Has Green Finance Facilitated China's Low-Carbon Economic Transition?

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top of the world. Excessive carbon emissions caused by economic development have led to climate warming, making climate-sensitive countries like China suffer greatly from this change. In 2003, the British government published the white paper "Future Energy - Creating a Low Carbon Economy", in which the concept of "low carbon economy" was first introduced. The concept of "low carbon economy" was first introduced in the UK government's White Paper "Energy for the Future - Creating a Low Carbon Economy" in 2003, emphasizing the need to achieve greater economic output by reducing natural resource consumption and greenhouse gas emissions (DTI, 2003). The low carbon economy has become the fifth revolutionary wave that changes the world economy after the two industrial revolutions, the information revolution, and the biotechnology revolution. The development approach of low carbon economy will transform the industrial civilization based on fossil fuels in all aspects and shift the social development to ecological economic civilization. This is a challenge but also an opportunity for China, which will strongly transform China from a high-carbon economy to a low-carbon economy. In the report of the 19th Party Congress, it is clearly proposed that accelerating the construction of ecological civilization is an important task in the new era, and that by promoting the construction of beautiful China to improve the laws and regulations of green production and consumption, in order to facilitate the realization of the country's general policy and thus promote the development of China's green low-carbon recycling economy. And in September 2020, China clearly put forward the "double carbon" goal of "carbon peak" by 2030 and "carbon neutral" by 2060. The support and driving force behind the development of modern market economy is the development of modern finance. Finance is to economic operation as blood is to human blood circulation, and the financial industry, which is regarded as the "lubricant" and "engine" of modern economic and social development, plays a great role in adjusting economic structure, promoting independent innovation, saving energy and resources, and protecting ecological environment (Levine, 2004). The financial industry plays a huge role in adjusting economic structure, promoting independent innovation, saving energy and resources, and protecting ecological environment (Levine, 2004). As an important innovation in the financial field at the turn of the century, green finance is a product of the integration of traditional finance and modern environmental awareness in the context of sustainable development. Although the process of transforming traditional finance into green finance will encounter some difficulties and challenges, it plays an important role in coordinating economic development with environmental protection and maintaining the long-term stable development of human society. The transformation of traditional high-carbon economy to low-carbon economy and the change of economic development mode urgently requires the transformation and

development of traditional finance to green finance.

Therefore, this paper takes a sample of 30 Chinese provinces from 2001-2019 (the sample data of Tibet Autonomous Region of China, Hong Kong Special Administrative Region, Macao Special Administrative Region and Taiwan are not covered in this study for the time being because of missing samples) to comprehensively examine the impact of green finance on the development of low-carbon economy and further analyze the mediating role played by low-carbon technological innovation between the two. The possible innovations of this paper are: (1) the promotion role of green finance on the transformation of the low-carbon economy is explored separately from China as a whole and locally, providing some reference for the development of each region in China. (2) The mediating effect test finds that low-carbon technology innovation plays a certain boosting role in the process of green finance promoting the transformation of low-carbon economy. (3) Based on the traditional regression, further analysis is done by spatial relationship test, and it is found that there is a strong spatial dependence between green finance development and low-carbon economic transformation in 30 Chinese provinces, but this dependence starts to decline after 2011.

II. Literature Review and Research Hypothesis

At present, most international scholars have focused their attention on the qualitative analysis of the concept, connotation, and operation mechanism of green finance. Salazar (1998), who has not defined the meaning and concept of green finance globally, argues that green finance is a financial innovation that emerged from the context of environmental protection and is an intermediate bridge between the financial industry and the environmental protection industry. Scholtens (2006) focuses on the interplay between green finance and sustainable development, finding that green finance facilitates economic operations by providing capital and is a driver of corporate social responsibility. Since the development of green finance is relatively late and the information disclosed varies from country to country, there is no unified standard to measure the development level of green finance internationally. The current academic research on the development level of green finance is mainly conducted by Marcel (2001) and Street (2001) from the micro level, focusing their research perspective on the green operation and management level of financial institutions, which is mainly divided into four target layers, such as internal management, business operation, information disclosure and green operation. This approach can better evaluate aspects such as the operation and service level of financial institutions.

At present, domestic and foreign research on low carbon economy mainly

focuses on the connotation and concept, relevant countermeasures and development level estimation. The concept of low carbon economy was first introduced in the energy white paper entitled "Future Energy - Creating a Low Carbon Economy" published by the British government in 2003, which emphasized the need to obtain greater economic benefits with less energy consumption and pollution (DTI , 2003). Claessens et al. (2007) argue that there is a broad and narrow sense of low-carbon economy, and that the narrow sense of low-carbon economy refers to the transfer of risk to achieve the purpose of environmental protection. The broad sense of low carbon economy, on the other hand, is expanded to refer to all market-based instruments that address environmental and climate issues.

