a certain level, the economic development becomes highly dependent on energy consumption, with a more apparent path dependence effect and lock-in effect of energy use (Qi and Li 2017). Combining the idea of path dependence with the energy economy, this paper aims to discuss the high dependence and internal inertia of the system on the production, technology, and industrial structure of fossil energy driven by the economic development due to the scale effect, adaptive expectation, cooperative effect and other factors (David 1988; Arthur 1994). Unruh (2000) pointed out that due to the increasing economies of scale in energy path dependence, the industrial economy would be locked into the energy system based on fossil fuels for a long time, which would hinder the policy and market forces of renewables. And for a very long time, under the extensive economic development mode of high input and low output, China has also generated serious energy dependence and lock-in effect on fossil energy. Especially in the middle parts and the western areas, it is hard to change the facilities construction and corresponding policies and systems that have been formed for fossil energy consumption.

In consideration of the above analysis, this study puts forward Hypothesis 2: Under the adjustment of the energy intensity, the renewables’ influence on the low-carbon economy appears as a nonlinear shock. Specially, when energy intensity exceeds the threshold value, it limits the beneficial effect of renewable consumption on the green economy to some extent.

(3) The level of economic development. The relationship between economic advance and energy consumption usually follows the rules described by the environmental Kuznets curve. In regions with better development of economy, the energy resources and economic system are dramatically decoupled with a smaller economic cost of energy substitution, and the diversified energy structure formed by factor substitution may contribute to the economic growth (He and Lin 2019; Wesseh Jr and Lin 2020). Generally speaking, areas with higher levels of economic development tend to possess the hardware foundation (such as investment in scientific research and infrastructure) and software foundation (such as consciousness of green development and environmental protection, and reservation of professional knowledge) required by non-fossil energy consumption. Under such conditions, no matter at the policy level or the market level, there are few obstacles to the consumption of non-fossil energy. Additionally, a higher level of economic development often leads to the continuous enrichment of enterprises’ investment in education funds and scientific research and innovation, thus attracting more social capital, cutting-edge technology, and high-tech talents, which are conducive to the formation of aggregation effect (Zhao and Lin 2019). After dividing 108 countries into four groups: high income, low income, and two types of middle incomes between the two, Al-Mulali et al. (2013) concluded that the higher the income level, the greater the sustainable and significant positive impact of the renewables utilization on the economy advance; based on the panel data of 28 EU member states, Qi and Li (2017) indicated that activities related to renewable energy have high economic costs and are detrimental to economic growth. Besides, the inhibition effect of the renewables on economic progress is visibly disparate in countries with various economic development levels; Huang et al. (2008) grouped 82 countries by the income level, finding that the energy consumption does not have the same effect on real GDP across groups, which was proved by Lee and Chang (2007) as well. It can be seen that once the economy climbs a certain height, the consumption of renewables will exert a completely opposite effect on green development.

On this basis, we further conceive Hypothesis 3: The utilization of renewables has a nonlinear impact on the progress of the LC economy. Meantime, with a higher development level of the economy, the driving effect of renewable energy consumption on the green economic advance is more evident.
Methodology and data

Econometric methodology

Setting of threshold model

Borrowing from Hansen’s (1999) findings, this study adopts a non-dynamic threshold model to examine the existence of threshold effect between the consumption of renewable energy sources and the green economy. As an econometric model of nonlinear relation test, this method could not merely precisely measure different values of the thresholds, but also statistically verify the significant level of endogenous “threshold characteristics”. With renewable energy consumption ($LCE_{it}$), energy intensity ($Energy_{it}$) and economic development level ($GDP_{it}$) as the moderating variables, the following single-threshold panel models are constructed.

\[
LCE_{it} = \theta + \beta_1 GOV_{it} + \beta_2 ICT_{it} + \beta_3 URB_{it} + \beta_4 POP_{it} + \beta_5 REG_{it} + \beta_6 Open_{it} + \beta_7 TES_{it} \\
\times I(TES_{it} \leq \gamma_1) + \beta_8 TES_{it} \times I(TES_{it} > \gamma_1) + \varepsilon_{it}.
\]

(1)

\[
LCE_{it} = \theta + \beta_9 GOV_{it} + \beta_{10} ICT_{it} + \beta_{11} URB_{it} + \beta_{12} POP_{it} + \beta_{13} REG_{it} + \beta_{14} Open_{it} \\
+ \beta_{15} TES_{it} \times I(Energy_{it} \leq \gamma_2) + \beta_{16} TES_{it} \times I(Energy_{it} > \gamma_2) + \varepsilon_{it}.
\]

(2)

\[
LCE_{it} = \theta + \beta_{17} GOV_{it} + \beta_{18} ICT_{it} + \beta_{19} URB_{it} + \beta_{20} POP_{it} + \beta_{21} REG_{it} + \beta_{22} Open_{it} \\
+ \beta_{23} TES_{it} \times I(GDP_{it} \leq \gamma_3) + \beta_{24} TES_{it} \times I(GDP_{it} > \gamma_3) + \varepsilon_{it}.
\]

(3)

In the above three formulas, $LCE$ represents the degree of the low-carbon economy. And three threshold variables in the corresponding models are respectively described by the consumption of the renewables ($TES_{it}$), the intensity of energy use ($Energy_{it}$) and the level of economic development ($GDP_{it}$). The formula also contains the same set of control variables, including government intervention ($Gov_{it}$), informatization ($ICT_{it}$), urbanization ($URB_{it}$), population density ($POP_{it}$), environmental regulation ($REG_{it}$), and the degree of openness ($Open_{it}$). $\beta$ expresses the vector of coefficients, and $\gamma$ refers to the specific value of the threshold. The formula also contains an index function ($\ast$), whose value is 1 when the corresponding condition holds, otherwise it is 0. $\varepsilon_{it}$ follows a normal distribution $N(0, \sigma^2)$.

