Has green finance facilitated China’s low-carbon economic transition?

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Abstract

The transformation of the traditional high-carbon economy to a low-carbon economy and the change in the economic development mode urgently require the transformation and development of traditional finance to green finance. This study examines the impact of green finance on the transition to a low-carbon economy in 30 Chinese provinces from 2001 to 2019 and further explores the role of low-carbon technological innovation in this facilitation process. We use the Global Malmquist-Luenberger index to measure low-carbon total factor productivity using gross regional product as the desired output, CO2 emissions as the undesired output, and capital stock, employment, and total energy consumption as input indicators to represent the low-carbon economic transition. We select seven indicators in four dimensions of green credit, green securities, green insurance, and green investment to construct a comprehensive green finance evaluation system, and then apply the entropy value method to calculate green finance indicators. The number of patents granted for low-carbon innovation is used to measure low-carbon technology innovation. Foreign direct investment, industrialization level, economic development level, and urbanization level are selected as control variables. Through panel data model, mediating effect model and 2SLS, we find that green finance can significantly contribute to the transformation of low-carbon economy, but this contribution decreases with the intervention of low-carbon technology innovation. The implications of our empirical results can help China to improve the development of green finance and thus promote the transformation and upgrading of a low-carbon economy.

Keywords

Green finance · Low carbon economy · Low carbon technology

Introduction

Since the reform and opening up, China’s economy has made world-renowned achievements. The gross domestic product has grown from 367.87 billion yuan in 1978 to 101,598.62 billion yuan in 2020, a nearly 276-fold increase. However, China’s past development was a crude development at the expense of large-scale resources and destruction of the environment, which brought many adverse effects to people’s living environment, and problems such as climate warming and resource shortage have become increasingly prominent. According to WMO data, by 2020, China’s total CO2 emissions will surpass those of other countries in the world and be at the top of the world. Excessive carbon emissions caused by economic development have led to climate warming, making climate-sensitive countries like China more affected by this change. Transforming the development mode to an economic development mode aiming at high efficiency, low pollution, low energy consumption, and low emission has become the next choice not only for China, but also for all countries in the world. 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 2005). The financial industry plays a huge role in adjusting economic structure, promoting independent innovation, saving energy and resources, and protecting ecological environment (Levine 2005). 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 require the transformation and development of traditional finance to green finance.

The purpose of this study is to investigate the decisive role played by green finance in the development of a low-carbon economy in China over the period 2001–2019, as well as to explore what role low-carbon technology innovation played in this process. Therefore, this paper takes a sample of 30 Chinese provinces from 2001 to 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 novelty of this paper is that (1) our selection of indicators for the low-carbon economic transition differs from traditional approaches in that the method used in this paper is transferable. The measurement of green finance is calculated from a global perspective, taking into account the national and regional levels. (2) The contribution of green finance to the transformation of low-carbon economy is explored from China as a whole and locally respectively, providing some reference for the development of each region in China. (3) Based on the traditional regression, the relationship between green finance and the transformation of low-carbon economy is further analyzed through spatial relationship test.

The rest of the paper consists of four parts. The “Literature review and research hypothesis” section includes the literature review and research hypotheses. The “Empirical model and data” section includes the model setting, data sources, and selection of indicators. The “Empirical analysis” section presents the results of the empirical evidence. The “Research conclusions and recommendations” section concentrates on the results and policy recommendations.

**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 and Feyen (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 and Feyen (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 and Acaravci (2013) discussed carbon emissions, financial development, financial development, energy consumption, and economic growth in the context of Turkey and the 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.

**Empirical model and data**

**Empirical model setting**

**Benchmark model**

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

\[
LCTFP_{it} = a_0 + a_1 GREEN_{it} + a_2 FDI_{it} + a_3 JN_{it} + a_4 RGDP_{it} + a_5 UI_{it}\ + year_{it} + city_{it} + e_{it}
\]

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 $t$. $RGDP_{it}$ represents 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 $\epsilon_{it}$ denotes the random disturbance term.