Greenwood et al. (1990) argue that there is a mutual influence between finance and economic growth, and that financial development can increase the rate of return on capital and thus promote economic growth, which in turn can Economic growth can in turn promote the development of finance in a more complex and diversified direction, and can also promote the transition to a low-carbon economy. Claessens et al. (2007) found that some irregular activities of enterprises are constrained to some extent by financial institutions, and a well-developed financial system can promote the development of low-carbon technologies and industries. Wara (2007) discusses the significance of green financial development for the transformation of low-carbon economy, and argues that the prosperous development of green financial market can boost the development of low-carbon economy and improve the sustainability of the whole society. Jeucken (2010) analyzed the relationship between banking and sustainable development through the lens of the most fundamental environmental issues and banking, and the findings suggest that the financial sector plays a crucial role in this process of changing traditional concepts to those of sustainable development. Ozturk et al. (2013) discussed carbon emissions, financial development, financial development, energy consumption, and economic growth in the context of Turkey. relationship between trade status, energy consumption and economic growth. It was found that financial development can promote economic growth and reduce energy consumption in the short term; however, in the long term effect, financial development hardly contributes to the reduction of carbon emissions per capita.

The functionalist theory of finance holds that the channels through which finance acts on economic growth are capital allocation and technological progress. Therefore, finance has an important role in the transformation of economic growth, and green finance, as an important innovation in the field of finance, has an irreplaceable role in the transformation of the economic model. First, the resource allocation function, financial institutions involved in the field of environmental protection, in the loan application process to join the environmental protection standards, through a strong

information identification mechanism, filter out the traditional "two high" projects, to support the new energy industry; and through a strong incentive reward and punishment mechanism, to reward energy-saving loans, track down the collection of environmentally polluting loans. In addition, we will guide the flow of social capital to green industries, improve the industrial structure, and promote the transformation of the economy from a high-carbon economy to a low-carbon economy. The second is to cultivate new dynamic energy. A very important piece of the low-carbon economy is the development of new energy and clean technology, an industry characterized by intensive human capital and fewer fixed assets. Green finance through venture capital funds and other forms, looking at the market prospects and high growth of the industry, in the initial stage of vigorous incubation and cultivation, with technology maturity listed after the cultivation of independent innovation capacity of environmental technology, the formation of sustained economic growth of the intrinsic power. Third, to guide socio-economic behavior. Green finance does not only stay in the field of corporate business, but also can be extended to the field of personal finance, developing financial products related to low carbon economy, such as green car credit and green mortgage, guiding and cultivating people's low carbon consumption concept and establishing a sustainable green economy. Therefore, this paper proposes the following research hypothesis.

H1: Green finance can facilitate China's low-carbon economic transition.

In the process of green finance promoting China's low-carbon economic transformation, there are many factors playing a boosting role, among which low-carbon technology innovation is an important factor. The development of green finance can promote low-carbon technology innovation through the technology spillover from foreign direct investment, the effective allocation of financial resources, and financial capital to support the accumulation of human capital. Mainly through the following aspects to influence low-carbon technology innovation: First, green finance through the technology spillover of foreign direct investment to promote the development of low-carbon technology. The technology spillover of FDI for the invested country is mainly through the positive impact of the technology demonstration effect of foreign enterprises, the competition effect and the exchange of employees from both sides. The full development of green finance in a country will attract financing from other countries, and external financing can better play the role of technology spillover and promote the innovation and progress of national technology. Second, green finance promotes innovation in low-carbon technology through the optimal allocation of resources. The resource allocation function of green finance can make social funds reasonably allocated in various industries. And scientific research cannot be done without the support of funds, and a large amount of

funds and national policies are needed to support the successful development of technology and its successful application to actual production and life. The development of low carbon economy is the main trend of future economic development in China and the world. The resource allocation function of green finance will effectively flow the human, material and financial resources of the society to this forward-looking industry, so that the scientific research of low-carbon technology can be carried out more smoothly. Third, green finance promotes the innovation of low-carbon technology through talent attraction. Human capital is one of the more special resources among all. The richer a country's human capital is, the better its technological innovation and transformation capabilities will be. The effective allocation of resources is one of the main functions of green finance, and human capital as one of the resources, green finance can also have a positive impact on its allocation. The investment of capital is a strong support for human capital accumulation. Education is the basis of human capital formation, and the investment cycle of education is relatively long, and this process needs a large amount of financial support. Green finance can take advantage of its own advantages to guide the flow of social resources to the training field about low-carbon technology, cultivate high-tech talents in this area, and then promote the innovation of low-carbon technology. To sum up, green finance can effectively promote the development and innovation of low-carbon technologies.

In the initial production process the goal of each company is to minimize production costs and thus increase profits (Chen and Shen, 2012). However, in recent years, as environmental problems have become more and more prominent, governments and companies have slowly started to pay attention to research related to environmental issues, and in order to reduce the negative impact of production pollution on the environment, some companies in developed countries such as the United States and the European Union have gradually invented and used some new technologies and production methods (Chen and Hao, 2015). One of the earliest policies to control carbon emissions is the cap-and-trade policy (Keohane, 2009). The cap-and-trade policy is to reduce the damage to the environment by providing incentives to companies that can achieve a reduction in carbon emissions. Such a policy can be effective in controlling pollution levels. However, it is managed through an external coercive means. In recent years, there has been a growing sense of environmental responsibility among some manufacturing companies, and in such a carbon-constrained market, companies should grow to meet both economic and carbon goals, i.e., increasing profits and reducing environmental damage. Therefore, companies are beginning to shift their attention to developing green technologies to produce. Among them, innovation of low carbon technology is a means to achieve

