RESEARCH ARTICLE

How green technology innovation affects carbon emission efficiency: evidence from developed countries proposing carbon neutrality targets

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Abstract

With the introduction of national carbon neutrality targets, carbon emission reduction actions in developed countries have become a hot topic as part of the international community's drive to take action to mitigate climate change. Carbon emission efficiency is an important indicator that can be used to measure progress toward carbon emission reduction targets. The relationship between green technology innovation and carbon emission efficiency has not been adequately studied, and the transmission mechanism is not yet clear. Based on the above research gaps, taking 32 developed countries that have proposed carbon neutral targets as research samples, this paper used spatial econometric models to explore the impact of green technology innovation on carbon emission efficiency and adopted spatial mediation model and spatial moderation model to analyze the transmission effects of economic development, urbanization, and financial development on environment-related green technology and carbon emission efficiency. This paper aimed to provide a policy basis for developed countries to mitigate carbon emissions and achieve carbon neutrality goals as soon as possible. The following results were obtained: (1) Luxembourg, Norway, and Switzerland were found to be efficient in terms of carbon emissions, while most developed countries were in an inefficient state. (2) Environment-related green technology innovation significantly improved carbon emission efficiency. (3) Economic development and urbanization had a mediating role on green technology innovation and carbon emission efficiency. In other words, green technology innovation could have an indirect impact on carbon emission efficiency by influencing economic development and urbanization. (4) Financial development could positively moderate the sensitivity of carbon emission efficiency to green technology innovation. Improving the level of green technology innovation is one way to improve carbon emission efficiency, and the mediating effect of economic development and urbanization can be used as a focus point to improve carbon emission efficiency. The pressure of carbon emission reduction can be moderated by finance development. The results of this study provide theoretical support that will assist developed countries in achieving their carbon neutrality targets.

Keywords Carbon neutrality · Carbon emission efficiency · Green technology innovation · Spatial mediation model · Spatial moderation model

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Introduction

Human economic activities have led to increased greenhouse gas emissions and severe haze pollution (Pan and Dong 2022; Zhang and Dong 2021). As a result of global warming, extreme climate events such as glacier melting, forest fires, intense hurricanes, floods, extreme cold in winter, and extreme heat waves in summer have occurred frequently in recent years (Apaydın and Ocakoğlu 2020; Ren et al. 2021). The occurrence of extreme events highlights the urgency of taking action to achieve net zero carbon dioxide (CO_2) emissions and adapt to climate change (Liu and Dong 2022).

More than 130 countries have already proposed carbon neutral targets that should be met by the middle of the twenty-first century (UNFCCC 2021), which are generally in line with the Intergovernmental Panel on Climate Change 1.5 °C guidelines (Iyer et al. 2021). Achieving net-zero CO_2 emissions and promoting sustainable human development by the middle of the twenty-first century have become a common goal pursued by the international community. Carbon emission efficiency is an important indicator to measure environmental quality and the progress of carbon neutrality goals.

Addressing climate change requires technological innovation. As the main driver of carbon emission reduction, technological innovation provides a breakthrough for countries around the world to reduce carbon emissions. Innovation-driven green development has become the key to achieving industrial transformation and upgrading and improving quality and efficiency in the new era (Wang and Li 2020). Environment-related green technology innovation is an effective technology that produces more positive environmental effects than ordinary technological innovation. It plays a crucial role in mitigating climate change (Zhang et al. 2016), which can not only promote green economic growth, but also effectively reduce CO_2 emissions. In short, green technology innovation should be given more attention. The carbon emission reduction actions of developed countries play a leading role in the international community and provide a platform for less developed countries to learn from. Therefore, this paper used green technology innovation as the core explanatory variable to measure its impact on carbon emission efficiency in developed countries.

Numerous studies have shown that technological innovation affects carbon emission efficiency, so does green technology innovation also affect carbon emission efficiency? If so, then what is the mechanism of green technology innovation's impact on carbon emission efficiency. Apart from the direct impact, is it necessary to consider whether green technology innovation also affects carbon emission efficiency through economic development and urbanization? In addition, will financial development moderate the sensitivity of carbon emission efficiency to green technology innovation? To address these issues, this study took a sample of 32 developed countries that proposed carbon neutrality targets and set a study period of 1990–2017. The carbon emission efficiency of developed countries was assessed based on a slacks-based measure (SBM) model in data envelopment analysis (DEA), which used a spatial econometric model to analyze the impact of green technology innovation on carbon emission efficiency. The mechanism by which green technology innovation influences carbon emission efficiency was fully investigated, and the mediating role of economic development and urbanization and the regulating role of financial development were analyzed.

Compared with previous studies, our study not only enhanced the body of theoretical research related to green technology innovation and carbon emission efficiency, but also made specific policy suggestions for developed countries to reduce carbon emissions and achieve the carbon neutrality target as soon as possible. The main innovations of this study were as follows: (1) Most of the previous literature has focused on several developed countries or China, and there is a lack of systematic studies on carbon emission efficiency in developed countries as a whole, with most of them using ordinary panel models. In this study, 32 developed countries that have proposed carbon neutrality targets were taken as the research sample, and the spatial effect of carbon emission efficiency was considered. Environment-related green technology innovation is rarely studied, while many other general technological innovations have been intensively investigated. (2) An empirical analysis was conducted using a large sample to further analyze the mechanism of green technology innovation's impact on carbon emission efficiency and to investigate whether economic development and urbanization play a mediating role in the process. (3) Financial development, which plays an important role in stimulating economic development, was included in the analysis framework of this study. The moderating role of financial development was evaluated, and it was found to improve the impact of green technology innovation on carbon emission efficiency.

The remainder of this paper is organized as follows. The "Literature review" section is a literature review. The "Research hypotheses" section describes the research hypothesis. The "Methodology and data" section briefly introduces the methodology and data. The "Analysis of the empirical results" section presents an analysis of the empirical results. The conclusions and policy implications are shown in the "Conclusions and policy recommendations" section. Figure 1 depicts the analysis framework of this study.

Literature review

Carbon emission efficiency

Carbon emission efficiency directly determines the overall level of carbon emissions (Gao et al. 2021). Consequently, the evaluation of carbon emission efficiency has become a hot research topic in recent years. A reasonable assessment of carbon emission efficiency is fundamental to the setting of emission reduction targets and will promote the overall improvement of environmental quality (Xie et al. 2021). Many researchers have used a single-factor indicator to measure carbon emission efficiency, such as carbon emissions per unit of gross domestic product (GDP), which
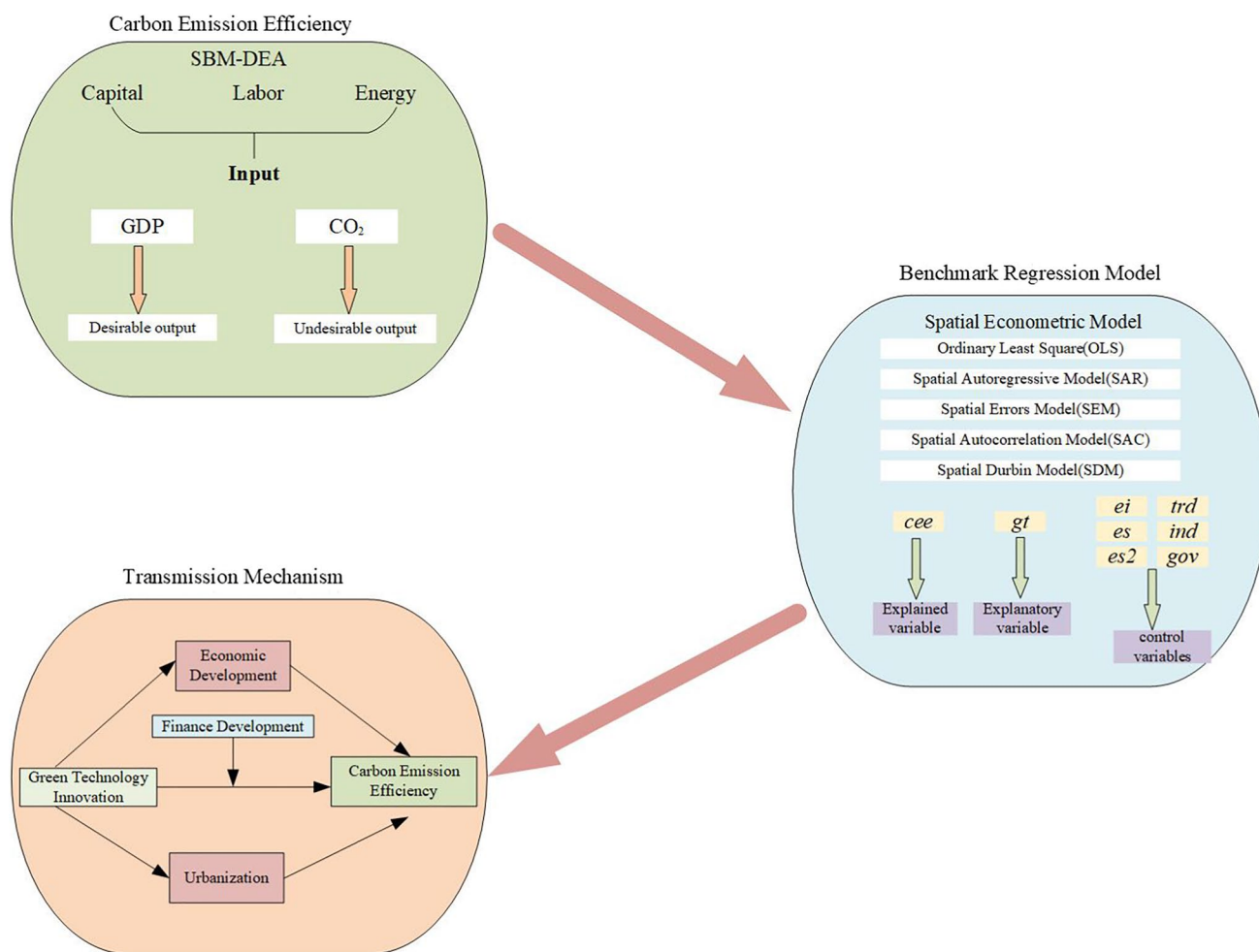
Fig. 1 Analysis framework

