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Climate risk, ESG integration and economic growth

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Climate risk, ESG integration and economic growth

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Editorial: Climate risk, ESG integration and economic growth

Sorin Gabriel Anton[1]*, Mihaela Onofrei[1], Syed Jawad Hussain Shahzad[2] and Martin Thomas Falk[3]

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KEYWORDS

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Editorial on the Research Topic
Climate risk, ESG integration and economic growth

This research topic aimed to explore factors affecting economic growth, Environmental, Social, and Governance (ESG) integration, and climate-aligned approaches and challenges. The current research topic comprises 10 relevant articles that fulfil the research objectives. The articles are written by authors from different countries (China, Malaysia, Pakistan, and Romania) and offer interesting insights from different perspectives and approaches.

Lyu et al. construct two different Tapio carbon decoupling models employing data from 30 Chinese administrative units over the period 2004-2017 and several methodologies. The authors highlight that emissions trading policies play a key role in promoting carbon decoupling in China. Two variables are important in this process, namely, gray technology innovation and clean technology innovation.

Zhao et al. examine the role of the sulfur dioxide emission trading pilot scheme in reducing the CO_2 emissions of Chinese firms over the period 1998-2013. Employing a propensity score matching-difference in differences methodology, the authors found that the introduction of this pilot scheme has an important reduction effect on corporate CO_2 emissions. Their results provide empirical evidence for the importance of environmental regulation policies.

Maxim et al. aim to analyze the willingness of Romanian households from the second poorest region of the European Union to pay a premium to support the development of renewable energy. The authors employed a discrete choice experiment for the purpose of their research. The most important social benefits in the eye of the Romanian households that will make them pay more for renewable energy are the creation of new jobs, higher country energy independence, and reduction of air, water and ground pollution. Their findings have significant policy implications outlined in the paper.

Using data from 22 European countries over the period 1990-2020, Liu et al. investigate the impact of several factors on CO_2 emissions. The key results show that the level of economic development, the degree of urbanization and energy power have a significant impact on CO_2 emissions. Furthermore, in 2020, the level of CO_2 emissions decreased during the COVID-19 pandemic.

Onofrei et al. analyze the dynamic link between economic growth and CO_2 in a sample of 27 European countries over the period 2000-2017. Employing several methodologies, the authors found a long-run cointegrating relationship between economic growth and CO_2

emissions, thus contributing to the growing literature focused on the determinants of CO_2 emissions.

Dinca et al. examine the role of governance quality and education in improving environmental performance. They use an extensive sample of countries (43) over the period 1995-2020 and several methodologies. The authors found a positive and statistically significant relationship between the level of education and CO2 emissions. However, the impact of institutional quality was positive but statistically significant.

Huang and Chen aim to analyze the role of Technologically Advanced Policy (TAP) on green innovation in a sample of listed Chinese SMEs over the period 2004-2021. Using manually collected data on green innovation and several econometric methodologies, the authors found a positive impact of stimulus policies on corporate green innovation. Furthermore, they highlight the different roles of stimulus mechanisms in supporting green innovation. The results proved to be robust for several tests and provide empirical evidence for the impact of public policies in China.

Zeng et al. construct a KMV-logit mixed model that incorporates an ESG index in order to estimate the credit risk of public internet finance firms from China. The model proved to be efficient in estimating credit risk and emphasize the role of firm-level variables in estimating default risk. Furthermore, the authors found that the coronavirus pandemic had a significant effect on the credit risk of public internet finance firms from China.

Huang et al. examine the impact of regional integration policy on total factor productivity (TFP) using a sample of Chinese firms over the period 2007-2020. They found a positive association between regional integration policy and total factor productivity and this relationship is higher in the case of state-owned firms. Furthermore, the authors identify as transmission mechanisms the industrial chains, green innovation, innovation, and market competitiveness.

In the last paper of this research topic, Firtescu et al. investigate the effect of environmental taxes on greenhouse gas emissions in a sample of 28 European countries over a long period (1995–2019). Employing several econometric techniques, the authors found a negative link between environmental taxes and greenhouse gas emissions.

Overall, these articles offer a deep empirical understanding of factors affecting economic growth, Environmental, Social, and Governance (ESG) integration, and climate-aligned approaches and challenges, based on various research methods applied to different geographical and institutional frameworks. The recent trends we are facing leave ample room for further research and insightful discussions on the role of additional factors or in other regions as soon as more data will be available.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Can Carbon Trading Policy Promote China's Decoupling of Carbon Emission From the Perspective of Technology-Driven Innovation?