low carbon economic transformation. Achieving low-carbon technology innovation is the key to promoting the transformation and upgrading of manufacturing industries, and is also an important factor for companies to occupy a certain dominant position in an increasingly competitive market. The role of low-carbon technology innovation on the transformation of low-carbon economy mainly includes the following ways: first, the innovation of technology can reset the technological track of enterprises and stimulate a series of related fields of innovation behind, forming a combination of new technologies and production processes, reducing the carbon emissions of enterprises and promoting the development of low-carbon economy (Lpez and Montalvo ,2015). For example, the manufacturing of new energy vehicles in the automotive industry has revolutionized the dependence of cars on fossil fuels, thus reducing carbon dioxide emissions (Cunico et al, 2017). Secondly, it has reduced the cost of carbon emissions. Developed countries and most developing countries pursued economic and industrial development in the past at the cost of excessive consumption of resources and environmental pollution in the future, but the resulting environmental problems are becoming more and more prominent, so there is a need to reduce carbon dioxide emissions through low-carbon technology innovation, which in turn reduces the costs paid by companies for carbon emissions. For example, technological improvements in manufacturing photovoltaic equipment have greatly reduced the cost of photovoltaic manufacturing worldwide, which to some extent allows manufacturing industries to reduce the use of traditional fossil fuels and promote the development of a low-carbon economy. This paper therefore proposes the following research hypothesis.

H2: Innovation in low-carbon technologies has a mediating role in the transition between green finance and low-carbon economies.

III. Empirical model and data

(i) Empirical model setting

1 Benchmark model

To test the above research hypothesis, the following benchmark regression model is set in this paper.

$$LCTFP_{it} = \alpha_0 + \alpha_1 GREEN_{it} + \alpha_2 FDI_{it} + \alpha_3 IN_{it} + \alpha_4 RGDP_{it} + \alpha_5 UI_{it} + year_t + city_i + \varepsilon_{it} \quad (1)$$

where $LCTFP_{it}$ is the low carbon economic transition index of province i in year t. $GREEN_{it}$ is the green financial development index of province i in year t. FDI_{it} is the ratio of the net fixed assets of the three capital enterprises to the regional GDP in province i in year t. IN_{it} represents the level of regional industrialization, and

is the ratio of industrial value added to regional GDP in province i in year t . $RGDP_{it}$ Representing the level of regional economic development, expressed by using the logarithm of GDP per capita of each province and city. UI_{it} represents the level of regional urbanization, expressed using the ratio of urban population to the total regional population in each province and city. In addition, the model controls for year effects and province effects, and ε_{it} denotes the random disturbance term.

2 Mediated effects model

In the previous analysis, it is mentioned that green financial development helps to enhance China's low-carbon technology innovation, which in turn promotes the successful transformation of the regional low-carbon economy. In order to test the hypothesis proposed in the previous section, this paper conducts a mediating effect analysis on green financial development to promote regional carbon technology innovation, and then promote the transformation and upgrading of China's low-carbon economy. Therefore, the following mediating effect model is established.

$$LCTFP_{it} = \alpha_0 + \alpha_1 GREEN_{it} + \alpha_2 FDI_{it} + \alpha_3 IN_{it} + \alpha_4 RGDP_{it} + \alpha_5 UI_{it} + year_t + city_i + \varepsilon_{it} \quad (2)$$

$$LCI_{it} = \beta_0 + \beta_1 GREEN_{it} + \beta_2 FDI_{it} + \beta_3 IN_{it} + \beta_4 RGDP_{it} + \beta_5 UI_{it} + year_t + city_i + \varepsilon_{it} \quad (3)$$

$$LCTFP_{it} = \gamma_0 + \gamma_1 GREEN_{it} + \gamma_2 LCI_{it} + \gamma_3 FDI_{it} + \gamma_4 IN_{it} + \gamma_5 RGDP_{it} + \gamma_6 UI_{it} + year_t + city_i + \varepsilon_{it} \quad (4)$$

Among them, equation (2) is the benchmark regression model, and its variable explanations are exactly the same as those in the benchmark regression, which will not be repeated here. The explanatory variable in equation (3) LCI_{it} is the low-carbon technology innovation in each province, and equation (4) is added to equation (2). LCI_{it} . This paper adopts the stepwise regression method of mediating effect test, whose general steps are: if the equation (2) in α_1 is not significant, it indicates that the causal relationship between green finance and low-carbon economic transformation is not significant, and randomly stop the intermediary effect test, if it is α_1 significant, the regression equation of equation (3) is continued to test whether green finance affects low carbon technology innovation in the province. If β_1 is not significant, it indicates that the causal relationship between green finance and regional low carbon technology innovation is weak, terminate the mediating effect test, and if it is significant, continue with equation (4) to test whether the mediating effect of low carbon technology innovation exists.

(ii) Sample selection and index selection

1 Sample selection

To study the impact of green finance on China's low-carbon economic

transformation, this paper uses data from 30 provinces and autonomous regions of China (sample data from Tibet Autonomous Region of China, Hong Kong Special Administrative Region, Macau Special Administrative Region and Taiwan are not covered in this study for the time being because of missing samples) from 2001-2019 as samples for empirical research. The data are mainly obtained from the China Statistical Yearbook, China Energy Statistical Yearbook, China Industrial Statistical Yearbook, and China Environmental Statistical Yearbook in previous years.