is referred to as carbon intensity. Jiang et al. (2018) believed that carbon intensity is more applicable to developed countries with a higher GDP and not to less developed countries. Moreover, the single-factor indicator element is not comprehensive due to its simplicity (Zhang et al. 2016).

In recent years, the stochastic frontier analysis (SFA) and DEA have been used to evaluate environmental performance (Aigner et al. 1977; Charnes et al. 1978). The SFA is a stochastic model that requires the determination of the production function form and is widely used to measure carbon emission performance (e.g., Lin and Du 2015; Moutinho et al. 2020; Yu et al. 2021). However, it has the insurmountable disadvantage that it cannot consider undesired output (Hannes et al. 2015). Compared to SFA, DEA without the concept of a production function is a non-parametric model that is often used to measure carbon performance, determining production boundaries through linear programming. The traditional DEA models (Charnes–Cooper–Rhodes and Banker-Charnes-Cooper) only enable a radial analysis. They do not take into account the non-desired outputs, nor do

they reflect the slack improvement component. Based on the above considerations, Tone (2001) proposed the SBM model, which incorporates the slack variables into the objective function. It not only solves the input–output slack problem, but also solves the efficiency evaluation problem of non-desired outputs. In addition, the SBM model can avoid the bias and influence caused by radial and angular selection and can reflect the essence of efficiency evaluation better than other models. Table 1 shows the carbon emission efficiency measured in previous studies using different methods.

In addition to measuring carbon emission efficiency, studies of the drivers of carbon emission efficiency are also a major research hotspot. Most researchers have used panel regression models and spatial econometric models to study the influence of variables on carbon emission efficiency. Technological progress (Xie et al. 2021), level of economic development (Zhang and Deng 2021), urbanization (Sun and Huang 2020), foreign direct investment (Hao et al. 2021), energy consumption (Liu et al. 2016), energy structure (Wang et al. 2020), industrial structure (Wang et al. 2019a,

Table 1 Studies on measuring carbon emission efficiency

Literature	Method	Research sample	Input	Desirable output	Undesirable output
Toshiyuki and Yan (2018)	Intermediate DEA	21 Asian nations	Primary energy consumption Electricity consumption	GDP per capita	The proportion of CO_2 in primary energy
Ding et al. (2019)	CE-MPI	30 Chinese provinces	Labor Employment Energy consumption	Regional GDP	CO_2 emissions
Cai et al. (2019)	SBM-DEA	280 Chinese cities	Labor Capital Energy consumption Water	GDP per capita	CO_2 emissions per capita
Zhou et al. (2019)	Super SBM-DEA	China's construction industry	Labor Capital Energy consumption	The industrial economic output	CO_2 emissions
Wang et al. (2020)	GML index	13 Chinese airlines	Fleet size Flight shifts Flight shifts	Operating income Turnover	CO_2 emissions

b), financial development (Li et al. 2018) and foreign trade (Dong et al. 2017) are all potential drivers that have been widely studied.

Most of the published literature explores the impact of technological innovation on carbon emissions, but the opinions derived from the findings are not unanimous. Tang and Tan (2013) argued that technological innovation can curb CO_2 emissions, while promoting economic development. For Asian countries, urbanization and energy consumption are positively correlated with carbon emissions, and technology and trade play an important role in reducing CO_2 emissions (Amin et al. 2020). In the EU-15, not only the importance of technological innovation for carbon emission reduction is emphasized, but the effectiveness of economic development, renewable energy, and market regulation on carbon emission reduction is also significant (Abolhosseini et al. 2014). The effectiveness of technological innovation on carbon emissions remains significant in different industries. In the construction sector, technological advances and a rational energy structure can improve carbon emission efficiency (Zhou et al. 2019). Similarly, the contribution of technology to carbon emission efficiency in the transportation, manufacturing, and thermal power sectors has been verified (Cui and Li 2015; Lan et al. 2020; Sun et al. 2018). In contrast, Acemoglu et al. (2012) argued that technological innovation, although it promotes economic development, can increase carbon emissions.

Green technology innovation

Technological innovation is the main driver of economic growth (Bekhet and Latif 2018). It can create green energy-saving products and reduce fossil energy consumption, thereby improving environmental quality and promoting economic growth (Tang and Tan 2013). Green technology

innovation (also known as "eco-innovation" and "environmental innovation") is a specific category of technological innovation that emphasizes not only economic benefits, but also environmental and ecological benefits. As a result, it can reduce resource wastage and achieving sustainable economic development.

At present, there is no unified definition of green technology innovation, but its connotation basically refers to innovation oriented to improve environmental performance, which can bring significant improvement in environmental performance (Deng et al. 2019). Huang et al. (2019) defined green technology innovation as technological innovation in energy conservation, pollution prevention, waste recycling, green product design, and environmental management. Li (2021) believed that green technology innovation includes four layers of terminal treatment technology, green technology, green products, and green consciousness innovation. Although some technology innovation can greatly increase productivity, they do not consider the external impact on the environment (Wang et al. 2021). For example, technological innovation can only increase the output of energy-intensive industries. Different from technological innovation, green technological innovation follows the principles of ecology and the laws of ecological economy. In the process of innovation, it considers saving resources and energy consumption and reducing pollution and damage to the ecological environment. Therefore, green technology innovation is more in line with the goal of sustainable development (Li and Liao 2020).

Although many studies have considered the impact of technological innovation on carbon emissions, green technology innovation as a factor directly related to the environment has rarely been considered. This study explores the impact of green technology innovation on carbon emission efficiency in more detail.

Research hypotheses

Hypothesis 1:Green technology innovation can significantly promote carbon emission efficiency in developed countries.

Macroeconomic theory emphasizes technology as the main driver of economic growth. The impact of technological innovation on carbon emission reduction differs among countries with different levels of economic development. Some studies have shown that technological innovation reduces carbon emissions in developed countries but increases them in developing countries (Kumar and Managi 2009), with an income threshold effect. Technological innovation can reduce environmental degradation, while promoting long-term economic development (Tang and Tan 2013). Environment-related green technology innovation, which is more environmentally beneficial than general technological innovations, is the main way to achieve sustainable development. Green technology innovation has a significant dampening effect on carbon emissions (Shao et al. 2021). Like technological innovation, green technology innovation also has an income threshold effect. The mitigation effect of green technology innovation on carbon emissions is significant for economies with high income levels and becomes insignificant for economies with low income levels (Du et al. 2019). Therefore, we proposed the hypothesis that green technology innovation can significantly promote carbon emission efficiency in developed countries.

Hypothesis 2: Economic development plays a mediating role between green technology innovation and carbon emission efficiency.