Examination methods of the threshold effect

In model estimation, the elimination of the individual effects of panel data can be removed by deleting the average value within the group, and the single-threshold model is expressed in the form of a matrix as follows:

\[
LCE_{it} = x^\ast(\gamma) \beta + \varepsilon^\ast
\]

(4)

For a given value, the consistent estimator of the parameter $\beta$ can be gained through the common least square method, namely:

\[
\hat{\beta}(\gamma) = \left[X^\ast(\gamma)'X^\ast(\gamma)\right]^{-1}X^\ast(\gamma)'Y^\ast
\]

(5)

The corresponding residual vectors $\hat{\varepsilon}^\ast(\gamma)$ and the residual sum of squares $S_1(\gamma)$ are shown below, respectively.

\[
\hat{\varepsilon}^\ast(\gamma) = Y^\ast - X^\ast(\gamma)\hat{\beta}(\gamma)
\]

(6)

\[
S_1(\gamma) = \hat{\varepsilon}^\ast(\gamma)'\hat{\varepsilon}^\ast(\gamma)
\]

(7)

By minimizing $S_1(\gamma)$ corresponding to Equation 5, we can get the estimated value of $\gamma$, that is, $\hat{\gamma} = \arg \min_\gamma S_1(\gamma)$, from which the residual vector $\hat{\varepsilon}^\ast = \hat{\varepsilon}^\ast(\gamma)$ and the variance of the residual $\hat{\sigma}^2(\gamma) = \frac{1}{n(T-1)}\hat{\varepsilon}^\ast'\hat{\varepsilon}^\ast = \frac{1}{n(T-1)}S_1(\hat{\gamma})$ can be further obtained.

Once the parameter estimate is reckoned, the model needs to be tested in the following two aspects.

One is to examine whether there is a threshold effect, whose null hypothesis is $H_0: \beta_1 = \beta_2$. Meantime, statistics are constructed for the likelihood ratio test:

\[
F_1 = \frac{S_0 - S_1(\hat{\gamma})}{S_1(\gamma)/n(T-1)}
\]

(8)

Among them, the specific value of the critical point cannot be identified on the basis of the null assumption, which results in the non-standard distribution of traditional test statistics. Accordingly, Hansen (1999) proposed that by means of self-sampling, the above deficiencies can be resolved effectively.

The other is to test whether the calculated threshold value is the same as the real value of the inflection point. Hansen (1999) proposed that the null hypothesis is still valid only by constructing a “non-rejection domain”, that is, satisfying $LR_1(\gamma_0) \leq c(\alpha)$, where $c(\alpha) = -2\ln(1-\sqrt{1-\alpha})$. For the null hypothesis $H_0: \beta_1 = \beta_2$, the likelihood ratio statistic is:

\[
LR_1(\gamma) = \frac{S_1(\gamma) - S_1(\hat{\gamma})}{\hat{\sigma}^2}
\]

(9)
It is assumed that there is only one threshold in the above model, but once a double or multiple threshold values is tested in the model, it can be expanded on the basis of the above model. Due to space constraints, this article will not go into details.

**Variable description**

The **explained variable: the level of low-carbon economy development (LCE)** As a sustainable development model with lower resource input and higher economic output, the low-carbon economy mainly focuses on both input and output. In this paper, a super-efficiency DEA-SBM (a slacked-based DEA model) considering non-expected pollutions is adopted to estimate the level of low-carbon economic development, which can effectively avoid the problem of efficiency overestimation and non-radial adjustment of input and output efficiency. To be more precise, we assume that returns to scale are constant (Zhou and Hu 2013). At the same time, this paper selects an output-oriented super-efficiency SBFM model and constructs an adjacent reference Malmquist index (Adjacent Malmquist). In the choice of input and output indicators, referring to researchers such as Yan et al. (2020) and Shen et al. (2020), the paper creatively adds the ecological footprint measured by the improved emergence method (Yang and Zhu 2016; Tan and He 2016). Table 1 shows the inputs of various biological accounts and energy accounts, and the elements of input-output listed in Table 2 are selected after careful consideration in the study.

The **core explanatory variable: The consumption of renewable energy (TES)** Under the framework of the Paris Agreement, the Chinese government has fully played its role as a “responsible major country” and set targets for renewable energy consumption and carbon reduction in China’s development. At the policy level, the Chinese government has issued three heavyweight documents: the 13th Five-Year Plan for Renewable Energy Development, the 13th Five-Year Plan for Energy Development, and the Revolution Strategy for Energy Production and Consumption 2016-2030. All of these documents set targets for renewable energy consumption, basically stipulating the proportion of non-fossil energy in primary energy consumption to 15% by 2020, 20% by 2030, and 50% by 2050. Increasing the proportion of non-fossil energy consumption is undoubtedly the basic requirement for promoting renewable energy consumption (Han et al. 2020). In this paper, the proportion of non-fossil energy consumption in primary energy consumption is applied to characterize the degree of renewable energy consumption. Due to the fact that the National Bureau of Statistics does not release official regional data on primary energy consumption, we attempt to convert the secondary energy consumption, such as coke, gasoline, and diesel, into ten thousand tons of standard coal on the basis of the reference coefficient of various energy sources. Thereafter, we subtract the total secondary energy consumption from the total regional energy and finally get the primary energy consumption of each province. The specific folding standard coal coefficient is summarized in Table 3.

**Threshold variables** In our research, the threshold indicators are respectively set as the consumption of the renewables (TES), energy intensity (Energy), and the level of regional economy advance (PGDP). Among them, the calculation method of renewable energy consumption has been described above. Referring to the research results of Qi and Li (2010), Hu et al. (2011) and other scholars, the energy intensity is expressed by total energy expenditure as a percentage of GDP. Moreover, in terms of estimation of the economic development, we adopted per capita GDP on the basis of the research of Su and An (2018).