2 Indicator selection

(1) Core variables

Low carbon economic transition (LCTFP): most of the existing literature uses low carbon total factor productivity as a measure of low carbon economic transition, but the index is not transferable and the linear programming may be unsolvable when calculating the intertemporal directional distance function, while the Global Malmquist-Luenberger (GML) index can overcome the above-mentioned shortcomings. Therefore, this paper uses the Global Malmquist-Luenberger index, which takes into account the directional distance function of the undesired output SBM, to measure low-carbon total factor productivity as a proxy for low-carbon economic transformation, following the approach of Qin et al. In this paper, the low-carbon total factor productivity is measured by Maxdea software, in which: the desired output indicator is regional GDP (billion yuan), the undesired output indicator is CO₂ emissions (million tons), and the input indicators are capital stock (billion yuan), employment (10,000 people), and total energy consumption (million tons of standard coal). The capital stock is accounted for using the perpetual inventory method of Haojie Shan, and is deflated using the fixed asset price index with 2001 as the base period to measure the capital stock (billion yuan) in constant prices in each province. CO₂ emissions are obtained by discounting the end-use energy consumption of each province. Maxdea's measured low-carbon total factor productivity is a relative value, and this paper converts the relative low-carbon total factor productivity into absolute low-carbon total factor productivity by multiplying the base period of 2001. In order to reduce the heteroskedasticity, this paper takes the logarithm of it.

Green finance (GREEN): summarizing the existing literature, we can find that the current construction of green finance evaluation system in China is mainly based on micro and macro perspectives. The evaluation of green finance based on macro perspective is mainly based on the overall situation, considering the development of green finance at national or regional level, and selecting 7 indicators in 4 dimensions of green credit, green securities, green insurance and green investment to build a comprehensive evaluation system of green finance.1. Green credit indicators. The

measurement of green credit indicators in China's academic circles mainly includes the percentage of green credit of the five major commercial banks, the percentage of loans for energy-saving and environmental protection projects in the China Banking Social Responsibility Report and the percentage of interest expenses of the six major high energy-consuming industries. This system measures the development of green credit in China by using the ratio of interest expenditure of the six major energy-consuming industries to the total interest expenditure of industrial industries in each province as the inverse indicator of green credit. Green credit indicators 2001-2019 related data are mainly from the China Industrial Statistical Yearbook and the statistical yearbooks of each region.

2. Green securities. The market value ratio of energy-saving and environmental protection enterprises and the market value ratio of six high-energy-consuming industries are selected as the characterization. The division of energy-saving and environmental protection enterprises is based on the division of the concept of energy-saving and environmental protection belonging to the Flush website. The six high-energy-consuming industries specifically include the non-ferrous metal smelting and rolling processing industry, petroleum processing and coking and nuclear fuel processing industry, chemical raw materials and chemical products manufacturing industry, ferrous metal smelting and rolling processing industry, non-metallic mineral products industry, electricity and heat production and supply industry, and other six major categories. The data of market value of energy-saving and environmental protection enterprises, market value of the six energy-consuming industries and total market value of A-shares (2001-2019) are obtained from the Guotaian CSMAR database.

3. Green insurance. The indicators of environmental liability insurance scale and environmental liability insurance payout rate are selected to reflect the development of green insurance in China. Based on the fact that the institutional framework of environmental pollution liability insurance was formally established in China only in 2007, the development of green insurance is at its initial stage and the relevant data are not perfect. Therefore, the scale of agricultural insurance and the payout rate of agricultural insurance are used instead of the scale of environmental liability insurance and the payout rate of environmental liability insurance indicators. The data of green insurance (2001-2019) are all from China Insurance Yearbook.

4. Green investment. Green investment indicators are selected from two indicators: the proportion of public expenditure on energy conservation and environmental protection, and the proportion of investment in the treatment of environmental pollution. Among them, the data of fiscal expenditure on energy conservation and environmental protection and total fiscal expenditure (2001-2019) are from wind database, and the data of investment in pollution control as a proportion of GDP (2001-2019) are from China Environmental Statistical

Yearbook.

Low Carbon Technology Innovation (LCI): Due to the objectivity and stability of the patent granting criteria, the number of patents can reflect the level of innovation very well. Class Y02 in the cooperative patent classification jointly issued by the European Patent Office and the United States Patent Office is defined as green technologies or applications that mitigate or adapt to climate change. In this paper, based on the approach of Chen et al. (2015), patents with classification numbers Y02B, Y02C, Y02D, Y02E, Y02P, Y02T and Y02W are regarded as low-carbon innovation patents, and the number of their grants is used as a measure of low-carbon technology innovation indicators in each province. In order to reduce the heteroskedasticity, this paper takes logarithms for them.

(2) Control variables

According to the existing literature, it is found that foreign direct investment (FDI), industrialization level, economic development level and urbanization level may have some influence on low carbon economic transformation, so these indicators are selected as control variables in this paper. Foreign direct investment (FDI): the ratio of net fixed assets to regional GDP of the three enterprises in each province and city; Industrialization level (IN): the ratio of industrial value added to regional GDP in each province and city; Economic development level (RGDP): the logarithm of per capita GDP in each province and city; Urbanization level (UI): the ratio of urban population to total regional population in each province and city. Descriptive statistics of the main variables are shown in Table 1.