In general, technological innovation has a dampening effect on carbon emissions, but it also has an impact on economic development. Technological innovation was emphasized as a source of economic growth by Schumpeter (1932). There have been many studies of the relationship between technological innovation and economic growth (Hasan and Tucci 2010; Capello and Lenzi 2014; Maradana et al. 2017), in line with Schumpeter's theory of technological innovation. The impact of economic development on carbon emissions cannot be ignored, and the classical environmental Kuznets curve (EKC) hypothesis describes the relationship between the two, with the curve being inverted U-shaped (Sephton and Mann 2013; Hanif 2018; Zhang et al. 2019), N-shaped (Daniel et al. 2018), or M-shaped (Yang et al. 2015). Therefore, it can be inferred that economic development has a mediating effect and green technology innovation can reduce CO_2 emissions while stimulating economic development.

Hypothesis 3: Urbanization plays a mediating role between green technology innovation and carbon emission efficiency.

There have been many studies on the impact of technological innovation on urbanization. There is a strong correlation between technological innovation and urbanization (Cheng 2010; Chen et al. 2020), and technological innovation plays a mediating role between urbanization and economic growth (Cheng 2009). In contrast, technological innovation plays an important role in the urbanization process, as observed during the first industrial revolution. Technological innovation significantly affects urbanization and there is a long-term stable equilibrium relationship (Shang et al. 2018). In addition, the relationship between urbanization and CO_2 emissions is nonlinear, and a U-shaped relationship has been confirmed (Sun and Huang 2020; Zhou et al. 2019). The impact of urbanization on carbon emissions has a threshold effect due to the different levels of technology and urbanization (Yao et al. 2021). To conclude, it can be inferred that urbanization can play a mediating role between technological innovation and the natural environment.

Hypothesis 4: Financial development plays a moderating role between green technology innovation and carbon emission efficiency.

Technological innovation activities generate market frictions and transaction costs. Financial activities and financial service can moderate these frictions and transaction costs, thereby generating more technological innovation. For example, the cost of information reduces the willingness of individual investors to invest. However, finance enables faster and more efficient access to the cost of investment opportunities, thereby reducing the need for individual investors to have access to large amounts of technical information. Promising production technologies and innovative entrepreneurs are then discovered (Blackburn and Hung 1998). Therefore, the role of financial development in promoting technological innovation is undeniable. On the other hand, financial development can encourage investment in technological innovation. A sound economic policy and financial system can improve a country's ability to innovate, thereby achieving economic growth (Meierrieks 2014). There was no definite conclusion on the impact of financial development on the environment. On the one hand, financial development provides an impetus to green technology innovation, with an emission reduction effect (Koondhar et al. 2021). On the other hand, financial development ensures technological progress, increases energy consumption, and increases carbon emissions, thereby damaging the quality of the environment (Acheampong et al. 2020). In general, it can be argued that financial development leads to more green

technology innovation and plays a moderating role between green technology innovation and carbon emission efficiency.

Methodology and data

Study sample and interval

The United Nations (UN) Development Programme has developed the Human Development Index, which is a comprehensive measure of health, education, and living standards, and provides an alternative to the assessment of economic development by GDP per capita. By 2010, the UN had identified 43 developed countries. Excluding those that have not proposed carbon neutrality targets and based on the availability of data, we finally selected 32 developed countries that have proposed carbon neutral goals and a study period of 1990–2017. These countries have proposed carbon neutrality target dates by incorporating strategies and legal regulations. Among the selected countries, Australia and Poland did not propose a carbon neutrality target at the national level. Adelaide in Australia proposed its own carbon neutrality target and the Polish Institute predicted that Poland would achieve carbon neutrality by 2056. Singapore has proposed a carbon neutrality target as soon as possible by the middle of this century. Table 2 shows the carbon neutrality target dates and the nature of the carbon neutrality commitments of the countries investigated in this paper.

Estimation methods

Baseline regression model

To achieve the carbon neutrality goal, developed countries have undertaken information exchanges and learnt from each other to improve their carbon emission efficiency. The traditional economic model does not incorporate spatial effects, but in this study, it was assumed that carbon emission efficiency is influenced by neighboring countries. The spatial weight matrix W was used to express the proximity of spatial regions in n locations, and the spatial effects were incorporated into the econometric model for a spatial econometric analysis. The spatial association of economic factors cannot be explained by the spatial weights formed by geographical distance. An economic distance weight matrix was established as follows.

$$W_{ij} = \begin{cases} \dfrac{1}{|g_i - g_j|}, i \neq j \\ 0, i = j \end{cases} \tag{1}$$

where g represents the economic development level of a country, namely, GDP.

Referring to Dong et al. (2021a), we started with a general nesting spatial model (GNS) that included all spatial items, as shown in Eq. (2).

Table 2 Carbon neutrality targets of developed countries

Country	Target year	Nature of commitment	Country	Target year	Nature of Commitment
UK	2050	In Law	Sweden	2045	In Law
France	2050	In Law	Denmark	2050	In Law
Hungary	2050	In Law	Germany	2045	In Law
Canada	2050	In Law	New Zealand	2050	In Law
Spain	2050	Proposed Legislation	South Korea	2050	Proposed Legislation
Ireland	2040	In Policy Document	Switzerland	2050	In Policy Document
USA	2050	In Policy Document	Slovakia	2050	In Policy Document
Australia	2025	In Policy Document	Portugal	2050	In Policy Document
Finland	2035	In Policy Document	Ireland	2050	In Policy Document
Japan	2050	In Policy Document	Austria	2040	In Policy Document
Singapore	Uncertain	In Policy Document	Norway	2050	In Policy Document
Czech Republic	2050	Target Under Discussion	Poland	2056	/
Netherlands	2050	Target Under Discussion	Cyprus	2050	Target Under Discussion
Estonia	2050	Target Under Discussion	Malta	2050	Target Under Discussion
Belgium	2050	Target Under Discussion	Italy	2050	Target Under Discussion
Greece	2050	Target Under Discussion	Luxembourg	2050	Target Under Discussion

Source: Energy & Climate Intelligence Unit.

(a) https://eciu.net/netzerotracker

$$lncee_{it} = \beta_0 + \delta W lncee_{it} + \beta_1 lngt_{it}$$

$$+\beta_2 lnX_{control}+\theta_1 W lngt_{it}+\theta_2 W lnX_{control} + \mu_{it} \tag{2}$$

$$u_{it} = \lambda W u_{it} + \varepsilon_{it}$$

where *cee* indicates the carbon emission efficiency of each country. *gt* represents green technology innovation, which is the core explanatory variable. *W* is the economic distance matrix. ε_{it} and u_{it} obey an independent uniform distribution.

If $\theta = 0$, the GNS degenerates into a spatial autocorrelation (SAC) model. At this point, if $\lambda = 0$, $\delta \neq 0$, it further degenerates into a spatial autoregressive (SAR) model; if $\lambda \neq 0$, $\delta = 0$, it degenerates into a spatial error model (SEM); if $\lambda = 0$, $\delta = 0$, it degenerates into an ordinary least squares (OLS) model. Only when $\lambda \neq 0$, $\delta \neq 0$, $\theta \neq 0$, GNS becomes the spatial Durbin (SDM) model. In the empirical analysis, the order of OLS-SEM-SAR-SAC-SDM was followed to select the most fitting form of the spatial econometric model.

Spatial mediation model

Spatial mediation models were constructed to confirm hypotheses 2 and 3. Equations (3), (4), and (5) are the mediating model of economic development that were used to test Hypothesis 2.

$$lncee_{it} = \gamma_0 + \gamma_1 lngt_{it} + \gamma_2 lnX_{control} + \delta_3 W lngt_{it} + \delta_4 W lnX_{control} + \varepsilon_{it} \tag{3}$$

$$lnpgdp_{it} = \beta_0 + \beta_1 lngt_{it} + \beta_2 lnX_{control} + \delta_5 W lngt_{it} + \delta_6 W lnX_{control} + \varepsilon_{it} \tag{4}$$

$$lncee_{it} = \gamma_0 + \gamma_3 lngt_{it} + \gamma_4 lnpgdp_{it}$$
$$+ \gamma_5 lnX_{control} + \delta_7 W lngt_{it} \tag{5}$$
$$+ \delta_8 W lnX_{control} + \varepsilon_{it}$$

First, a significance test was conducted for β_1 and γ_4. If γ_4 passed the test, then γ_3 was tested. If γ_3 passed the test, it indicated that this was a partial mediating effect. If it did not pass the test, it indicated that this was a significant full mediating effect of economic development. If one of β_1 or γ_4 did not pass the test, a Sobel test was required. If the Sobel test was significant, it indicated that the mediating effect of economic development was significant. Otherwise, the mediating effect was not significant.