**Control variables** For fear of the overall model being disturbed by other factors, we have read a large number of relevant literature and finally decided to add the following control indicators into the model. (1) Government intervention (GOV). The government participates in regional economic activities through fiscal policy, which is represented by taxation, thus supporting the development of environmental protection enterprises and green technology innovation. But in the short term, given the hidden competition between regions for economic revenue and the performance of local officials, governments may be more focused on economic favors than environmental benefits. Hence, the impact of government intervention on green development is uncertain. Referred to Hong et al. (2014), the research adopts the percentage of government spending in GDP excluding public expenditures on technology, education, medical treatment, and society cultures to express the degree of government intervention. (2) Level of information, communication, and technology (ICT). Advances in information technology can availably solve the problem of information island, and the network information platform can provide opportunities for both supply and demand to integrate information, thus improving their resource allocation efficiency and effectively promoting the process of the low carbon economy from

**Table 1** The index table of input and output

| Input                      | Capital | Labor | Ecological footprint |
|----------------------------|---------|-------|----------------------|
| Output                     | Gross domestic product | Carbon dioxide emissions |

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both the productive and the living ends. For another, the construction of various new digital infrastructures also forces certain pressure on the regional economic growth and the improvement of ecological performance, with rampant discussions on the “productivity paradox”. Therefore, there remains indeterminacy about the relationship between the level of information and the advancement of the green economy. In light of research results of Huang et al. (2019), Yuan and Liu (2019), the percentage of post and telecommunications business volume in gross population is calculated to indicate ICT. (3) Level of urbanization (URB). On the one hand, with the growing urbanization process, abundant factors, such as capital and labor, are constantly aggregating, which is conducive to the optimization of resource allocation and knowledge spillover and thus can motivate the green economy. On the other hand, the pollution effect of infrastructure brought by urbanization and the congestion effect caused by factor agglomeration will inhibit the low-carbon economic development. Therefore, the impact of urbanization on the advancement of the LC economy remains still dubious. Referred to the measurement methods of Zhang et al. (2015), this study employs the percentage of permanent urban residents in the general population to express the level of regional urbanization. (4) The population density (POP). According to the theory of classical economics and new economics, the population size is often taken as the representation variable of the labor force, which is one of the basic components of economic increase. Yet, there has been no consensus on the linkage between the population and LC development. This paper introduces the population intensity into the control factor, which is described as the ratio of the total resident population at the end of the year to the area of the province (Qiu and Zhou 2020). (5) Environmental regulation (REG). Traditional neoclassical economists generally believed that environmental regulation would inhibit the development of the low-carbon economy through “cost effect” and “constraint effect”, while Porter put forward that reasonable environmental regulation could encourage enterprises to carry out the relevant technological innovation so as to realize the coordinated progress of economic growth and ecological environment. Due to the uncertain relationship between the two, this paper then uses the amount of pollution control divided by GDP to express the indicator of environmental regulation (Wang 2016). (6) Degree to openness (Open). The export-oriented economy characterized by import and export trade is an important engine of China’s rapid economic growth. But in fact, China’s foreign trade activities are mainly manifested in the labor-intensive and resource-intensive export trade and the “three imports and one supplement” low-technology foreign investment, which is not beneficial for sustainable evolution. Thereby, this paper refers to the calculation method of Shen (2017) and takes the degree of openness as one of the control variables. Table 4 shows the definition and measurement of all variables.

Data source

By setting the year from 2000 to 2017 as the research period, this paper selects 30 mainland regions in China as the research data. Because of the obvious information missing in Hong Kong, Taiwan, Tibet, and Macao, we have eliminated them. On the one hand, this time span covers the period from the “10th Five-Year Plan” to the “13th Five-Year Plan”, which has a wide range of statistical significance. On the other hand, the period selected crosses two rounds of “electricity system reform” and the initial stage of “structural reform on the supply side”, which can fully verify the linkage between consumption of renewables and the process of LC economy in China.

The data of low-carbon and green growth process in the study are almost obtained from China Statistical Yearbook and Wind - Economic Database. The consumption of various types of energy are primarily collected from the National Energy Model Integration Platform of Beijing Institute of Technology, China Energy Statistical Yearbook, and various public statistical information; the data of economic development level and control variables are referred to the sources, such as Population and Employment Statistical Yearbook of China, China Statistical Yearbook and Annual Database by Provinces on the website of the National Bureau of Statistics.

For the sake of the weakness of data credibility and comparability caused by price fluctuations, the paper sets the base period as 2000, deflates the prices of all monetary quantities, and adjusts them to comparable prices by means of a basket of price indexes such as fixed asset investment price indexes. Moreover, for fear of heteroscedasticity and multicollinearity, the logarithm processing is carried out on the related variables. Table 5 collects the specific descriptive statistics of the correlation coefficient matrix among the variables.

Empirical analysis of the threshold effect of renewable energy consumption on low-carbon economic development

Results of panel variables testing

Multicollinearity test

First, the correlation analysis is conducted. On the one hand, Table 6 shows that all the independent variables are significantly correlated with the explained variable LCE of low-carbon economic development, which proves the rationality of the selection of independent variables;
on the other hand, in terms of correlation coefficients among explanatory variables, only the correlation coefficients between PGDP, ICT, and URB are relatively large, but still below 0.8, indicating that there is a weak correlation between variables. It is worth noting that the remaining independent variables all show the insignificant statistical relationships or low dependency relationships. Therefore, it can be preliminarily judged that there is no multicollinearity in the regression of the panel model.