Table 1 Descriptive statistics values of main variables

Variable	Average value	Standard deviation	Minimum value	Maximum value	Observed values
LCTFP	0.276	0.117	0.104	0.598	570
GREEN	0.141	0.093	0.042	0.793	570
LCI	6.799	1.468	2.392	9.653	570
FDI	0.022	0.017	0.004	0.081	570
IN	0.379	0.087	0.111	0.592	570
RGDP	10.189	0.829	7.971	12.009	570
UI	0.522	0.151	0.234	0.907	570

IV. Empirical Analysis

(i) Baseline regression

A preliminary examination of the intrinsic relationship between green finance and low-carbon economic transition is first conducted. In terms of research methodology, this paper uses OLS as the benchmark regression and further employs a

two-way fixed effects (FE) model with fixed time and area effects to test the theoretical hypothesis. Table 2 presents the contents of the benchmark regression results. In order to investigate the impact of green finance on low-carbon economic transformation under different conditions, this paper presents the regression results with and without the inclusion of control variables in the benchmark regressions. The OLS regression results are presented in (1)-(2). Column (1) shows that the impact of green finance on low-carbon economic transformation is significantly positive when no control variables are included, which initially proves the research hypothesis. With the inclusion of control variables, the effect of green finance on low carbon economic transformation remains significantly positive. Columns (3)-(4) show that the impact of green finance on low-carbon economic transformation remains significantly positive after applying the fixed-effects model and further controlling for time and area effects.

Table 2 Baseline regression results

Variable	(1) OLS	(2) OLS	(3) FE	(4) FE
GREEN	0.387*** (7.66)	0.681*** (10.60)	0.527*** (8.97)	0.416*** (6.49)
FDI		0.028*** (9.36)		0.040*** (13.44)
UI		-0.002*** (-4.28)		-0.002*** (-5.69)
IN		0.647*** (12.43)		0.500*** (8.81)
RGDP		-0.078*** (-7.11)		(0.02) (-1.38)
_cons	0.221*** (26.03)	0.463*** (5.11)	0.234*** (11.17)	(0.03) (-0.28)
Time fixed effects	NO	NO	YES	YES
Regional fixed effects	NO	NO	YES	YES
N	570	570	570	570
R ²	0.09	0.46	0.13	0.57
F	58.70	82.84	4.24	30.17

Note: Standard errors in parentheses, *, **, *** indicate significant at the 10%, 5%, and 1% levels, respectively

(ii) Analysis of mediating effects

Table 3 reports the regression results of the mediating effect played by low-carbon technology innovation in the transition between green finance and

low-carbon economy. Column (1) shows the regression results of the benchmark test using two-way fixed effects, and column (2) shows the regression results of the green finance index (GREEN) on low-carbon technology innovation (LCI), from which it can be seen that the development of green finance can promote the level of low-carbon technology innovation. Column (3) further adds low carbon technology innovation to column (1), and after the inclusion of mediating variables, the regression coefficient of green finance on low carbon economic transformation remains significantly positive, but the significance decreases. Meanwhile, the coefficient of low carbon technology innovation is significantly positive, indicating that low carbon technology innovation plays a part of the mediating effect and the research hypothesis is verified.

Table 3 Mediating effect test

Variable	(1) LCTFP	(2) LCI	(3) LCTFP
GREEN	0.416*** (6.49)	0.408*** (6.40)	0.019** (2.14)
LCI			0.972*** (82.68)
FDI	0.040*** (13.44)	0.040*** (13.63)	0.004 (0.88)
UI	-0.002*** (-5.69)	-0.003*** (-6.04)	0.0002 (0.57)
IN	0.500*** (8.81)	0.563*** (9.99)	-0.048*** (-2.99)
RGDP	(0.02) (-1.38)	(0.01) (-0.83)	-0.007** (-2.26)
_cons	(0.03) (-0.28)	(0.12) (-1.18)	0.085*** (3.35)
Time fixed effects	YES	YES	YES
Regional fixed effects	YES	YES	YES
N	570	570	570
R ²	0.569	0.599	0.972
F	30.168	34.033	750.395

Note: Standard errors in parentheses, *, **, *** indicate significant at the 10%, 5%, and 1% levels, respectively

(iii) Endogeneity test

In general, regions with a higher degree of green finance development have

higher economic growth rates and a higher degree of low carbon economic transition. Therefore, there is inevitably a degree of endogenous correlation problem between green finance development and low-carbon economic transformation, and ignoring this endogeneity may lead to obtaining biased estimation results. Therefore, this paper uses the instrumental variables approach to overcome this difficulty. The lagged one-period of the green financial development index is used as the instrumental variable (GREEN_IV). The 2SLS method is used for estimation in the IV regression, and the estimation results are shown in Table 4. The positive correlation between the instrumental variables and the green financial development index in the first stage and passed the significance test at the 1% level, while the F-value is greater than 10, which also proves that there is no weak instrumental variable, and the whole regression results passed the Sargan test. The regression results of the second stage show that the relationship between green finance and China's low-carbon economic transformation remains significantly positive, which is consistent with the baseline regression results of this paper and further proves the robustness of the above judgment on the causal relationship between green finance development and low-carbon economic transformation.