Equations (3), (6), and (7) are the mediating model of urbanization used to test Hypothesis 3.

$$lnurb_{it} = \beta_0 + \beta_3 lngt_{it} + \beta_4 lnX_{control} + \delta_9 W lngt_{it} + \delta_{10} W lnX_{control} + \varepsilon_{it} \tag{6}$$

$$lncee_{it} = \gamma_0 + \gamma_6 lngt_{it} + \gamma_7 lnurb_{it}$$
$$+ \gamma_8 lnX_{control} + \delta_{11} W lngt_{it} \tag{7}$$
$$+ \delta_{12} W lnX_{control} + \varepsilon_{it}$$

The test procedure was the same as Hypothesis 2.

Spatial moderation model

The spatial moderation model was used to test Hypothesis 4. To test Hypothesis 4, a spatial moderation model for *fd* was constructed, with $lngt \times lnfd$ as the interaction term, namely, Eq. (8).

$$lncee_{it} = \eta_0 + \eta_1 lngt_{it} + \eta_2 lngt_{it} \times lnfd_{it} + \eta_3 lnX_{control}$$
$$+ \delta_1 W lngt_{it} + \delta_2 lnX_{control} + \varepsilon_{it} \tag{8}$$

If the estimated coefficient η_2 was not zero and the *p* value was less than 0.1, it indicated that *fd* has an impact on *gt* influence *cee*. α_2 reflected the extent of the moderating effect.

Variable selection

Dependent variable

The SBM with undesirable outputs was used to measure the carbon emission efficiency of the developed countries and was expressed using the following:

$$\rho^* = \min \frac{1 - \frac{1}{m} \sum_{i=1}^{m} \frac{s_i^-}{x_{i0}}}{1 + \frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1} \frac{s_r^g}{y_{r0}^g} + \sum_{r=1}^{s_2} \frac{s_r^b}{y_{r0}^b}\right)}$$

$$s.t. \begin{cases} x_0 = X\lambda + s_i^- \\ y_0^g = Y^g\lambda - s^g \\ y_b^0 = Y^b\lambda + s^b \\ s_i^- \geq 0, s^g \geq 0, s^b \geq 0, \lambda \geq 0 \end{cases} \tag{9}$$

where X, Y^g, and Y^b represent the input elements, desirable outputs, and undesirable outputs, respectively. The vectors s^- and s^b represent the slack variables of inputs and undesirable outputs, respectively, while s^g represents the slack variables of desirable outputs. λ is the weight vector. The objective function ρ^* strictly decreases with respect to s^-, s^g, and s^b, and $\rho^* \in [0,1]$. For a particular evaluated unit, only when $\rho^* = 1$, that is, when s^-, s^b, and s^g are 0, is the evaluated unit efficient. When $\rho^* < 1$, the evaluated unit is inefficient, that is, the input–output can be improved. The evaluated unit can be improved by reducing the excess of inputs and bad outputs and increasing the shortage of desirable output. It can also show that there is energy waste in the decision-making unit.

The carbon emission efficiency of 32 developed countries during 1990–2017 was evaluated. According to traditional macroeconomic theory, capital stock, labor force, and primary energy consumption were selected as the input variables to measure carbon emission efficiency, with the desirable output being the GDP of each country and CO_2 being

the undesirable output. Table 3 shows the indicators used to measure the carbon emission efficiency.

The capital stock was obtained using the perpetual inventory method with the following formula:

$$K_{i,t} = K_{i,t-1}(1 - \delta_{i,t}) + I_{i,t} \qquad (10)$$

where i refers to the i-th country, t refers to t year, K is the capital stock, and I is gross fixed capital formation. In the absence of a consensus, the capital depreciation rate was set to 6% (Vander et al. 2021), using 1990 as the base period.

Independent variable

Green technology innovation (*gt*). The improvement of carbon emission efficiency by green technologies is significant (Xie et al. 2021) and can effectively reduce carbon emissions. We used the Organization for Economic Cooperation and Development (OECD) database of environment-related technologies as a proportion of all technologies to represent green technology innovation (Razzaq et al. 2021; Paramati et al. 2021), which includes the eight categories shown in Table 4.

Mediating variables

Economic development (*pgdp*). The relationship between economic development and carbon emissions was consistent with the EKC hypothesis (Sephton and Mann, 2013; Daniel et al. 2018; Yang et al. 2015). In this study, we adopted the national GDP per capita to reflect the level of economic development of a country. For convenience, we did not consider the nonlinear relationship between the two.

Table 3 Indicators for measuring carbon emission efficiency

	Indicators	Unit
Input	Labor	Thousand people
	Capital stock	Billion USD
	Energy consumption	Billion Btu
Desirable output	Regional GDP	Billion USD
Undesirable output	CO_2 emissions	Million ton

Urbanization (*urb*). The effect of urbanization on carbon emission efficiency was also consistent with the EKC hypothesis (Sun and Huang 2020). In this study, the urban population as a proportion of the total population was used to indicate the urbanization rate. Similarly, urbanization does not consider the quadratic term.

Moderating variable

Financial development (*fd*). Financial development has a significant impact on carbon emissions (Koondhar et al. 2021; Acheampong et al. 2020). This paper uses the Financial Development Index developed by the International Monetary Fund's (IMF) Financial Development Index database (Svirydzenka 2016).

Control variables

Energy intensity (*ei*). The central objective of climate policy is to reduce the energy intensity of production processes, which is an important means of reducing carbon emissions (Wurlod and Noailly 2018). In this study, energy intensity was measured by the total primary energy consumption as a proportion of GDP.

Energy structure (*es*). Renewable energy is indispensable in reducing environmental degradation (Cheng et al. 2019). The energy structure was characterized as the total renewable energy consumption as a percentage of primary energy consumption. Given that the relationship between renewable energy and carbon emissions is nonlinear (Xiao and Zhang 2019), a quadratic term for *es* was introduced.

Government influence (*gov*). The government plays a more significant role in carbon reduction than enterprises (Yao et al. 2020). General government consumption expenditure as a proportion of GDP was used to reflect the influence of a country's government on the economy and society.

Industrial structure (*ind*). Upgrading the industrial structure can reduce carbon emissions (Zhang et al. 2020; Dong et al. 2021b). The was measured by the contribution of industrial output to total GDP. Industry in this study included mining, manufacturing, utilities, and construction.

Degree of external openness (*trd*). Trade can expand the scale of production, thereby affecting carbon emissions (Du

Table 4 Classification of green technologies

Environment-related technologies	1. Climate change mitigation technologies related to buildings
	2. Climate change mitigation technologies related to energy generation, transmission or distribution
	3. Capture, storage, sequestration or disposal of greenhouse gases
	4. Environmental management
	5. Climate change mitigation technologies related to transportation
	6. Water-related adaptation technologies
	7. Climate change mitigation technologies in the production or processing of goods
	8. Climate change mitigation technologies related to wastewater treatment or waste management

et al. 2019). In this study, we characterized this effect as the value of total export and import goods and services as a proportion of GDP.

Data sources and stationary test

A constant growth rate was assumed to estimate the missing values. To reduce the effect of heteroskedasticity, a logarithmic transformation was performed on both the dependent and independent variables. Variables related to prices are deflated to 2010 constant price. The raw data were mainly obtained from the World Development Indicators published by the World Bank, OECD, US Energy Information Administration (EIA), United Nations Conference on Trade and Development (UNCTAD), and IMF. Tables 5 and 6 show the definition, data source, and descriptive statistics of the variables.

Table 11 of the Appendix presents the correlation coefficients and variance inflation factor (VIF) values for variables. The maximum correlation coefficient between the independent variables was 0.527, and the VIFs were all less than 10, indicating that there was no serious multicollinearity.

To avoid pseudo-regression, all variables were subjected to stationary tests (the Levin-Lin-Chu (LLC) and Im-Pesaran-Shin (IPS) tests), and the results are shown in Table 12 of the Appendix. Only $lnpgdp$ and $lnes$ failed the LLC and IPS tests, while both $dlnpgdp$ and $dlnes$ passed the tests. Overall, the variables selected in this study were found to be first-order stable. A cointegration test was then performed and the results are displayed in Table 13 of the Appendix. All variables passed at the 1% significance level, and there was a cointegration relationship. In a word, there was no pseudo-regression problem.