Secondly, the variance inflation factor VIF is analyzed. On the basis of the correlation analysis, the variance inflation factor test can provide more powerful evidence for the multiple linearity of the variables. For the variables in the paper, the VIF test results of variance inflation factors are set out in Table 7. Among all variables, the maximum VIF value is 4.46, much less than 10. This indicates that although there is a certain degree of statistical dependence between PGDP, ICT, and URB, it does not lead to multicollinearity of the model as a whole. What is certain is that combining with the results of correlation coefficient and variance inflation factor VIF, it appears no multicollinearity among variables (Wang and Liu 2007).

### Unit root test

For fear of spurious regression, the unit root test must be carried out before regression analysis of the panel model. Actually, there are many methods for unit root tests, including the tests of LLC, IPS, Breitung, Fisher-ADF, and Fisher-PP. In order to prevent the possible defects brought by a single test method, the special tests whose null assumption is the existence of panel unit root are respectively applied in this paper for variables through the software Eviews 9.0. According to Table 8, under the original value test, only three variables (LCE, GOV, REG) have passed the three tests at the significance level below 10%, while the other variables all had unit-roots. In the case of the first-order difference test, all statistics pass the four tests at the significance level of less than 5%, indicating that all of the variables have stationarity after the first-order difference processing, which behaves as a comprehensive first-order integer.

### Co-integration test

As can be seen from Table 9, the KAO test method is used to perform the co-integration test on the variables of the three basic models respectively. Once the value of P is smaller than 0.01, we can believe that the null assumption is statistically rejected, that is, all the indices in each model are co-integrated over the long term.

### Estimation of the threshold model

#### Threshold effect test

After setting the core explanatory variable as the consumption of renewable energy, we examine the existence of the threshold effect and sort the results in Table 10. When the threshold variable is set as the renewable energy consumption (TES), the single-threshold effect is significant (P-value is 0.0400), while

| Land type               | Species of biological resources                           |
|-------------------------|-----------------------------------------------------------|
| Arable land             | Cereals, beans, potatoes, cotton, oil plants              |
| Woodland                | Wood, tea, fruit, apple, pear, grape                      |
| Grassland               | Beef, pork, mutton, milk, poultry eggs                   |
| Fossil energy land      | Crude oil, natural gas, kerosene, coke, diesel, gasoline, fuel oil, coal |
| Construction land       | Electric power                                            |
| Water area              | Fish, shrimp, crabs, and other aquatic products            |

**Table 2** Ecological footprint account

| Land type               | Species of biological resources                           |
|-------------------------|-----------------------------------------------------------|
| Arable land             | Cereals, beans, potatoes, cotton, oil plants              |
| Woodland                | Wood, tea, fruit, apple, pear, grape                      |
| Grassland               | Beef, pork, mutton, milk, poultry eggs                   |
| Fossil energy land      | Crude oil, natural gas, kerosene, coke, diesel, gasoline, fuel oil, coal |
| Construction land       | Electric power                                            |
| Water area              | Fish, shrimp, crabs, and other aquatic products            |

**Table 3** The conversion standard coal reference coefficient of various secondary energy

| Coke                  | Fuel oil                      | Gasoline                     | Kerosene                   | Diesel                      | Liquefied petroleum gas    | Power (equivalent)         |
|-----------------------|-------------------------------|------------------------------|----------------------------|-----------------------------|----------------------------|-----------------------------|
| Coefficient of conversion to standard coal | 9714 tons of standard coal/ten thousand tons | 14,286 tons of standard coal/ten thousand tons | 14,714 tons of standard coal/ten thousand tons | 14,714 tons of standard coal/ten thousand tons | 17,143 tons of standard coal/ten thousand tons | 0.1229 kilogram standard coal/kilowatt hour |

**Note:** The conversion standard coal coefficient of various energy sources comes from the latest national standard GB/T 2589-2008 General Rules for Comprehensive Energy Consumption, which was formally implemented on June 1, 2008.
the double threshold effect is not significant (P-value is 0.1900). That is, there is merely a single threshold value; in the case of energy intensity Energy as the moderating variable, the value of P in the single threshold is 0.0300, and the inspection value of the other test is 0.5733, indicating that only the single-threshold effect comes into play; once the economic development level (GDP) is taken as the threshold indicator, the single threshold utility has passed the 5% significance inspection, while the effect of double threshold failed, manifesting that there is only one critical value in the model.

When the 5% quantile of the threshold variable is taken as the starting point of the search, the threshold variable value with the minimum sum of squares of residuals is the right estimation of the threshold. After the threshold estimator is obtained, it is also necessary to verify the similarity between the estimated threshold and the real value.

Table 11 displays the test results. It is found that when the threshold variable is set as the consumption of renewables TES, the test value of single threshold effect is 0.0093, and the corresponding 95% confidence intervals are respectively (0.0091, 0.0099); while the intensity of energy consumption Energy is set as the threshold variable, the value of the critical value is 1.1766, whose 95% confidence intervals is between 1.1078 and 1.1815; under the adjustment effect of economic development level GDP variable, a single threshold 0.6366 is obtained, which is in the 95% confidence interval of 0.6074 to 0.6444.

To acquire the threshold and the confidence interval in a more intuitive way, we further identify the threshold value by the feat of the least square likelihood ratio statistic LR. The threshold estimate is the statistic when LR is zero. Figure 1 presents the likelihood ratio function graphs covering the

| Variable | Mean | Standard deviation | Min | Max | Sample volume |
|----------|------|--------------------|-----|-----|---------------|
| LCE      | 0.9986 | 0.0713            | 0.6865 | 1.1864 | 540          |
| TES      | 0.1178 | 0.1095            | 0.0006 | 0.4278 | 540          |
| Energy   | 1.2480 | 0.7350            | 0.2546 | 4.3065 | 540          |
| GDP      | 3.0835 | 2.4162            | 0.2645 | 12.9060 | 540          |
| GOV      | 0.1470 | 0.0707            | 0.0058 | 0.4979 | 540          |
| ICT      | 0.1375 | 0.1052            | 0.0095 | 0.6256 | 540          |
| URB      | 0.4919 | 0.1524            | 0.1389 | 0.8961 | 540          |
| POP      | 0.0429 | 0.0610            | 0.0007 | 0.3826 | 540          |
| REG      | 0.0017 | 0.0014            | 0.0007 | 0.0099 | 540          |
| Open     | 0.3091 | 0.3822            | 0.0162 | 1.6802 | 540          |
threshold value in the three kinds of threshold models, respectively.