Table 4 Regression results of instrumental variables

Variable	Phase I GREEN	Phase II lctfp
GREEN_IV	1.058*** (17.57)	
GREEN		0.385*** 5.68
FDI	0.0003639* 1.40 (0.12)	0.039*** 12.81 (0.00)
UI	(0.32)	(-5.22)
IN	(0.01) (2.38)	0.499*** 8.66
RGDP	0.0024*** 2.33 (0.01)	(0.15) 1.19 (0.04)
_cons	0.45	(-0.44)
Time fixed effects	YES	YES
Regional fixed effects	YES	YES

Note: Standard errors in parentheses, *, **, *** indicate significant at the 10%, 5%, and 1% levels, respectively

452 (iv) Robustness test

453 In this paper, the robustness of the baseline regression results is tested by the
454 following two ways, and the regression results are shown in Table 5.

455 1. replace the explanatory variables. Referring to Li and Yu (2013), the energy
456 economy TFP, i.e., using the results without considering the non-desired output
457 carbon emissions, based on the traditional ML index measure, is used as a proxy
458 variable for the low-carbon economic transition. The regression results are shown in
459 Table 5 (1)-(2). (1) is the OLS regression result with the inclusion of control variables,
460 and (2) is a two-way fixed-effects model with the inclusion of control variables and
461 controlling for time and area effects. From the regression results, it can be seen that
462 the regression results of green financial development on low carbon economic
463 transformation remain significantly positive after replacing the explanatory variables.

464 2 Excluding super tier 1 provinces. In order to exclude the effect of extreme
465 samples, the North, Shanghai and Guangzhou regions are excluded from the overall
466 sample. The regression results are shown in columns (3)-(4) of Table 5. From the
467 regression results, we can see that green finance still significantly contributes to
468 China's low-carbon economic transformation after excluding super tier 1 provinces,
469 and the baseline regression results are more robust.

Table 5 Robustness tests

Variable	(1) LCTFP_S	(2) LCTFP_S	(3) LCTFP	(4) LCTFP
GREEN	2.679*** (5.05)	0.924* (1.70)	0.999*** (7.49)	0.586*** (4.48)
FDI	0.188*** (7.66)	0.267*** (10.76)	0.024*** (7.86)	0.035*** (11.51)
UI	-0.010*** (-2.80)	-0.013*** (-3.75)	-0.003*** (-4.83)	-0.003*** (-6.48)
IN	3.759*** (9.11)	2.633*** (5.68)	0.552*** (10.47)	0.305*** (4.48)
RGDP	-0.426*** (-4.81)	(0.03) (-0.25)	-0.087*** (-6.79)	0.00 (0.02)
_cons	2.779*** (3.85)	(0.43) (-0.53)	0.587*** (5.71)	(0.09) (-0.77)
Time fixed effects	NO	YES	NO	YES
Regional fixed effects	NO	YES	NO	YES
N	570	570	513	513
R ²	0.309	0.414	0.413	0.529

	F	41.224	14.993	57.739	21.091
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Note: Standard errors in parentheses, *, **, *** indicate significant at the 10%, 5%, and 1% levels, respectively

(v) Further discussion

1. Split time to examine

In 2010, the first annual meeting of Low Carbon China Forum was held in Beijing, with the purpose of "developing low carbon economy and sharing low carbon China", and focused on promoting the construction of low carbon cities, low carbon industry development and exchange and cooperation at home and abroad, and published the "2011-2020 China Low Carbon Economy Development Plan", and advocated the establishment of May 20 as the global "Low Carbon Day". It also advocated the establishment of May 20 as the global "Low Carbon Day". In addition, the China Low Carbon Economy Forum, Boao Forum for Asia and the International Forum on Low Carbon Development were also held in the same year to discuss how to build low carbon cities and advocate low carbon living. Therefore, Zhang (2010) regarded 2010 as the first year of low carbon economy in China.

Therefore, this paper takes 2010 as the time cut-off point and analyzes the impact of green finance development on China's low-carbon economic transition according to different time periods, and the estimated results are shown in Table 6. It can be seen that before 2010, the impact of green finance on low-carbon economic transformation is significantly positive, but the regression coefficient is only 0.178, while after 10 years, the impact of green finance on low-carbon economic transformation is significantly higher, reaching 0.874. The possible explanation is that after the first year of low-carbon transformation, due to the high attention of local governments, human and financial resources are invested in the low-carbon economic transformation in China. The green economy transition process in China has been accelerated due to the high priority of local governments, which also includes a large amount of financial resources.

Table 6 Examination by time period

Variable	(1)	(2)
	2001-2010	2011-2019
GREEN	0.178** (2.10)	0.874*** (4.58)
FDJ	0.058*** (10.93)	0.038*** (7.97)
UI	-0.003*** (-5.42)	-0.016*** (-4.06)

IN	0.355***	0.591***
	(3.90)	(6.30)
RGDP	(0.00)	-0.040**
	(-0.16)	(-2.06)
_cons	-0.479**	0.13
	(-2.28)	(0.86)
Time fixed effects	YES	YES
Regional fixed effects	YES	YES
N	300	270
R ²	0.586	0.584
F	24.889	23.776

Note: Standard errors in parentheses, *, **, *** indicate significant at the 10%, 5%, and 1% levels, respectively

2. Regional heterogeneity examination

According to the traditional regional division, China's provinces are divided into the eastern region, central region, western region and northeast region. Since the northeast region of China is a traditional old industrial base, the pressure and motivation for low-carbon economic transformation is greater, so it is especially necessary to study the low-carbon economic transformation in the northeast region. The regression results of green finance and low-carbon economic transformation by region are shown in Table 7. From the regression results, it can be seen that there is regional heterogeneity in the impact of green finance on low-carbon economic transformation. Specifically, the impact of green finance development on low-carbon economic transformation is more significant in the eastern, central and northeastern regions of China, while it is not significant in the western region, probably because of the lower degree of green finance development in the western region, which plays a weaker role in low-carbon economic transformation. From the numerical point of view, the impact of green finance development on low-carbon economic transformation is most significant in the northeast region, so we believe that we should vigorously develop green finance in the northeast region to promote low-carbon economic transformation in the northeast region.