Table 6 Descriptive statistics of the variables

Variables	Obs	Mean	Std. Dev	Min	Max
Capital	896	3,070,000	6,220,000	7819.550	43,000,000
Labor	896	15,383.640	27,964.910	136.300	164,000
Energy	896	6,850,000	16,600,000	27,660.44	101,000,000
GDP	896	1,190,000	2,500,000	4241	17,400,000
CO_2	896	390.735	966.908	2.100	6003.100
$lncee$	896	−0.586	0.365	−1.552	0
$lngt$	896	3.687	2.130	0	8.713
$lnpgdp$	896	10.378	0.588	8.614	11.626
$lnurb$	896	−0.271	0.153	-0.736	0
$lnfd$	896	−0.551	0.609	-9.210	0
$lnei$	896	1.748	0.468	0.582	3.149
$lnes$	896	1.417	4.163	−13.816	4.425
$lnes2$	896	19.322	40.587	0.015	190.868
$lngov$	896	−1.630	0.227	−2.447	−0.971
$lnind$	896	−1.428	0.230	−2.287	−0.856
$lntrd$	896	−0.291	0.652	−1.908	1.409

Analysis of the empirical results

Calculation of carbon emission efficiency

The carbon emission efficiency of the 32 developed countries was calculated using Eq. 13. Figure 2 shows the average carbon emission efficiency during the sample period. There were differences in the *cee* of the 32 countries. Only three countries had an efficient *cee* (*cee* = 1): Luxembourg, Norway, and Switzerland, which are located in northern and central Europe. Denmark (0.988) is fourth. These four countries also had the highest average GDP per capita of all the countries studied. The higher the level of economic development, the more sophisticated the technology level, and the more complete the service sector, the lower the overall carbon emission level, resulting in a higher carbon emission efficiency. The other countries were non-efficient. The

Table 5 Definition and data source of the variables

|	Variable	Definition	Unit	Data Source
Dependent variable	*gt*	Proportion of environment-related technologies in all technologies	Percent	OECD
Mediating variables	*pgdp*	Gross domestic product per capita	US dollar	World Bank
	urb	Proportion of the urban population in the total population	Percent	World Bank
Moderating variable	*fd*	Financial Development Index	/	IMF
Control variables	*ei*	Proportion of the total primary energy consumption in GDP	Percent	EIA
	es	Proportion of renewable energy consumption in total final energy consumption	Percent	EIA
	gov	Proportion of general government consumption expenditure in GDP	Percent	UNCTAD
	ind	Proportion of industrial output in GDP	Percent	UNCTAD
	trd	Proportion of the value of total export and import goods and services in GDP	Percent	World Bank
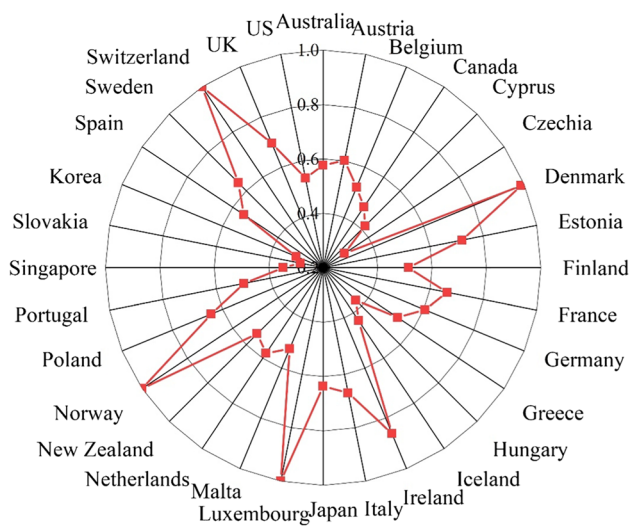
Fig. 2 Average carbon emission efficiency of 32 developed countries from 1990 to 2017

Table 7 *lncee* global spatial autocorrelation test

Year	I	p value
1990	0.064	0.210
1991	0.062	0.214
1992	0.081	0.170
1993	0.049	0.248
1994	0.054	0.234
1995	0.033	0.290
1996	0.030	0.299
1997	0.054	0.233
1998	0.078	0.175
1999	0.082	0.166
2000	0.191[**]	0.028
2001	0.211[**]	0.019
2002	0.268[***]	0.005
2003	0.261[***]	0.006
2004	0.166[**]	0.045
2005	0.146[**]	0.064
2006	0.254[***]	0.007
2007	0.385[***]	0.000
2008	0.355[***]	0.000
2009	0.270[***]	0.005
2010	0.288[***]	0.003
2011	0.285[***]	0.003
2012	0.277[***]	0.004
2013	0.248[***]	0.000
2014	0.208[***]	0.008
2015	0.209[***]	0.000
2016	0.195[***]	0.000
2017	0.208[***]	0.000

Standard errors in parentheses. 1%, 5%, and 10% significant level are indicated by [***], [**], and [*], respectively

countries with a *cee* below 0.4 were Slovakia (0.286), Czech Republic (0.294), South Korea (0.307), Singapore (0.346), and Hungary (0.369). Except Singapore, the average GDP per capita of these countries was the lowest of the countries studied, indicating a relationship between the level of economic development and carbon emission efficiency.

Spatial correlation test

The Moran's I was used to describe the degree of association of the overall *lncee*, and Table 7 shows the results of a global spatial autocorrelation test of the *lncee*. In terms of time, the Moran's I of *lncee* only became significant after 2000. The global Moran's I was always positive and was highly significant at the 5% significance level, fluctuating around 0.2. It indicated that the *lncee* had a positive spatial correlation. Generally, it was appropriate to use the spatial econometric model to assess carbon emission efficiency.

The global Moran's I can only reflect the average correlation and not the spatial correlation of each country. By contrast, Moran's I scatter plot was used to test for spatial dependence. The global Moran's I only showed a correlation from 2000. For brevity, only 2000, 2006, 2012, and 2017 were selected to draw the local Moran scatter plot shown in Fig. 3, in which the circle is the performance of the carbon emission efficiency of each country. The first quadrant (top right) and the third quadrant (bottom left) show the interactions between homogeneous countries. The first quadrant shows the interaction between high level countries and other high level countries (i.e., high-high level). The third quadrant shows the interaction between low level countries and other low level countries (i.e., low-low level). The second

quadrant (top left) and the fourth quadrant (bottom right) show the interactions between heterogeneous countries. The second quadrant shows the interaction between low level countries and high level countries (i.e., low–high level). The fourth quadrant shows the interactions between high level countries and low level countries (i.e., high-low level). Most countries were clustered in the first and third quadrants, and the carbon emission efficiency was both spatially heterogeneous and spatially clustered.