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The emissions trading policy is considered a key measure for China to achieve its "double carbon" goal. In this study, two types of Tapio carbon decoupling models are constructed, panel data for 30 provinces and cities in China from 2004 to 2017 are selected, and the difference-in-differences (DID) model is used to evaluate the role of carbon trading policies in carbon decoupling. The study shows that carbon emissions trading policies can significantly promote carbon decoupling in China and that the formulation and implementation of such environmental regulations promote carbon decoupling with the help of two intermediary variables: gray technology innovation and clean technology innovation. Based on the findings, it is concluded that China should actively build a unified national carbon trading market, ensure the synergistic coupling of emission reduction targets and economic growth targets, and effectively play the role of the carbon trading market in inducing and promoting low-carbon technology innovation to help decouple carbon.

Keywords: carbon emission decoupling, differences-in-difference, carbon trading, technology innovation, carbon emission

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INTRODUCTION

Since the 18th National Congress, China has incorporated the construction of ecological civilization into the Five-in-One overall layout, and "Beautiful China" has become the shared vision for all Chinese people. China has committed to reducing CO_2 emissions per unit of GDP by 60–65% by 2030, compared to 2005, as part of the Paris Agreement. The establishment of a national carbon emissions trading market is considered one of the most critical steps toward China's 2030 carbon reduction target. After years of research, the National Development and Reform Commission (NDRC) launched a carbon trading pilot in seven provinces across the country in 2011, followed by the official launch of the national trading market at the end of 2017. In the framework of the Chinese economy's new normal, China must address the relationship between economic development and carbon emission while enacting a policy of carbon emission reduction. Carbon emission decoupling refers to the relationship between the change in CO_2 emissions and economic growth. When economic growth is realized, the negative growth rate of CO_2 emissions, or a growth rate less than the economic growth rate, can be regarded as decoupling. Its essence is to measure whether economic growth comes at the cost of resource consumption and environmental damage. The major issues to be explored in the development of the carbon trading market are whether China's carbon emissions trading scheme (ETS) can enhance carbon emission decoupling and how the contradiction between economic growth and carbon emission reduction can be balanced. The Chinese government has put forward the goal of "double carbon": at the General Debate of the 75th United Nations General Assembly in September 2020, China proposed for the first time that its carbon dioxide emissions should reach their peak before 2030 and stated that it was striving to achieve the goal of carbon neutrality by 2060. Low-carbon technological innovation is, in fact, seen as a win–win solution both for economic development and emission reduction (Kurtzman, 2015). The NDRC and the National Energy Administration (NEA) jointly issued the Energy Technology Revolution Innovation Action Plan (2016–2030), which identifies 15 key tasks for technological innovation and proposes that, by 2023, energy technology will be close to advanced world standards, with China joining the ranks of powerful countries in terms of energy technology. Most of the current ETS research for low-carbon technological innovation has been concentrated on the EU's carbon trading market (Rubashkina et al., 2015), with very little research on China. Therefore, the fact that the China's carbon trading scheme can achieve a win–win situation regarding economic growth and the ETS through an innovation-driven mechanism is crucial to China's low-carbon transition success. Accordingly, this study uses the quasi-natural experiment with a difference-in-differences (DID) model to evaluate the effect of China's carbon trading pilot on carbon emission decoupling, subsequently discussing the driving mechanism based on low-carbon technological innovation and the specific path of low-carbon technological innovation to advance carbon decoupling, with the aim of providing insights into the construction and promotion of the national carbon emission trading market.

LITERATURE REVIEW

Carbon Trading Policy and Carbon Decoupling

Carbon emissions trading aims to balance the contradiction between economic development and carbon emissions by using market instruments to reduce the total amount of carbon dioxide emissions (Burnett et al., 2013). Current studies on the effect of carbon trading have mainly focused on the economic and environmental effects of carbon emissions trading at the regional and national levels. In the context of economic effects, Wang et al. (2015) constructed a general equilibrium model with Guangdong province as the study target to assess the economic effects of carbon trading. This study revealed that strict targets for carbon emission reduction led to significant economic losses; however, carbon trading using market instruments can successfully mitigate such losses. Rose et al. (2006) conducted a cost–benefit analysis, concluding that the cost-saving effect of the carbon trading market would increase as the number of carbon trading subjects increases. Some researchers, however, have disagreed, such as Commins et al. (2011), who investigated EU enterprises from 1996 to 2007. Their results indicated that carbon trading drastically reduced the capital return for EU enterprises. In the context of environmental effects, Ren and Fu (2019) investigated the synergistic emission reduction effects of carbon trading policies on regional pollutants in China using panel data for 30 provinces from 2008 to 2015. Li and Zhang (2017) used panel data for 30 Chinese provinces to perform an empirical analysis of the effects of carbon trading on industrial carbon emissions and carbon intensity. Most studies in the literature, however, have focused on the effect of carbon trading from a single perspective instead of the policy's combined economic and environmental implications. The majority of studies on China's ETS have used simulation methods; hence, empirical research using econometric methods is lacking. Carbon emission decoupling is considered an idealized process of continuously weakening, or even removing, the relationship between economic growth and greenhouse gas (GHG) emissions. Therefore, it is a significant instrument for measuring the process of low-carbon development as well as a good example of the region's synergistic control of economic development and carbon emission reduction.