**Analysis of the threshold regression model**

On the basis of different threshold variables, this article establishes three threshold panel models. Table 12 demonstrates the concrete results of three panel regressions.

In Model (1), when the consumption of renewables is low ($TES_{it} \leq 0.0093$), it appears unfavorable for the progress of the LC economy. ($-8.0152$), which is significant at the 1% level; when $TES_{it}$ gets greater ($TES_{it} > 0.0093$), the blossom of the low-carbon economy will be driven by renewable energy consumption, with the elastic coefficient $0.1034$ passing the 0.1 significance test. Hereby, we can easily conclude that there is a complex nonlinear correlation between the consumption of renewable energy sources and the growth of the low-carbon economy, which is regulated by the process of energy structure adjustment. As the consumption of the renewable source steps over the inflection point, the direction of the influence of the renewable share on the LC economy advancement will change from negative to positive evidently. Therefore, Hypothesis 1 in this paper is further verified.

In terms of the results of Model (2), along with a relatively lower intensity of energy use ($Energy_{it} \leq 1.1766$), the consumption of renewable sources can make a strong thrust for the green development effectively ($0.1233$), and it has passed the significance level test of 0.01; while along with a relatively higher intensity of energy use ($Energy_{it} > 1.1766$), renewable energy consumption is no longer beneficial to low-carbon economy development, conversely showing an insignificant negative effect. It is not difficult to conclude that renewable energy consumption is highly susceptible to energy consumption intensity, thus generating a nonlinear shock on the green economy progress. Once the degree of dependence on traditional energy sources reaches a special critical value, the two core indicators studied in this paper present an influence of structural mutation, which is reflected in the fact that renewable consumption no longer wields a remarkable influence on the low-carbon economy evolution, thus convincingly confirming the Hypothesis 2.

In the case of a relatively low level of economic development ($PGDP_{it} \leq 0.6366$), the consumption of renewable sources will inhibit the progress of the LC economy, whose elasticity coefficient is $-0.2107$, as shown in Model (3); it is worth noticing that moderated by a better economic advance ($PGDP_{it} > 0.6366$), the consumption of renewables in turn significantly advance the process of low carbon economy, with an influence coefficient of $0.1326$ which is significant at 0.05 level. Taking the indicator of $GDP$ as the threshold variable, the existence of a non-simple linear correlation between the renewable consumption and green economic advance has been confirmed. On both sides of the threshold of

| Table 6 | Correlation matrix and summary statistics of variables |
|---------|------------------------------------------------------|
| Variable | LCE | TES | Energy | PGDP | GOV | ICT | URB | POP | REG | Open |
| LCE    | 1.000 | | | | | | | | | |
| TES    | 0.1016** | 1.000 | | | | | | | | |
| Energy | $-0.4018^{***}$ | $-0.0914^{**}$ | 1.000 | | | | | | | |
| PGDP   | 0.4203*** | $-0.086$ | $-0.5885^{***}$ | 1.000 | | | | | | |
| GOV    | 0.1671** | 0.3523*** | 0.2281*** | 0.0437 | 1.000 | | | | | |
| ICT    | 0.4086*** | $-0.0407$ | $-0.4080^{***}$ | 0.744*** | 0.0245 | 1.000 | | | | |
| URB    | 0.349*** | $-0.142^{**}$ | $-0.5164^{***}$ | 0.7909*** | $-0.06$ | 0.7146*** | 1.000 | | | |
| POP    | 0.0998*** | $-0.2499^{***}$ | $-0.3236^{***}$ | 0.5172*** | $-0.2107^{***}$ | 0.5056*** | 0.4879*** | 1.000 | | |
| REG    | $-0.1308^{**}$ | $-0.1307^{**}$ | 0.5234*** | $-0.2815^{***}$ | 0.0976** | $-0.2387^{***}$ | $-0.2094^{***}$ | $-0.209^{**}$ | 1.000 | |
| Open   | 0.1545*** | $-0.1775^{***}$ | $-0.3624^{***}$ | 0.4357*** | $-0.307^{***}$ | 0.5868*** | 0.6032*** | 0.6999*** | $-0.1722^{**}$ | 1.000 |

*Note: The statistical values at 10%, 5% and 1% levels are indicated by *, ** and *** respectively.

| Table 7 | VIF of each variable |
|---------|----------------------|
| Variable | TES | Energy | PGDP | GOV | ICT | URB | POP | REG | Open | Mean |
| VIF     | 1.36 | 2.33 | 4.46 | 1.55 | 2.93 | 3.69 | 2.41 | 1.41 | 3.13 | 2.59 |
| 1/VIF   | 0.74 | 0.43 | 0.22 | 0.65 | 0.34 | 0.27 | 0.41 | 0.71 | 0.32 | 0.45 |
economy growth, the influence of renewable resource consumption on the advancement of low-carbon economy is obviously opposite, and it reaches the expected effect in the later stage, empirically proving Hypothesis 3 proposed above.

Analysis of spatio-temporal heterogeneity

In terms of different threshold values, we further divide the samples into various intervals. Thus, we are able to observe the number of regions within each threshold. The detailed results are collected in Table 13.