Baseline regression results

To select the appropriate spatial econometric model, a spatial correlation test of the residuals based on the OLS results was performed, and the results are displayed in Table 8. Lagrange error, Robust error, Lagrange lag, and Robust lag
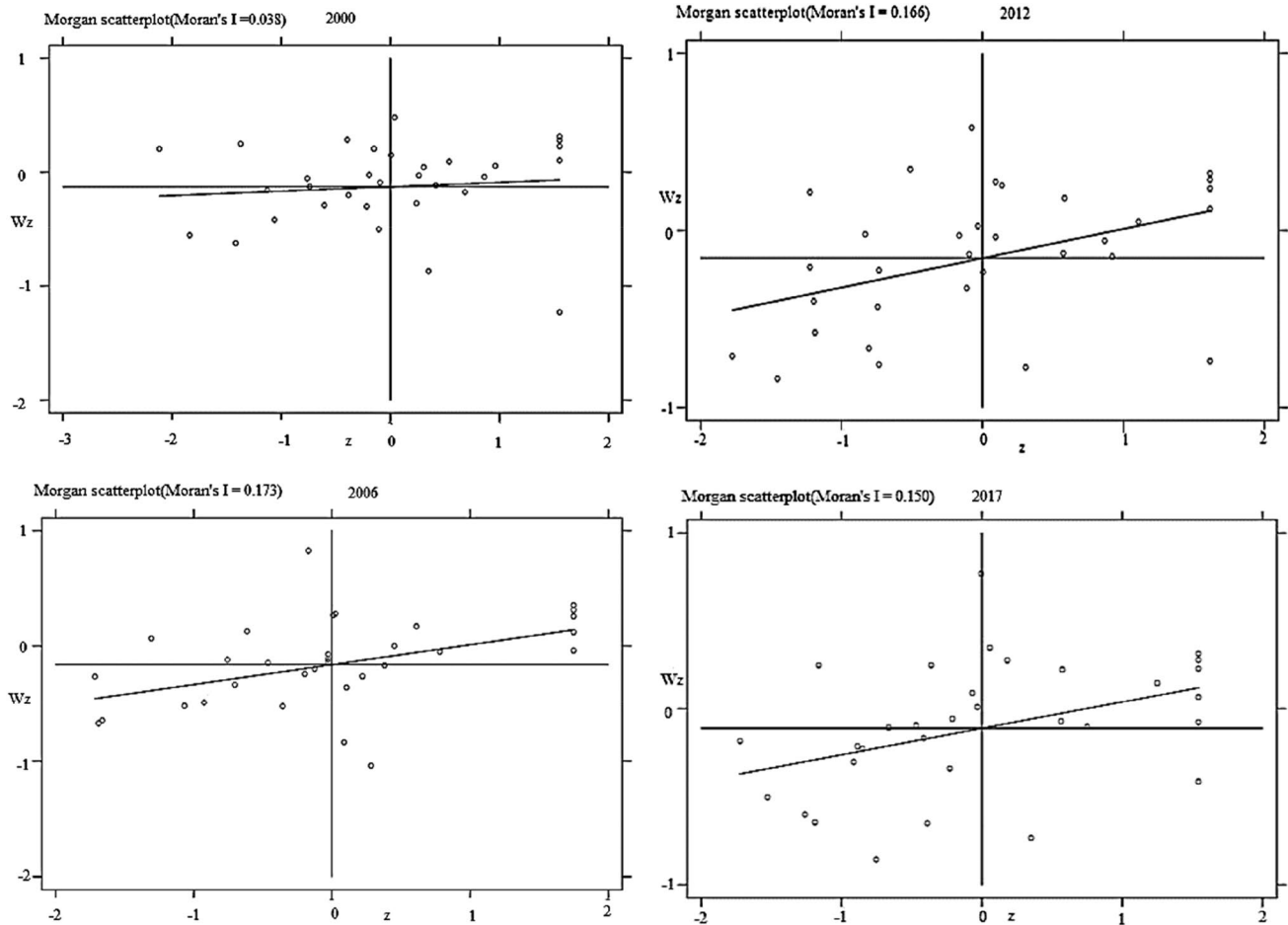
Fig. 3 Moran I scatter plot of carbon emission efficiency

Table 8 Residual space correlation test based on OLS estimation results

Indicator	Statistic	*p* value
Lagrange error	231.533[***]	0.000
Robust error	40.965[***]	0.000
Lagrange lag	243.770[***]	0.000
Robust lag	53.202[***]	0.000

were significant. In general, the SDM was selected as the baseline regression model. In addition, the Hausman test results showed that the corresponding statistical value was 64.69 ($p = 0.000$) and original hypothesis was rejected at the 1% significance level. Therefore, the SDM fixed effect was finally selected.

The Wald test and likelihood ratio (LR) test were performed on the SDM, and the *p* values of the Wald and LR spatial lag tests, as well as the spatial error test, were 0 at the 1% significance level, indicating that the SDM model had a better fit compared with the other models.

For a visual comparison, Table 9 shows the baseline regression results, including the OLS, SAR, SEM, SAC, and SDM results. Models 1–4 were fixed effects models. Models 5 and 6 were the SDM. Model 5 was a panel model with fixed individual effects, and model 6 was a double fixed effects model. Models 1–6 showed that green technology innovation made a significant contribution to the carbon emission efficiency. The estimated coefficient of *lngt* in model 6 was 0.03, with a *p* value of 0. The *lngt* was also significant in other models. As a result, Hypothesis 1 was confirmed. The increase of environment-related green technology innovation will lead to the expansion of production scale, increase of output, and reduction of energy consumption, thereby improving carbon emission efficiency of enterprises. The signs of the coefficients of all variables did not change, indicating that the results were robust.

It is worth noting that the relationship between energy structure and carbon emission efficiency was nonlinear,

Table 9 The results of benchmark regression

Variable	Model 1 OLS	Model 2 SAR	Model 3 SEM	Model 4 SAC	Model 5 SDM	Model 6 SDM
lngt	0.015**	0.045***	0.045***	0.048***	0.049***	0.041***
	(0.007)	(0.010)	(0.010)	(0.010)	(0.010)	(0.011)
lnei	−0.159***	−0.034	−0.033	−0.018	−0.123***	−0.089**
	(0.035)	(0.040)	(0.041)	(0.040)	(0.041)	(0.041)
lnes	0.039***	0.044***	0.044***	0.041***	0.048***	0.054***
	(0.013)	(0.013)	(0.013)	(0.014)	(0.014)	(0.013)
lnes2	0.003***	0.003***	0.003***	0.003***	0.003***	0.003***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
lngov	−0.317***	−0.510***	−0.511***	−0.505***	−0.530***	−0.530***
	(0.062)	(0.063)	(0.063)	(0.065)	(0.065)	(0.063)
lnind	−0.041	−0.072	−0.071	−0.048	−0.129**	−0.069
	(0.048)	(0.062)	(0.063)	(0.063)	(0.061)	(0.061)
lntrd	−0.145***	−0.113***	−0.114***	−0.138***	−0.067	−0.078*
	(0.026)	(0.038)	(0.040)	(0.040)	(0.041)	(0.041)
_cons	−0.933***					
	(0.171)					
ρ		−0.453***	−0.435***		−0.246***	−0.455***
		(0.068)	(0.123)		(0.066)	(0.070)
λ			-0.019	−0.419***		
			(0.126)	(0.074)		
σ²		0.016***	0.016***	0.016***	0.016***	0.015***
		(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Industry fixed	No	Yes	Yes	Yes	Yes	Yes
Time fixed	No	Yes	Yes	Yes	No	Yes
N	896	896	896	896	896	896

Standard errors in parentheses.

*$p < 0.1$, **$p < 0.05$, ***$p < 0.01$.

which was consistent with Xiao and Zhang (2019) and Dong et al. (2022a). The estimated coefficients of energy structure and its quadratic term were always positive, and energy structure and carbon emission efficiency showed a positive U-shaped relationship. With a small proportion of renewable energy, *cee* decreased with *es*. But when the share of renewable energy crossed a certain threshold, *cee* increased with *es* and the increase became more rapid. Renewable and fossil energy sources are alternative, with the use of renewable energy reducing CO_2 emissions and easing the pressure on the environment. A small share of renewable energy had a suppressive role on carbon emission efficiency. This may be because the scale of renewable energy was small. There was no scale effect and the cost of the development and utilization of renewable energy was high, which was not beneficial to emission reduction. However, when the share of renewable energy exceeded a certain threshold, the carbon emission efficiency increased rapidly. The technology available for the development and utilization of renewable

energy was more advanced. When the scale of renewable energy was expanded, the cost of use decreased, which was beneficial to carbon emission reduction. In conclusion, countries all over the world are striving to transition from fossil fuels to renewable energy as a means to reduce emissions and achieve carbon neutrality (Zhang et al. 2021; Dong et al. 2022b).

The estimated coefficients of the other control variables were in line with expectations. The negative coefficient of energy intensity indicated that the higher the energy intensity, the higher the primary energy consumption, and the more greenhouse gases were produced. A high energy intensity was detrimental to carbon emission reduction (Wang et al. 2019a). Government intervention will be conducive to carbon emission reduction. Because government regulation will likely lead to market failure, which is not conducive to the optimization of resources, the carbon market should follow the law of market development. Market allocation of resources will be more conducive to

carbon emission efficiency. It is also reasonable that industrial structure and degree of openness to the outside world are significantly negatively related to carbon emission efficiency. The secondary industry is a highly polluting industry, which is not conducive to carbon emission reduction. Rationalization and advanced industrial structure can improve carbon emission performance (Wang et al. 2019b). Foreign trade activities expand production scale, increase energy consumption, and raise carbon dioxide emissions (Dong et al. 2017).

Analysis of the transmission mechanism

From the baseline regression results in Table 9, it can be seen that green technology innovation had a positive impact on carbon emission efficiency in the 32 developed countries. However, the transmission mechanism by which green technology innovation affects carbon emission efficiency was not clear. We examined the transmission mechanism from the perspective of economic development and urbanization and how financial development moderated green technology innovation and carbon emission efficiency to confirm hypotheses 2, 3, and 4, respectively. Table 10 shows the empirical results of the spatial mediated and spatial moderation models. Figure 4 shows the model estimation coefficients for each path.