### 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.

$$LCITFP_{it} = \gamma_1 \times \gamma_4 \times \text{GREEN}_{it} + \gamma_2 \times \text{LCI}_{it} + \gamma_3 \times FDI_{it} + \gamma_4 \times \text{IN}_{it} + \gamma_5 \times GDP_{it} + \gamma_6 \times \text{UI}_{it} + \text{year}_{it} + \text{city}_{it} + \epsilon_{it} \tag{4}$$

Among them, Eq. (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 Eq. (3) $LCI_{it}$ is the low-carbon technology innovation in each province, and Eq. (4) is added to Eq. (2). $LCI_{it}$. This paper adopts the stepwise regression method of mediating effect test, whose general steps are: if the Eq. (2) in $a_1$ is not significant, it indicates that the causal relationship between green finance and low-carbon economic transformation is not significant, and randomly stops the intermediary effect test, if it is $a_1$ significant, the regression equation of Eq. (3) is continued to test whether green finance affects low carbon technology innovation in the province. If $\beta_1$ 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 Eq. (4) to test whether the mediating effect of low carbon technology innovation exists.

### Sample selection and index selection

#### 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 to 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.

#### Indicator selection

**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 transformation, 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 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 CO$_2$ 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. CO$_2$ 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 as follows: (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.

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. As can be seen from Table 1, the skewness of the explanatory variable low carbon economic transition is 0.011 and the kurtosis is 0.072, which shows that the data on low carbon economic transition in China basically obeys a normal distribution. Similarly, the skewness of green finance is 0.177 and the kurtosis is 0.978; the kurtosis value is greater than 0, which indicates that the data distribution is steeper and the skewness value is positive, which indicates that green finance shows a right skewed trend in most regions. Overall, China’s low carbon economic transition and green finance indices do not deviate significantly from the normal distribution characteristics.
Variable correlation test. In this study, a panel model was used to examine the relationship between the variables. First, the correlation analysis was conducted with reference to Batranica (2021) with the aim of controlling for potential multicollinearity problems, which may bias the empirical results. In general, in econometric models, strong correlations between independent variables can easily exist due to the presence of other factors, and if such correlations are strong, it may affect the robustness of the empirical results. To ensure the reliability of the test results in the future, this paper uses Pearson correlation coefficient matrix and variance inflation factor for covariance testing. First, the Pearson correlation coefficient matrix between variables is used to make a preliminary determination of cointegration. The results of the correlation coefficient matrix are shown in Table 2.

The table shows that there is a correlation between low carbon economic transition and green finance, low carbon technology innovation, foreign direct investment, level of industrialization, level of economic development, and level of urbanization. It indicates that there is a certain relationship between them, and linear regression can be conducted to further explore the specific relationship between them. At the same time, it is necessary to test whether there is multicollinearity among the variables and do further variance inflation factor tests between the highly correlated variables. The results of the multicollinearity test are shown in Table 3.

As can be seen from Table 3, using variance inflation factors to do further tests, different variance inflation factors (VIF) indicate the existence of different degrees of multicollinearity among variables and have different effects on the regression results. According to the experience, when $0 < \text{VIF} < 10$, there is no multicollinearity; when $10 \leq \text{VIF} < 100$, there is strong multicollinearity; when $\text{VIF} \geq 100$, there is serious multicollinearity. The calculation shows that all the VIFs are less than 5, and it can be assumed that there is no multicollinearity among them.

**Empirical analysis**

**Baseline regression**

First of all, a preliminary examination of the intrinsic relationship between green finance and low carbon economic transition was conducted. The descriptive statistics values of main variables are shown in Table 1. The correlation test results are shown in Table 2. The results of the multicollinearity test of variables are shown in Table 3.
transformation is conducted. In terms of research methodology, this paper uses OLS as the benchmark regression, and in the selection of fixed effects and random effects, we based on the results of the Hausman test, and a p value of 0.000 indicates that a fixed-effects model should be used, and the test results are shown in Table 4.

From the Hausman test results, it is clear that we should choose a fixed-effects model rather than a random-effects model, and after comprehensive analysis, we use a two-way fixed effects (FE) model with fixed time and area effects to test the theoretical hypothesis.

Table 5 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 6 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.