Table 7 Regression results of regional heterogeneity

Variable	(1)	(2)	(3)	(4)
	Eastern Region	Central Region	Western Region	Northeast Region
GREEN	0.484*** (5.12)	0.641** (2.00)	0.20 (1.25)	2.149** (2.58)
FDI	0.078*** (11.03)	0.008** (2.18)	0.028*** (8.57)	0.082*** (4.70)

UI	-0.003*** (-4.73)	-0.005** (-2.21)	-0.006*** (-5.73)	-0.019** (-2.72)
IN	0.609*** (6.76)	0.202*** (3.49)	(0.00) (-0.01)	-0.386** (-2.40)
RGDP	-0.180*** (-7.48)	0.180*** (4.84)	0.01 (0.48)	0.04 (0.50)
_cons	1.221*** (5.72)	-1.417*** (-4.52)	(0.00) (-0.02)	(0.60) (-0.83)
Time fixed effects	YES	YES	YES	YES
Regional fixed effects	YES	YES	YES	YES
N	190	114	209	57
R ²	0.704	0.471	0.421	0.788
F	16.535	3.396	5.473	5.136

517 Note: Standard errors in parentheses, *, **, *** indicate significant at the 10%, 5%,
518 and 1% levels, respectively

519 (vi) spatial relationship test

520 It has been analyzed that the common problem of estimating the spatial panel
521 model using the traditional OLS method is manifested by the bias of the estimated
522 coefficients, while the MLE method is more effective in estimating the spatial panel
523 model. The results of the spatial autocorrelation test between green financial
524 development and low carbon economic transformation in 30 provinces across China
525 are shown in Table 8. This paper uses the global Moran' I to test the data for spatial
526 autocorrelation, and gives the Moran' I indices and statistical results of the
527 standardized geospatial weight matrix. As can be seen from the table: overall, the
528 statistical values of each year remain around 0.2 and the p-values are significant at the
529 1% level, indicating a strong spatial dependence among the 30 provinces. In terms of
530 time series characteristics, from 2001-2011, Moran' I index shows a steady increase,
531 indicating a certain spatial dependence of economic growth among the provinces.
532 From 2011-2019, the Moran' I index shows a slight decreasing trend, and the
533 dependence of economic growth among provinces gradually decreases, which may be
534 related to the overall economic environment of China from a comprehensive analysis.
535 In terms of numerical characteristics, the Moran' I index was 0.014 in 2001 at the
536 beginning of the observation period, and it has been increasing in the following years,
537 reaching a maximum value of 0.205 in 2011, and then decreasing until 0.196 in 2019.
538 economic transition in China is spatially relevant.

Table 8 Moran Index of Low Carbon Economic Transition, 2001-2019

Annual	I	P-value	Annual	I	P-value
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2001	0.014	0.000	2011	0.205	0.001
2002	0.133	0.000	2012	0.200	0.001
2003	0.155	0.000	2013	0.198	0.001
2004	0.163	0.000	2014	0.201	0.001
2005	0.172	0.006	2015	0.181	0.002
2006	0.167	0.006	2016	0.155	0.005
2007	0.162	0.006	2017	0.128	0.001
2008	0.176	0.003	2018	0.191	0.001
2009	0.183	0.003	2019	0.196	0.001
2010	0.197	0.002			

539 By calculating Moran' I, it is found that there is a positive correlation and
540 regional variability between low carbon economic transition and green financial
541 development in space, and the spatial Durbin model is selected by LM test and
542 Hausman test, and then the significance test by combining the time-space fixed effects,
543 and according to the results of the statistics of Wald and LR test, the final selection of
544 the time-fixed effect. The regression results are shown in Table 9 below. As can be
545 seen from the table, the spatial spillover coefficient of the model rho is significantly
546 positive and significant at the 1% level, indicating that overall green financial
547 development shows positive spillover effects.

Table 9 Regression results of the spatial spillover effect of green finance on regional low-carbon transition and upgrading

Variable	Main	Direct effect	Indirect effects	Total effect
GREEN	4.646*** (4.36)	4.524*** (5.10)	13.526*** (4.47)	18.05*** (5.86)
FDI	1.5506*** (8.49)	1.584*** (9.91)	1.574** (2.45)	3.158*** (4.45)
UI	0.077*** (8.37)	0.077*** (9.49)	-0.258 (-0.137)	0.052*** (3.34)
IN	2.401 (-1.02)	0.791 (-0.69)	2.955 (-0.97)	3.747 (-1.01)
RGDP	12.529*** (2.61)	11.866*** (4.42)	1.399** (-0.029)	2.128 (0.36)
rho	0.210*** (8.102)			
sigma2_e	43.388*** (16.29)			
N	570			
R ²	0.3505	0.3505	0.3505	0.3505