Models 7–9 in Table 10 were used to test hypothesis 2. Model 7 only contained the core explanatory variables and control variables, and the results showed that green technology innovation had a positive effect on carbon emission

Table 10 Results of the spatial mediation effect model and the spatial moderating effect model

Variable	Model 7 lncee	Model 8 lnpgdp	Model 9 lncee	Model 10 lnurb	Model 11 lncee	Model 12 lncee
lngt	0.049***	0.034***	0.034***	0.008***	0.042***	0.058****
	(0.010)	(0.005)	(0.010)	(0.002)	(0.010)	(0.011)
lnpgdp			0.448***			
			(0.062)			
lnurb					0.319*	
					(0.174)	
lngt×lnfd						0.036***
						(0.009)
ρ	0.246***	0.065***	−0.238***-	−0.179***	−0.314***	−0.546***
	(0.066)	(0.054)	(0.065)	(0.066)	(0.067)	(0.071)
Industry fixed	Yes	Yes	Yes	Yes	Yes	Yes
N	896	896	896	896	896	896

Notes: Standard errors in parentheses. $^*p<0.1$, $^{**}p<0.05$, $^{***}p<0.01$. The results of the control variables are not shown in the table

Fig. 4 Regression coefficient of the model. Note: * indicates $p<0.1$; ** indicates $p<0.5$; *** indicates $p<0.01$
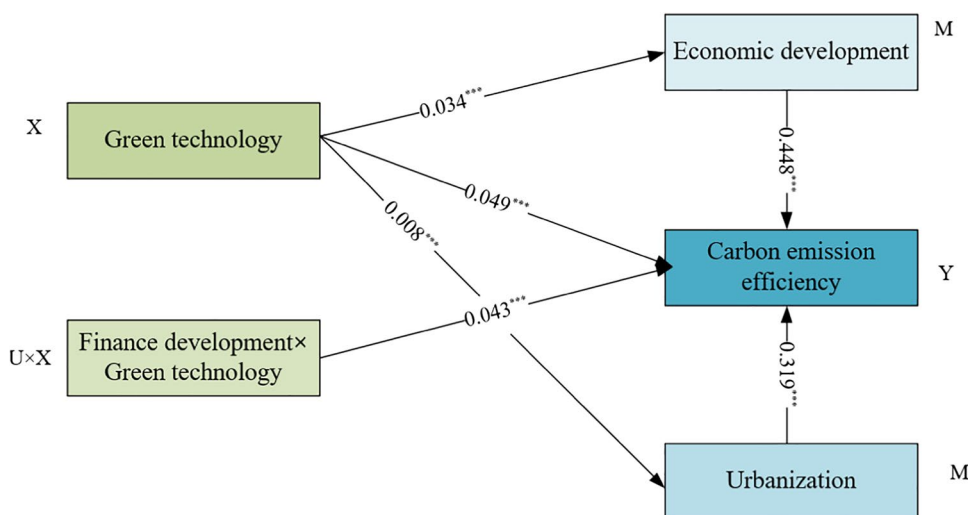
efficiency. Model 8 used the mediating variable of the level of economic development as the explained variable to analyze the relationship between the level of economic development and green technology innovation. Model 9 also considers the impact of economic development level and green technology innovation on carbon emission efficiency. Finally, by comparing the estimated coefficients of the variables in the three models, it was determined whether the effect of green technology innovation on carbon emission efficiency could be realized through the level of economic development.

In model 7, the results showed that green technology innovation could significantly contribute to carbon emission efficiency. In other words, increasing the availability of environment-related technology reduced carbon emissions and increased carbon emission efficiency. In addition, the more environment-related technologies a country had, the more consideration it gave to environmental benefits and the more attention it gave to environmental pollution. Therefore, hypothesis 1 was confirmed. Economic development was further considered in model 9. The results showed that when economic development and green technology innovation were considered simultaneously, the contribution of green technology innovation to carbon emission efficiency decreased, and the estimated coefficient decreased from 0.049 to 0.034. A higher level of economic development improved carbon emission efficiency. Model 8 analyzed the relationship between green technology innovation and economic development, and the results showed that green technology innovation significantly contributed to economic development. This indicated that the more environment-related green technology innovation that was available, the more beneficial the country's level of economic development.

By combining models 7 and 8 a spatial mediating effect of economic development was constructed. It was a partial mediating effect, and hypothesis 2 was confirmed, which was consistent with Liu and Dong (2021). Green technology innovation was positively correlated with carbon emission efficiency. In other words, countries with more environment-relevant green technology innovation faced less pressure to reduce emissions. Additionally, green technology innovation had an indirect positive effect on carbon emission efficiency through the level of economic development. This indicated that countries with more green technology innovation had higher level of economic development, and higher level of economic development could improve the carbon emission efficiency. The direct impact of green technology innovation on carbon emissions was relatively small. Green technology innovation could have a large impact on national carbon emission efficiency by influencing the level of economic development.

Technological change is the engine of long-term economic growth, and both the quantity and quality of innovative activity are responsible for determining the level of technological innovation. Environmentally related green technology innovation is a high-quality technology that not only accompanies the increase in output and efficiency and the reduction in production costs, but also stimulates economic growth and promotes the sustainable economic development of the economy. The higher the level of economic development of a country, the more it focused on environmental benefits, and the more it could afford to commit to environmental management, and the easier it was to achieve carbon reduction targets, thereby realizing a green growth economy. Therefore, green technology innovation has a promoting effect on carbon emissions, highlighting the importance and necessity of green technological innovation in pollution control. This is consistent with the conclusion of Feng et al. (2021).

Models 7, 10, and 11 in Table 10 were used to test hypothesis 3. Model 7 served the same purpose as above. In model 10, urbanization was used as the explained variable to empirically analyze the relationship between urbanization level and green technology innovation. In model 11, how the urbanization level of the intermediary variable affects the impact of green technology innovation on carbon emission efficiency was examined. Finally, by comparing the estimated coefficients of the variables in the three models, it could be determined whether the effect of green technology innovation on carbon emission efficiency was realized through the level of urbanization.

Urbanization was further considered in model 11, with the results showing that when urbanization and green technology innovation were considered simultaneously, the contribution of green technology innovation to carbon emission efficiency was slightly weaker. The estimated coefficient changed from 0.049 to 0.042, and a higher level of urbanization led to improve carbon emission efficiency. Model 12 analyzed the relationship between green technology innovation and urbanization, with the results showing that green technology innovation was significantly positively related to urbanization. However, this was a weak relationship, indicating that the more environment-related technology is available, the more conducive it is to an improvement in a country's urbanization level.

Combining models 7, 11, and 12, the spatial mediated effects of urbanization could be constructed, which was a partial mediating effect. Therefore, hypothesis 3 was confirmed. Green technology innovation was positively correlated with carbon emission efficiency, but there was also a positive moderating effect between green technology innovation and carbon emission efficiency through the level of

urbanization. This indicated that countries with more green technology innovation had a higher level of urbanization, which could be accompanied by a higher carbon emission efficiency. In addition, the direct effect of green technology innovation on carbon emissions was relatively small. Green technology innovation could have a large impact on national carbon emission efficiency by influencing the level of urbanization.

There was a two-way causal relationship between green technology innovation and urbanization. On the one hand, technological innovation is the basis of urbanization. Through the knowledge spillover effect, green technology innovation can promote the development of the technology economy and accelerate the flow and exchange of technology and knowledge. This enables the transformation, promotion, and application of technological achievements and promotes technological upgrading and high-quality urbanization. On the other hand, urbanization highlights the advantages of green technology innovation. The expansion of city size and number of city within a country leads to an expansion of technological innovation inputs, thereby improving technological innovation capacity. Senior professionals and specialized enterprises gather in cities, and the diversified environment provides opportunities for the exchange of skilled workers from different industries and disciplines, thereby promoting the generation and diffusion of new technologies and industries (Wu et al. 2020). Most researchers believed that the relationship between urbanization and carbon emissions in developed countries has an inverted U-shape (Wang et al. 2015; Zhang et al. 2017; Wang et al. 2021) and has crossed a threshold. The relationship between urbanization and carbon emissions has reached the second stage. In other words, carbon emissions decline as urbanization increases. Developed countries have a high total GDP and GDP per capita. Knowledge spillover and technological innovation will give rise to the generation of clean technologies and the application of renewable energy. Urbanization has a scale effect on resource use, so that the agglomeration effect of urbanization leads to less carbon emission increase than the efficient use of resources by cities. This is consistent with the conclusion of Wang et al. (2018). In a word, future urbanization will suppress carbon emissions, thus improving carbon emission efficiency.