**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

| Table 4 Hausman test results | (b) | (B) | (b−B) | sqrt(diag(V_bV_B)) |
|-----------------------------|-----|-----|-------|-------------------|
| FE | RE | Difference | S.E. |
| GREEN | 0.409096 | 0.283182 | 0.125914 | 0.026178 |
| FDI | 0.12408 | 0.08853 | 0.03555 | 0.01029 |
| IN | 0.0191 | 0.0531 | 0.034 | 0.0362 |
| RGDP | 0.1969663 | 0.2042227 | −0.0072565 | 0.0014977 |
| UI | 0.118049 | 0.104475 | 0.013574 | 0.003747 |
| _cons | 0.0979958 | 0.1019444 | −0.0039486 | |

b = consistent under Ho and Ha; obtained from xtreg.
B = inconsistent under Ha, efficient under Ho; obtained from xtreg.
Test: Ho: difference in coefficients not systematic.
chisq(6)=(b−B)[(V_b−V_B)(−1)−(b−B)] = 54.70.
Prob > chisq = 0.0000.
(V_b−V_B is not positive definite).

**Analysis of mediating effects**

Table 5 Baseline regression results

| Variable | (1) | (2) | (3) | (4) |
|----------|-----|-----|-----|-----|
| GREEN    | 0.387*** | 0.681*** | 0.527*** | 0.416*** |
| FDI      | 0.028*** | 0.040*** | (9.36) | (13.44) |
| UI       | −0.002*** | −0.002*** | (−4.28) | (−5.69) |
| IN       | 0.647*** | 0.500*** | (12.43) | (8.81) |
| RGDP     | −0.078*** | (−7.11) | (−1.38) |
| _cons    | 0.221*** | 0.463*** | 0.234*** | (0.03) |

Time-fixed effects | No | No | Yes | Yes |
Regional-fixed effects | No | No | Yes | Yes |
N | 570 | 570 | 570 | 570 |
R² | 0.09 | 0.46 | 0.13 | 0.57 |
F | 58.70 | 82.84 | 4.24 | 30.17 |

Standard errors in parentheses, *, **, *** indicate significant at the 10%, 5%, and 1% levels, respectively.
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 7. 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.

Robustness test

In this paper, the robustness of the baseline regression results is tested by the following two ways, and the regression results are shown in Table 8.

1. Replace the explanatory variables. Referring to Li and Yu (2013), the energy economy TFP, i.e., using the results without considering the non-desired output carbon emissions, based on the traditional ML index measure, is used as a proxy variable for the low-carbon economic transition. The regression results are shown in Table 8 (1)–(2). Column (1) is the OLS regression result with the inclusion of control variables, and column (2) is a two-way fixed-effects model with the inclusion of control variables and controlling for time and area effects. From the regression results, it can be seen that the regression results of green financial development on low carbon economic transformation remain significantly positive after replacing the explanatory variables.

2 Excluding super tier 1 provinces. In order to exclude the effect of extreme samples, the North, Shanghai and Guangzhou regions are excluded from the overall sample. The regression results are shown in columns (3)–(4) of Table 8. From the regression results, we can see that green finance still significantly contributes to China's low-carbon economic transformation after excluding super tier 1 provinces, and the baseline regression results are more robust.

Further discussion

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 9. 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 8  Robustness tests

| Variable | (1) LCTFP_S | (2) LCTFP_S | (3) LCTFP | (4) LCTFP |
|----------|------------|------------|------------|------------|
| GREEN    | 2.679***   | 0.924*     | 0.999***   | 0.586***   |
|          | (5.05)     | (1.70)     | (7.49)     | (4.48)     |
| FDI      | 0.188***   | 0.267***   | 0.024***   | 0.035***   |
|          | (7.66)     | (10.76)    | (7.86)     | (11.51)    |
| UI       | -0.010***  | -0.013***  | -0.003***  | -0.003***  |
|          | (-2.80)    | (-3.75)    | (-4.83)    | (-6.48)    |
| IN       | 3.759***   | 2.633***   | 0.552***   | 0.305***   |
|          | (9.11)     | (5.68)     | (10.47)    | (4.48)     |
| RGDP     | -0.426***  | (0.03)     | -0.087***  | 0.00       |
|          | (-4.81)    | (-0.25)    | (-6.79)    | (0.02)     |
| _cons    | 2.779***   | (0.43)     | 0.587***   | (0.09)     |
|          | (3.85)     | (-0.53)    | (5.71)     | (-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     |

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

Table 9  Examination by time period

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

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

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 are 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 10. 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.