In the first place, as for the threshold variable of renewable consumption (TES), its low-value range contains only five regions at the beginning of the sample period. By 2010, the driving role of renewable energy source utilization in promoting low-carbon economy has been fully evident in that all 30 regions in China had entered the high-level range of renewable consumption. Nevertheless, the consumption standards of the renewables in Inner Mongolia and Shanxi declined significantly and fell back in the low-level transitional range until 2017. In particular, this paper argues that Inner Mongolia and Shanxi are two provinces with obvious fossil energy endowment, and the harmonious situation among economy and ecology in Shanxi province is seriously restricted by its leading industrial chain of coal, coke, and steel, which shows an energy rebound effect in the long-term process of renewable energy consumption; secondly, As far as the intensity of energy consumption is concerned, there are 24 regions reaching the high range in 2000, while only four provinces remain until the year of 2015 and 2016. Notably, Shanxi province crossed back into the zone of high-level intensity in 2017. Similar to the above analysis, this study argues that it mainly roots in the strong dependence on fossil fuels in Shanxi Province. On the whole, the energy consumption intensity in the vast majority of regions in China does not step over the critical value, which manifests that these regions may well get rid of the energy dependence, showing a relatively weak effect of energy path dependence; thirdly, considering the standards of economic advance, it shows half of the regions were in the low-level range at the beginning, while only Guizhou province is left by 2005. It can be seen intuitively that until 2010, all regions in China have entered a new span of economic development levels with no rebound.

Generally, in most provinces in China, the large-scale energy transition measures have reaped good benefits and effectively promoted green growth, but there are still some regions that need to reduce their energy intensity. Hence, under the background of “new normal”, it is absolutely a critical step to realize the transition of energy consumption so as to accelerate the intensive transition of economic advance mode in China.

Robustness test

In order to avoid instability of the empirical model, a robustness test is inevitably performed to examine the certain threshold effect of different research samples. Drawing on the method of robustness test of Qi and Li (2018), we attempt to adjust

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### Table 8 The results of panel unit root test

| Variable | LLC | IPS | ADF-Fisher | Fisher-PP | LLC | IPS | ADF-Fisher | Fisher-PP |
|----------|-----|-----|------------|-----------|-----|-----|------------|-----------|
| LCE      | -2.31*** | -9.15*** | 192.09*** | 225.09*** | -43.08*** | -41.50*** | 494.91*** | 583.24*** |
| TES      | -1.81** | -2.04** | 99.01** | 88.33 | -9.60*** | -9.70*** | 199.16*** | 298.03*** |
| Energy   | -3.80** | -0.82 | 74.96** | 76.42** | -9.50*** | -7.93*** | 167.71*** | 234.87*** |
| PGDP     | -4.69*** | 0.32 | 61.07 | 84.7045** | -7.70*** | -1.89** | 79.79** | 90.21** |
| GOV      | -2.77** | -1.91** | 90.40** | 99.34 | -15.76*** | -14.58*** | 268.48*** | 353.42*** |
| ICT      | 0.10 | -0.58 | 52.92 | 53.23 | -16.36*** | -11.72*** | 221.40*** | 224.86*** |
| URB      | 6.44 | -0.20 | 70.07 | 105.52** | -125.45*** | -33.78*** | 227.54*** | 335.32*** |
| POP      | -4.82*** | 0.73 | 91.35** | 57.60 | -6.30*** | -3.52*** | 118.96** | 124.72*** |
| REG      | -10.04*** | -9.46*** | 182.35*** | 157.35*** | -21.85*** | -19.22*** | 338.58*** | 419.59*** |
| Open     | -4.54*** | -0.87 | 67.69 | 38.44 | -13.88*** | -11.07*** | 215.27*** | 320.70*** |

*Note: The statistical values at 10%, 5%, and 1% levels are indicated by *, **, and *** respectively*
the research samples and test the possible errors of outliers on the results so as to investigate the robustness of the model results shown above. In this paper, the sample areas with the maximum and minimum renewable energy consumption index of around 1%, 5%, and 10% are deleted accordingly, and then three threshold model tests are conducted for 28, 26, and 24 regions in China, respectively. According to Table 14, it is not hard to find that in each model, no significant fluctuations have occurred in the value of the impact coefficient or the level of significance. More specifically, either the threshold effect or threshold value is similar to the above, and there is no apparent fluctuation in the measurement results of the control variables. On this basis, it can be considered that the threshold model constructed in this paper has good robustness.

**Discussion**

In line with the general theory, the change of energy consumption structure will exert influence on many factors to a certain extent, such as enterprise energy cost, economic profit, and environmental benefit (Shen and Li 2020). Many studies have explored the impact of different types of energy use on the green economy, such as fossil energy consumption, clean energy development, and non-fossil energy consumption (Irene and Marco 2019). Yet, in terms of the available literature, there are still some divergences in conclusions concerning the association between energy consumption and the system of economy and society. Arguably, this study provides a new perspective on the basis of regional heterogeneity regulation, obtaining that due to the particularity of different regions, renewable energy consumption affects the development of the low-carbon economy differently.