Number of province	30	30	30	30
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V. Research conclusions and recommendations

This paper constructs the influence mechanism of the relationship between green finance and low-carbon economy based on three perspectives: green finance, low-carbon economy and low-carbon technology innovation, and conducts an empirical study using data from 30 provinces in China from 2001-2019 to test the effect of green finance on the development of low-carbon economy, and further studies the intermediary role played by low-carbon technology innovation between the two, concluding that (1) from China Overall, green finance can significantly contribute to the development of low-carbon economy. However, when China is divided into four regions, the impact of green finance development on low-carbon economic transformation is more significant in the eastern, central and northeastern regions of China, with the best impact effect in the northeastern region, followed by the central region and finally the eastern region. And it is not significant in the western region. (2) By testing the mediating effect of low-carbon technology, it is found that after adding low-carbon technology to the model, green finance still has a significant contribution to the low-carbon economic transformation, but this contribution decreases with the intervention of low-carbon technology. The results also show that green finance can significantly promote the innovation of low-carbon technology, while the innovation of low-carbon technology can further promote the transition to a low-carbon economy. This suggests that low carbon technology innovation plays a partial mediating effect. (3) The robustness of the benchmark regression is verified by testing the endogeneity problem through the instrumental variables method, the results of the traditional ML index measurement as a proxy variable for low-carbon economic transformation, and the exclusion of first-tier provinces, further indicating that green finance has a significant promoting effect on the transformation of low-carbon economy, and this promoting effect has some stability. (4) The test of spatial relationship finds that there is a strong spatial dependence between green finance development and low-carbon economic transformation in 30 Chinese provinces. However, the dependence among provinces tends to weaken after 2011. Further, the Durbin model test reveals that the green financial development in China as a whole shows a positive spillover effect on the low-carbon economic transformation.

Accordingly, several suggestions are put forward: (1) strengthen the development of green finance and give full play to its positive role in the process of low-carbon economic transformation. According to the results of the above study, green finance

can promote the development of low-carbon economic transformation, but this promotion effect is not very strong. Therefore, China needs to develop green finance in depth to promote the transformation of low-carbon economy, which is the main way of China's current and future economic development. Specifically, firstly, a special institution should be established for green finance to change the current superficial development of green finance and make it develop continuously and deeply; secondly, the construction of green finance talents should be strengthened, and financial institutions should attract relevant talents and establish scientific and systematic training institutions; thirdly, traditional concepts should be changed, and enterprises should be actively guided to establish green and low-carbon development methods, and consumers should be guided to establish low-carbon consumption concept, so that low carbon enters every aspect of society. (2) Differentiated development according to local conditions and regional characteristics. By dividing China into four regions for research, it is found that there are obvious differences in the degree of influence of green finance on low-carbon economic transformation in different regions. The main reason is that each region has a different level of financial development and a different industrial structure due to the previous development approach of "emphasizing the economy over the environment", which makes the impact of green finance on the low-carbon economic transformation different. Therefore, each region should set up different development priorities by taking into account the unique linkage between green finance and low-carbon economy development in the region, so as to achieve efficient development nationwide. On the one hand, the Chinese government should formulate policies and development approaches that are appropriate for each region and should be tailored to local conditions rather than generalized. On the other hand, it should steadily promote the development of the national carbon trading market, encourage green financial innovation, and expand carbon financial trading products. (3) Promote the research and development of low-carbon technologies. According to the study of intermediary effect above, green finance can curb carbon emissions by promoting the R&D and innovation of low-carbon technologies, and thus promote the transition to a low-carbon economy. Therefore, on the one hand, the government can establish green technology profiles of enterprises, identify the extent of their green technology R&D and application, and help small and medium-sized enterprises with technology R&D to go public for financing, while financing and loans for those enterprises with high consumption, high pollution and high emissions should be restricted to a certain extent. On the other hand, corresponding incentive policies can be established to encourage enterprises to carry out technological innovation. Through preferential interest rate policies, loan facilities and other forms of technology research and

development enterprises to technology pointed out, to stimulate the enterprise's low carbon technology innovation and application.

Declarations

Ethical approval There are no ethical issues involved in this thesis and no harm will be caused to individual organisms. This entry does not apply to this thesis.

Consent to participate Not applicable.

Consent to publish Not applicable.

Conflict of interest The authors declare that they have no conflict of interests.

Author contribution Wenqi Li proposed the research topic and designed the research protocol. He was also responsible for the technical and material support of this thesis, provided and designed the research methodology, and served as the supervisor of this thesis. As the corresponding author, he ensured the accuracy of the content described in the paper. Jingjing Fan wrote this article based on the empirical results, and researched and organized the relevant literature. The paper was revised and translated. And reviewed the final paper. She was also responsible for the submission and revision of the thesis. Jiawei Zhao collected and organized the research data required for the thesis. Statistical analysis was conducted and the accuracy of the empirical analysis process was verified. All authors read and approved the final manuscript.

Data availability Most of the data generated or analyzed in this study are included in this published article. The remaining datasets used for analysis are available in the China Statistical Yearbook, China Energy Statistical Yearbook, China Industrial Statistical Yearbook, China Environmental Statistical Yearbook, China Insurance Yearbook, CSMAR database [<https://www.gtarsc.com/>], wind database [<https://www.wind.com.cn/NewSite/edb.html>].

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