**Spatial relationship test**

It has been analyzed that the common problem of estimating the spatial panel model using the traditional OLS method is manifested by the bias of the estimated coefficients, while the MLE method is more effective in estimating the spatial panel model. The results of the spatial autocorrelation test between green financial development and low carbon economic transformation in 30 provinces across China are shown in Table 11. This paper uses the global Moran’s $I$ to test the data for spatial autocorrelation, and gives the Moran’s $I$ indices and statistical results of the standardized geospatial weight matrix. As can be seen from the table, overall, the statistical values of each year remain around 0.2 and the $p$ values are significant at the 1% level, indicating a strong spatial dependence among the 30 provinces. In terms of time series characteristics, from 2001 to 2011, Moran’s

| Table 10 Regression results of regional heterogeneity |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Variable                        | (1) Eastern region | (2) Central region | (3) Western region | (4) Northeast region |
| GREEN                           | 0.484***         | 0.641**         | 0.20            | 2.149***         |
| (5.12)                          | (2.00)           | (1.25)          | (2.58)          |
| FDI                             | 0.078***         | 0.008**         | 0.028***        | 0.082***         |
| (11.03)                         | (2.18)           | (8.57)          | (4.70)          |
| UI                              | −0.003***        | −0.005**        | −0.006***       | −0.019**         |
| (−4.73)                         | (−2.21)          | (−5.73)         | (−2.72)         |
| IN                              | 0.609***         | 0.202***        | (0.00)          | −0.386**         |
| (6.76)                          | (3.49)           | (0.01)          | (−2.40)         |
| RGDP                            | −0.180***        | 0.180***        | 0.01            | 0.04             |
| (−7.48)                         | (4.84)           | (0.48)          | (0.50)          |
| _cons                           | 1.221***         | −1.417***       | (0.00)          | (0.60)           |
| (5.72)                          | (−4.52)          | (−0.02)         | (−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           |

Standard errors in parentheses, *, **, *** indicate significant at the 10%, 5%, and 1% levels, respectively.
I index shows a steady increase, indicating a certain spatial dependence of economic growth among the provinces. From 2011 to 2019, the Moran’s I index shows a slight decreasing trend, and the dependence of economic growth among provinces gradually decreases, which may be related to the overall economic environment of China from a comprehensive analysis. In terms of numerical characteristics, the Moran’s I index was 0.014 in 2001 at the beginning of the observation period, and it has been increasing in the following years, reaching a maximum value of 0.205 in 2011, and then decreasing until 0.196 in 2019. Economic transition in China is spatially relevant.

By calculating Moran’s I, it is found that there is a positive correlation and regional variability between low carbon economic transition and green financial development in space, and the spatial Durbin model is selected by LM test and Hausman test, and then the significance test by combining the time–space fixed effects, and according to the results of the statistics of Wald and LR test, the final selection of the time-fixed effect. The regression results are shown in Table 12. As can be seen from the table, the spatial spillover coefficient of the model rho is significantly positive and significant at the 1% level, indicating that overall green financial development shows positive spillover effects.

| Variable | Main effect | Direct effect | Indirect effect | Total effect |
|----------|-------------|---------------|----------------|-------------|
| GREEN    | 4.646***    | 4.524***      | 13.526***      | 18.05***    |
|          | (4.36)      | (5.10)        | (4.47)         | (5.86)      |
| FDI      | 1.5506***   | 1.584***      | 1.574**        | 3.158***    |
|          | (8.49)      | (9.91)        | (2.45)         | (4.45)      |
| UI       | 0.077***    | 0.077***      | −0.258         | 0.052***    |
|          | (8.37)      | (9.49)        | (−0.137)       | (3.34)      |
| IN       | 2.401       | 0.791         | 2.955          | 3.747       |
|          | (−1.02)     | (−0.69)       | (−0.97)        | (−1.01)     |
| RGDP     | 12.529***   | 11.866***     | 1.399**        | 2.128       |
|          | (2.61)      | (4.42)        | (−0.029)       | (0.36)      |
| rho      | 0.210***    |               |               |             |
|          | (8.102)     |               |               |             |
| sigma2_e | 43.388***   |               |               |             |
|          | (16.29)     |               |               |             |
| N        | 570         |               |               |             |
| R²       | 0.3505      | 0.3505        | 0.3505         | 0.3505      |
| Number of province | 30 | 30 | 30 | 30 |

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 to 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. Furthermore, 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.

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, 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, and reviewed the final paper. The paper was revised and translated. 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.

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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/edh.html].

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.