Firstly, in terms of renewable consumption, it will affect the development of low-carbon economy inordinately in different stages and even cause a complete change in the direction of influence. The reason for this may lie in a wide-ranging and complex energy transition system. In the process of new energy supply and energy use, great capital support is undeniably required, which is highlighted by the renewal of infrastructure and the improvement of technical capacity. Under the pressure of high-cost facilities, technologies and crafts, the government has to invest huge amounts of subsidies in encouraging the consumption of non-fossil energy, which seriously aggravates the financial burden of the government and partly transfers it to downstream enterprises and end consumers, thus generating a large base effect on other government and private sector expenditures and consumption. Therefore, renewable energy consumption presents a certain economic cost in the early stages. With the increasing proportion of non-fossil energy consumption, the scale effect and dry-learning effect of energy transformation are gradually manifested due to the initial cost allocation, the accumulation of technological capital, and the diffusion of cleaner production technology, thus forming a well-functioning 3E system with greater energy efficiency, higher economy quality, and

| Table 10 Statistical analysis of threshold effect |
|-----------------------------------------------|
| Model | Threshold variable | Threshold effect | $F$-value | $P$-value | BS number | The critical value |
|-------|---------------------|------------------|------------|-----------|------------|-------------------|
|       |                     |                  |            |            |            | 0.01    | 0.05    | 0.10    |
| Model (1) | TES | Single threshold | 15.88** | 0.0400 | 300 | 13.7399 | 15.2373 | 20.7347 |
|         |       | Double threshold | 10.35  | 0.1900 | 300 | 13.9775 | 17.6793 | 26.7207 |
| Model (2) | Energy | Single threshold | 16.46** | 0.0300 | 300 | 10.9593 | 12.9263 | 19.5390 |
|         |       | Double threshold | 5.69   | 0.5733 | 300 | 12.2030 | 13.9146 | 19.1169 |
| Model (3) | GDP | Single threshold | 36.14** | 0.0167 | 300 | 21.8923 | 27.1765 | 38.5323 |
|         |       | Double threshold | 3.78   | 0.8300 | 300 | 12.6770 | 14.5299 | 17.6840 |

*Note: The statistical values at 10%, 5%, and 1% levels are indicated by *, **, and *** respectively.*

| Table 11 The results of threshold estimates |
|---------------------------------------------|
| Model | Threshold variable | Test | Threshold estimates | 0.95 confidence interval |
|-------|-------------------|------|---------------------|-------------------------|
| Model (1) | TES | Single threshold value | 0.0093 | 0.0091, 0.0099 |
| Model (2) | Energy | Single threshold value | 1.1766 | 1.1078, 1.1815 |
| Model (3) | GDP | Single threshold value | 0.6366 | 0.6074, 0.6444 |
better ecological environment. Hence, only high renewable energy consumption can effectively promote the low-carbon progress of the economy.

Secondly, in view of the limited moderating effect of energy intensity, it is essential to give full consideration to energy intensity when discussing the correlation between the

### Table 12: The regression results of three thresholds models

| Variable | Model (1) | Model (2) | Model (3) |
|----------|-----------|-----------|-----------|
| GOV      | 0.2712** (2.97) | 0.2436** (2.63) | 0.1012 (1.08) |
| ICT      | 0.2727*** (6.32) | 0.2707*** (6.19) | 0.2394*** (5.58) |
| URB      | 0.15577*** (3.79) | 0.1760*** (4.27) | 0.2061*** (5.10) |
| POP      | -1.47067*** (-4.29) | -1.4983*** (-4.33) | -1.5160*** (-4.51) |
| REG      | 1.2716 (0.47) | 2.3173 (0.83) | 0.9156 (0.35) |
| Open     | 0.05037** (1.98) | 0.0473* (1.84) | 0.0331 (1.32) |
| TESi≤0.0093 | -8.0152*** (-3.85) | 0.10347 (1.88) | 0.1034* (1.88) |
| TESi>0.0093 | 0.10347 (1.88) | 0.10347 (1.88) | 0.10347 (1.88) |
| Energyi≤1.1766 | 0.1233*** (2.21) | 0.1233*** (2.21) | 0.1233*** (2.21) |
| Energyi>1.1766 | 0.1233*** (2.21) | 0.1233*** (2.21) | 0.1233*** (2.21) |
| PGDPi≤0.6366 | 0.10347 (1.88) | 0.10347 (1.88) | 0.10347 (1.88) |
| PGDPi>0.6366 | 0.10347 (1.88) | 0.10347 (1.88) | 0.10347 (1.88) |
| cons     | 0.8805*** (3.60) | 0.8750*** (3.08) | 0.8913*** (4.61) |

**Note**: The statistical values at 10%, 5%, and 1% levels are indicated by *, **, and *** respectively.

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**Fig. 1** The function graphs of the likelihood ratio of threshold values in different models (1), (2), and (3)
consumption of renewables and green development. In regions of high energy consumption intensity, economies can hardly do without fossil energy consumption, which can easily bring about a high degree of dependence and internal inertia of the system. Thereby, in the course of the gradual replacement of fossil fuels by non-fossil fuels, these regions are bound to face formidable obstacles to clean energy technology innovation and renewable energy consumption, which is likely to create a serious divide among regions. The areas with low energy consumption intensity not only rely less on energy consumption, but also have lower economic costs to replace fossil fuels with clean energy, thus showing a greater substitution effect. It follows that when the energy intensity achieves a certain height, the driving effect of the renewable consumption on the development of green economy is relatively limited, which is also an issue that the regional government ought to put particular effort into during the project of the energy transition.

Thirdly, regional economic advancement does play a big part in the effect of renewable energy consumption on green advancement. We conjecture that the reason may be that the high standards of economic growth are often associated with a more reasonable industrial structure and intensive development mode, which is in favor of the evaluation of non-fossil energy. Driven by the awareness of ecological preservation and the demand for green, the input and inflow of factors featured by technology, talent, and knowledge are more smooth in these regions, which makes the innovation of green technology reveal unparalleled advantages. Gradually, more benefits are emerging, including higher levels of cleaner production, lower research and development costs, and greater energy efficiency. Accordingly, it is necessary to coordinate the transition to clean energy and the advancement of the economy.