To analyze the moderating effect of financial development on the relationship between green technology innovation and carbon emission efficiency, the interaction terms of *lngt* and *lnfd* were generated. Model 12 in Table 10 was a spatial moderation model used to test hypothesis 4, which considered how financial development regulates the relationship between green technology innovation and carbon emission efficiency. *lngt* and *lngt* × *lnfd*

both passed the test at the 1% significance level, and the estimated coefficient of the interaction term was 0.036. This result verified hypothesis 4, indicating the significant role of the interaction term. It is worth noting that the contribution of green technology innovation to carbon emission efficiency was enhanced by adding the interaction term. The estimated coefficient increased from 0.049 to 0.048 and passed the test at the 1% significance level, indicating that financial development positively moderated the contribution of green technology innovation to carbon emission efficiency.

A good financial system provides the technological innovation system of a country with the large-scale financing needed for technological innovation. Capital markets promote long-term, stable, and sustainable technological innovation by providing long-term incentive functions, risk diversification, and shared opportunities for investors in technological innovation (Tadesse 2002). Financial development reduces the high cost of access to information for individual investors, and promising production technologies and good entrepreneurs can be developed. Financial development also reduces regulatory costs, making investment in technological innovation activities more attractive to investors. Promising production technologies and innovative entrepreneurs are also able to receive financial support, and more green technology innovation are invented, thereby increasing the overall level of innovation. In general, financial development positively moderated the impact of green technology innovation on carbon emission efficiency, which leads to the contribution of green technology innovation to carbon emission efficiency more obvious.

Conclusions and policy recommendations

Conclusions

Technological innovation plays an important role in carbon emission reduction. All countries have increased their investment in innovation, and environmentally related green technology innovation has a direct mitigation effect on carbon emissions which is worth more attention. Clarifying the relationship and mechanism between green technology innovation and carbon emission efficiency is conducive to improving carbon emission efficiency and enabling countries to achieve carbon neutrality goals as soon as possible. In this study, we considered 32 developed countries that have proposed carbon neutrality targets as research samples. From the perspective of mediating and moderating effects, the influence of environment-related green technology innovation on carbon emission efficiency

and the transmission mechanisms were explored by considering spatial spillover effects, and the mediating role of economic development and urbanization and moderating role of financial development were analyzed. The following four research outcomes were obtained.

(1) According to the efficiency measurement results, Luxembourg, Norway, and Switzerland were found to have achieved carbon emission efficiency. The other countries were in an inefficient state, and there was great potential for carbon reduction.

(2) Environment-relevant green technology innovation significantly improved carbon emission efficiency. Based on a sample of 32 developed countries, countries with more environment-related green technology innovation were more likely to have a high carbon emission efficiency, thereby reducing the pressure on carbon emission reduction, and improving the environmental efficiency of the country.

(3) Economic development and urbanization had a mediating role on green technology innovation and carbon emission efficiency. Green technology innovation could have an indirect impact on carbon emission efficiency by influencing economic development and urbanization. Countries with higher levels of economic development and urbanization were more focused on environmental benefits and more capable of committing to environmental management.

(4) Financial development could positively moderate the sensitivity of carbon emission efficiency to green technology innovation. Innovation activity is an expensive process that requires expensive start-up and operating costs. The enhancement of financial development provides financial support for green technology innovation and moderates the contribution of green technology to carbon emission reduction.

Policy recommendations

(1) Building a market-oriented green technology innovation system, developed countries should stimulate the innovative capacity of enterprises, universities, and research institutions. The importance of environmental pollution research is emphasized. Financial regulations are used rationally, and it is necessary to increase financial investment and strengthen the reduction of green technology innovation platforms. Then, they should also construct reasonable green technology standards to guide the direction of green technology innovation research, so that green technology innovation can be better evaluated and certified.

(2) While developing carbon neutrality goals, developed countries still regard economic development as one of their pursuit goals. Sufficient capital investment is an important driving force for the country to adopt carbon emission reduction measures. At the same time, they should continue to accelerate the pace of urbanization, rationally plan and comprehensively use urban land, better design and manage cities, and achieve green city development.

(3) The role of financial development on carbon emission efficiency is also highlighted. Policy makers should use market regulation and policy guidance to protect financial development, provide adequate credit support for green technology innovation, and reduce the risks and costs of financial development. It is necessary to guide financial institutions and R&D institutions to establish long-term cooperative relations, so that R&D institutions have sufficient funds. On the other hand, policy makers should use financial tools to increase investment in green technological innovation.

(4) To achieve carbon neutrality and reduce carbon emissions, it is necessary to drastically cut fossil fuel consumption and break the path dependence on traditional energy consumption. Policy makers need to formulate long-term carbon emission reduction plans to limit the proportion of high energy-consuming, high-emission, and high-polluting industries, vigorously develop green emerging industries and give play to the role of renewable energy in reducing carbon emissions.

Outlook

This paper focuses on the impact of green technology innovation on carbon emission efficiency that other scholars rarely pay attention to. In addition, the spatial mediation effect and the spatial moderation effect models provide new ideas for other scholars to analyze the influencing factors of carbon emission efficiency, but there are some for further research. First, compared with other models, the SBM-DEA model in this study needs to improve accuracy in measuring carbon emission efficiency. Secondly, our research is limited to developed countries, and it is also necessary to explore whether the influence mechanisms of developing countries or different regions within a country are the same. Finally, this paper only focuses on the mediating effects of economic development and urbanization and the moderating effect of financial development. Other transmission mechanisms have yet to be discovered.

Appendix

Table 11 Variable correlation

Variables	lngt	lnpgdp	lnurb	lnfd	lnei	lnes	lngov	lnind	lntrd
lngt	3.55								
lnpgdp	0.474***	2.19							
lnurb	0.220***	0.430***	2.1						
lnfd	0.443***	0.527***	0.249***	1.76					
lnei	−0.351***	−0.591***	0.086***	−0.366***	1.59				
lnes	0.386***	0.514***	0.158***	0.276***	-0.228***	1.56			
lngov	0,012	−0.081	−0.01	−0.201***	0.120***	0.108***	1.56		
lnind	0.163***	−0.165***	−0.230***	−0.062*	0.152***	0.052	−0.086***	1.26	
lntrd	−0.433***	0.083***	0.136***	−0.027	0.027	−0.182***	−0.227***	−0.242***	1.17

Note: The diagonal value is the VIF, whose mean value is 1.86, indicating that there is no serious multicollinearity.

Table 12 Unit root test

Variables	LLC	IPS
lncee	−30.608***(0.000)	−3.387***(0.000)
lngt	−25.121***(0.000)	−7.133***(0.000)
lnpgdp	−0.715(0.237)	1.252(0.895)
lnurb	−6.786***(0.000)	−1.058(0.145)
lnfd	−36.236***(0.000)	−27.778***(0.000)
lnei	−3.340***(0.000)	−16.223***(0.000)
lnes	14.377(1.000)	12.577(1.000)
lngov	−1.918**(0.000)	−1.691**(0.000)
lnind	−3.162***(0.000)	−4.312**(0.000)
lntrd	−11.508***(0.000)	−1.686***(0.000)
Δlncee	−25.804***(0.000)	−19.463***(0.000)
Δlngt	−4.895***(0.000)	−25.261***(0.000)
Δlnpgdp	−11.354***(0.000)	−13.630***(0.000)
Δlnurb	−22.327***(0.000)	−2.702***(0.003)
Δlnfd	−1.100***(0.000)	−38.060***(0.000)
Δlnei	−16.726***(0.000)	−18.071***(0.000)
Δlnes	−49.479***(0.000)	−20.562***(0.000)
Δlngov	−8.095***(0.000)	−11.556***(0.000)
Δlnind	−13.003***(0.000)	−14.396***(0.000)
Δlntrd	−15.716***(0.000)	−16.067***(0.000)

Note: The null hypothesis is that there is a unit root. Δ denotes the first-difference. p values are in parentheses; * indicates $p < 0.1$; * *indicates $p < 0.05$; * * *indicates $p < 0.01$.

Table 13 The results of co-integration test

Kao		Pedroni	
Modified Dickey-Fuller t	−8.061***(0.000)	Modified Phillips-Perron test	4.115***(0.000)
Dickey-Fuller t	−5.752***(0.000)	Phillips-Perron test	−8.351***(0.000)
Augmented Dickey-Fuller t	−3.830***(0.000)	Augmented Dickey-Fuller test	−7.706***(0.000)

Note: The null hypothesis is that there is no co-integration relationship. p values are in parentheses; * indicates $p < 0.1$; * *indicates $p < 0.05$; * * *indicates $p < 0.01$.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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