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References

Batrancea L (2021) An econometric approach regarding the impact of fiscal pressure on equilibrium: evidence from electricity, gas and oil companies listed on the New York Stock Exchange

Batrancea L, Rathnaswamy MK, Batrancea I. A panel data analysis on determinants of economic growth in seven non-BCBS countries [J]. Journal of the Knowledge Economy:1–15

Claessens S, Feyen E (2007) Financial sector development and the millennium development goals [M]. The World Bank 2(89):15–31

Chen X, Hao G (2015) Sustainable pricing and production policies for two competing firms with carbon emissions tax. Int J Prod Res 53(21):6408–6420

Chen X, Shen Z (2012) A n analysis of a supply chain with options contracts and service requirement. IIE Trans 44(10):805–819

Cunico E, Cirani CBS, Lopes EL et al (2017) Eco-innovation and technological cooperation in Cassava processing companies: structural equation modeling [J]. Revista De Administrao 52(1):36–46

Chris B, Guivarch C, Stephane H (2018) Carbon prices across countries [J]. Nat Clim Chang 8(8):648–650

Chen W, Song X, Guarda T et al (2019) Enterprise management innovation in the internet of things from the perspective of contingency [J]. Journal of Intelligent & Fuzzy Systems 37(5):5829–5836

DTI (2003) U.K. energy white paper: our energy future creating a low carbon economy. DTI, London

Fang JG, Lin FL (2019) Research on the relationship between green finance and sustainable economic development—an empirical analysis based on 30 inter-provincial panel data in China [J]. Journal of China University of Petroleum (social Science Edition) 35(01):14–20

Fan J, Li J, Wu Y (2016) The effects of allowance price on energy demand under a personal carbon trading scheme [J]. Appl Energy 170:242–249

Greenwood J, Jovanovic B (1990) Financial development, growth, and the distribution of income [J]. UWO Department of Economics Working Papers, pp 51–63

Guo H, Shen R (2012) A study on the impact of environmental inclusion and uncertainty on business model innovation of enterprises [J]. Economic and Management Research 10:97–104

Jeucken M (2010) Sustainable finance and banking: the financial sector and the future of the planet [M]

Keohane NO (2009) Cap and trade, rehabilitated: using tradable permits to control US greenhouse gases. Rev Environ Econ Policy 3(1):42–62

Levine R (2005) Finance and growth: theory and evidence [J]. Handbook of Economic Growth (a):865–934

Lopez FJD, Montalvo C (2015) A comprehensive review of the evolving and cumulative nature of eco-innovation in the chemical industry [J]. J Clean Prod 102:30–43

Liu JG, Ma DQ, Chen CJ et al (2016) Research on the innovation path of “Internet+” business model based on rooting theory—an example of dropping out [J]. Soft Science 30(7):30–34

Li J, Zhu CL, An L (2013) Historical changes and regional differences in the performance of China’s low-carbon economic transition [J]. China Soft Science 5:172–187

Marcel J (2010) Sustainable finance and banking: the financial sector and the future of the planet [M]. Taylor and Francis, pp 320

Ozturk I, Acaravci A (2013) The long-run and causal analysis of energy, growth, openness and financial development on carbon emissions in Turkey[J]. Energy Economics 36:262–267

Salazar J (1998) Environmental finance: liking two word [J]. Presented at a Workshop on Financial Innovations for Biodiversity Bratislava, pp 2–18

Scholtens B (2006) Finance as a driver of corporate social responsibility[J]. J Bus Ethics 68(1):19–33

Street P, Monaghan PE (2001) Assessing the sustainability of bank service channels: the case of the co-operative bank [J]. Sustainable Banking: The Greening of Finance 72–87(16)

Saebi T, Lien L, Foss NJ (2017) What drives business model adaptation? The impact of opportunities, threats and strategic orientation [J]. Long Range Plan 50(5):567–581

Thakur PC, Cabrera DD, De Carolis N et al (2018) Innovation and commercialization strategies for three-dimensional bioprinting technology: a lean business model perspective [J]. J Commer Biotechnol 24(1):78–87

Wara M (2007) Is the global carbon market working?[J]. Nature 445(7128):595–596

Yi GB, Xie DM, Gao JW (2015) An empirical study on the factors influencing business model innovation of high-tech enterprises - based on knowledge perspective [J]. Scientific Research Management 36(2):50–59

Zhang W (2010) China 2010: low carbon year - low carbon city - eco - economic game - examining the low carbon economic forum and eco-city construction in the transition period [J]. National Business News (Theoretical Research) (10):9–11+14

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