Carbon trading policy is a type of market-incentive environmental regulation that differs significantly from other kinds of environmental regulation. The heterogeneity of environmental regulatory instruments imposes various cost limitations on enterprises, influencing the policy's "economic effect" and "environmental effect." As previously stated, carbon decoupling refers to the relationship between the change in CO_2 emissions and economic growth, such that when economic growth is realized, the negative growth rate of CO_2 emissions, or a growth rate less than the economic growth rate, can be regarded as decoupling. Therefore, it is worthwhile studying the rational portfolio of policy instruments. In view of this, the present research uses a quasi-natural experiment to examine whether carbon trading pilots improve carbon emission decoupling and whether the portfolio of policy instruments has an effect on the decoupling of carbon emissions in the context of the interaction between the ETS and environmental regulations.

Carbon Trading, Environmental Regulation Portfolio, and Technological Innovation

One of the important mechanisms for carbon trading is to promote carbon reduction and technological progress. In line with the Porter hypothesis, environmental regulations can trigger innovation and generate net benefits for enterprises instead of increasing the costs, thus improving enterprises' international competitive advantages. Carbon trading is considered an environmental regulatory instrument in the context of perfect competition. Through carbon quotas and associated costs, carbon trading can increase the price of carbon emission factors. Subsequently, enterprises with carbon emissions are forced to re-examine the costs of paying for a carbon quota and new technology R & D, which in turn induces the progress of low-carbon technological innovation. However, there are disagreements regarding the effect of carbon trading on enterprises' innovation activities. Cong and Wei (2010) suggested that carbon trading stimulates the development of environmentally friendly technology through carbon pricing by adjusting the relative costs of different power-generation technologies. In contrast, Grubb et al. (2005) argued that restrictions on market emission quotas seriously damage enterprises' overall innovation activities. Huang et al. (2015), taking the Shenzhen coal power industry as the study subject, found that carbon trading facilitated investment in emission reduction technology in the short term; however, the incentive was not evident in the long term.

Two Types of Low-Carbon Technological Innovation

Considering the heterogeneity within low-carbon technological innovations, the present study draws on study to classify low-carbon technological innovations into two types from the function perspective: gray and clean. It is generally assumed that gray technological innovation is aimed at improving the utilization efficiency of fossil-fuel energy with potential energy-saving effects. However, gray technological innovation improves energy utilization and the total energy consumption, which might lead to a "rebound effect" (Shao et al., 2013) in CO_2 emissions. Jin et al. (2014) explored the role of technological progress on carbon emissions using panel data for 35 industries in China from 1999 to 2011. The results indicated that the gains in emission reduction caused by improved energy efficiency could not offset the CO_2 growth resulting from economic growth. Shen et al. (2010) used panel data from 1997 to 2009 to examine the effect of technological progress on CO_2 emissions in China as a whole, specifically in the eastern, central, and western regions. The results showed that the direct effect of technological progress was negative, which was not sufficient to offset the indirect positive effect of technological progress on CO_2 emissions. On the other hand, clean technology is intended to achieve zero carbon production and consumption, which has a significant inhibitory effect on carbon intensity. Based on the world patent database and panel data for 15 economies from 1996 to 2011, analyzed the effect of different types of technological innovation on carbon intensity, and the findings showed that clean technological innovation has a significant inhibitory effect on carbon intensity and can achieve economic growth without increasing carbon emissions. In light of the aforementioned literature, it is necessary to conduct an empirical analysis of the specific paths of different types of low-carbon technological innovations to reduce carbon intensity and achieve carbon decoupling and subsequently to explore how to promote synergies to achieve a win–win situation for economic development and carbon emission reduction comparing two kinds of low-carbon technological innovations in the context of the ETS.

MODEL AND VARIABLE DESIGN

Differences-in-Difference

The purpose of this study was to accurately assess the effect of implementing a carbon emissions trading policy on the decoupling of China's economic growth from CO_2 emissions. Previous studies have usually used the DID approach to evaluate the effects of policy. In the process of empirical analysis, DID takes both *ex ante* difference and time difference into consideration, with the addition of other control variables affecting the dependent variable, in order to identify treatment effects, reduce errors, and improve the explanatory power of the model. Compared with general regression models, this approach can effectively avoid endogeneity issues and is currently the main method used to assess the utility of public policies.