Conclusions and suggestions

Considering the effects including the energy substitution effect, path dependence effect and technology base effect, this study explores the complicated role of renewable consumption in the provincial low-carbon economic development in China. Using China’s inter-provincial panel data and setting the research period as 2000 to 2017, this paper empirically probes into the nonlinear correlation between the two core variables respectively moderated by the indicator of renewable energy utilization, energy consumption intensity and economic development level. As a result, all the three hypotheses put forward in the study have been empirically confirmed, and we obtained that there is a significant threshold between renewable energy consumption and low-carbon economic development, which is subjected to nonlinear shocks by factors such as renewable energy consumption, energy intensity and GDP. The specific conclusions are as follows: (1) in the path of realizing the transformation of energy structure, the

Table 14 The results of robustness tests

| Variable | Model 1 | Model (2) | Model (3) |
|----------|---------|-----------|-----------|
| GOV      | 0.305*** (2.63) | 0.2157* (1.79) | 0.2094 (1.77) |
| ICT      | 0.2032*** (4.49) | 0.2172*** (4.78) | 0.2040*** (4.52) |
| URB      | 0.2144*** (4.38) | 0.2395*** (4.88) | 0.2145*** (4.39) |
| POP      | -1.6529*** (-4.66) | -1.6990*** (-4.76) | -1.5505*** (-4.35) |
| REG      | 1.5075 (0.50) | 2.4653 (0.81) | 0.0152 (0.34) |
| Open     | 0.0339 (1.33) | 0.0318* (1.23) | 0.0297 (1.16) |
| TESi≤0.0102 | -8.175*** (-4.00) | 0.1142* (1.92) |
| TESi>0.0102 |                      |                      |
| Energyi≤1.6967 | 0.1115* (1.86) | 0.1158 (1.96) | -0.1591 (-1.46) |
| Energyi>1.6967 |                  |                      |
| PGDPi≤0.6366 | 0.8720*** (3.05) | 0.8727*** (9.39) | 0.8808*** (9.80) |
| PGDPi>0.6366 | 0.8720*** (3.05) | 0.8727*** (9.39) | 0.8808*** (9.80) |

Note: The statistical values at 10%, 5%, and 1% levels are indicated by *, **, and *** respectively.
negative externalities resulting from fossil energy use force economies into an unsustainable state. However, with the gradual replacement of fossil energy by renewable energy, it gradually appears more positive externalities of energy consumption, showing the more favorable influence on the progress of green economy; (2) the long-term extensive economic growth mode in China has resulted in the lock-in effect of fossil energy use, especially in the mid-west areas, forming a developmental pattern of quantity growth rather than quality growth. More often than not, in areas with low energy dependence, renewable energy consumption is more effective in promoting low-carbon economic growth; (3) the imbalance of China’s regional economic development level gives rise to regional economic heterogeneity, which makes the basic conditions of renewable energy consumption differ in varying degrees, and thus has the opposite effect on the social low-carbon and green development. As can be seen from the empirical research results, for regions with better economic conditions, the driving impact of renewable consumption on the low-carbon economy is more apparent.

In consideration of the above findings, this paper believes that efforts can be made from the following three aspects to push the utilization of renewable energy sources and boost the evaluation of China’s low-carbon economy.

Firstly, for regions where traditional polluting energy consumption still occupies a large proportion, the development of non-fossil energy may cause certain economic losses due to high economic costs. In such regions, the government ought to accelerate the energy transition through appropriate policy interventions and perfect supporting mechanisms so as to enhance the potential of economic growth. For instance, the government can subsidize the production of non-fossil energy such as photovoltaic and wind power. Meantime a corresponding mechanism should be established to restrain the producer. Unlike fossil fuels, renewable energy needs to be turned into electricity before it can be utilized by both the producing and consuming sectors. Yet, on account of the cost disadvantage of the renewables, it is more necessary to subsidize producers such as photovoltaic and wind power. However, under the background of imperfect system and management, subsidy policies are prone to breed “subsidy” behavior; that is, some producers will take advantage of policy loopholes to steal state subsidies. Therefore, the government needs to continuously improve relevant systems and management to give full play to the due effectiveness of subsidy policies.

Secondly, for regions with high energy consumption intensity, efforts should be made to break the path dependence on energy consumption, improve the technical quality of exploration and application of non-fossil energy resources, and strengthen the infrastructure and institutional construction of non-fossil energy transportation and Internet, so as to promote the transformation of economic development model and enhance the potential of low-carbon economic development. Driven by the rapid development of industry and the gradual expansion of cities, people have higher requirements for high-energy products such as steel and cement, which in turn has advanced the development of energy-intensive enterprises. Accordingly, policies such as China’s 14th Five-Year Plan for Energy and Smart transformation to low-carbon energy all stressed the elimination of outdated production facilities and supported the development of strategic emerging industries. In order to get rid of regional energy dependence and break the locking effect of fossil fuels on economic growth, the government is obliged to focus on promoting the transformation and improvement of industries to foster intensive economic progress. For one thing, instead of the blind expansion of high-energy industries, the government should raise the access standards for high-input and low-output industries, and transform and upgrade high-carbon industries. For another, some financial means, such as tax relief and financial credit, can be adopted to stimulate the development of intelligent manufacturing and high-tech industries, thus accelerating the internal resource restructuring and structural upgrading of the industry.

Thirdly, proceeding from the reality of unbalanced regional development, the government has to adhere to the principle of implementing energy policies with clear boundaries and formulates renewable energy consumption strategies by category based on the actual economic conditions of different regions. Particularly in the regions with low-income economies, the progress of clean fuels is faced with greater institutional obstacles and practical difficulties. In regions with such characteristics, the government should further reinforce the intensity of both subsidies and support, and enhance the confidence of enterprises to drive the energy transition strategy, thereby stimulating a moderate transition of the energy structure.

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Data availability All data can be downloaded from China’s National Bureau of Statistics.

Declarations

Ethics approval and consent for participate Not applicable
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