According to the basic form of the DID model, the regression model is constructed in this study as follows:

$$y_{it} = \alpha_0 + \alpha_1 treated_{it} * time_{it} + \beta_1 X + \beta_t + \beta_i + \varepsilon_{it} \tag{1}$$

where y_{it} is the dependent variable, X is a set of control variables, i represents individuals, t represents years, $treated_{it}$ is a dummy variable by grouping (if the individual is affected by the policy implementation, the individual belongs to the treatment group, and the corresponding $treated$ is taken as 1, corresponding to the carbon trading pilot area in this study; if the individual belongs to the control group, the corresponding $treated$ is taken as 0, corresponding to a region without a carbon trading pilot in this study), and $time_{it}$ is a dummy variable for policy implementation (for which 0 is before implementation and one is after). The coefficient of $treated_{it} * time_{it}$ is the interaction term of the group dummy variable and the policy implementation dummy variable, and its coefficient α_1 is the influence coefficient of policy implementation. Finally, β_t is the time fixed effect and β_i is the individual fixed effect.

The Chinese government formally established the carbon emissions trading pilot in 2011, including seven pilot areas (Beijing, Tianjin, Shanghai, Hubei, Guangdong, Shenzhen, and Chongqing); therefore, the present study designates 2011 as the policy implementation year. Since Guangdong province includes the pilot city Shenzhen, this study combines the data from the two regions mentioned previously with a total of six pilot regions as the experimental group and the non-pilot regions as the reference group. The ETS is used to denote the carbon trading policy, where one is implementation and 0 otherwise.

Indicators of Carbon Emission Decoupling

In recent years, the concept of carbon emission decoupling has been used to describe the relationship between economic growth and carbon dioxide emissions. Generally speaking, there is a positive relationship between economic growth and carbon dioxide emissions. However, with the adoption of an appropriate emission reduction policy and the application of low-carbon technological innovation, high-quality economic development can be achieved at a low carbon level, i.e., "carbon decoupling." Based on the Tapio decoupling model, this study constructs decoupling indicators for China's economic growth and carbon emissions as follows:

$$E = \frac{\%\Delta carbon}{\%\Delta GDP} = \begin{cases} \dfrac{(carbon_t - carbon_{t-1})/carbon_{t-1}}{(GDP_t - GDP_{t-1})/GDP_{t-1}} \text{ (a)} \\[2ex] \dfrac{(carbon_t - carbon_{t-1}) \Big/ \left(\dfrac{carbon_t + carbon_{t-1}}{2}\right)}{(GDP_t - GDP_{t-1}) \Big/ \left(\dfrac{GDP + GDP_{t-1}}{2}\right)} \text{ (b)} \end{cases} \tag{2}$$

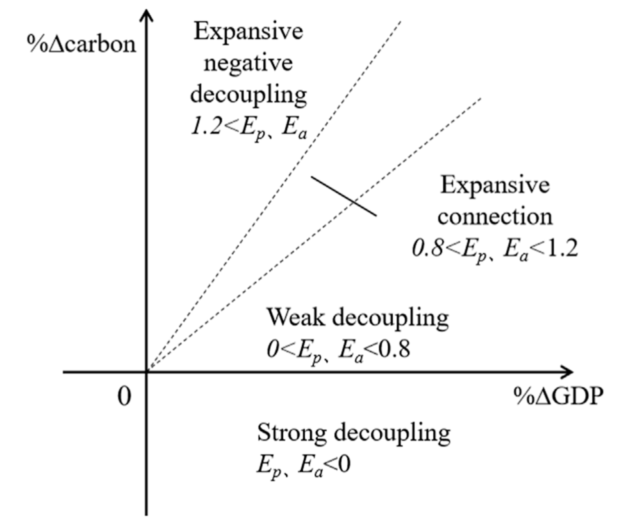

FIGURE 1 | Categories of carbon emission decoupling in China.

where E is a decoupling indicator of China's economic growth and carbon emissions, $\%\Delta carbon$ represents the change rate of carbon emissions, and $\%\Delta GDP$, the change rate of GDP. Considering that the elasticity is divided into point elasticity and arc elasticity, this study sets the index of point elasticity carbon emission decoupling and the index of arc elasticity carbon emission decoupling, respectively, for which **Eq. 2a** is the calculation for the index of point elastic carbon emission decoupling E_p, and **Eq. 2b** represents the calculation for the index of arc elastic carbon emission decoupling E_a.

Tapio (2001) divided the decoupling values into eight categories based on the value size. The smaller the value is, the greater the decoupling degree between two variables. Due to the positive economic growth in China, four categories of carbon emission decoupling were selected in this study: strong decoupling, weak decoupling, expansionary linkage, and expansionary negative decoupling. A decoupling value below 0 denotes strong decoupling, representing positive economic growth and negative carbon emission growth. A decoupling value between 0 and 0.8 represents weak decoupling, showing that the growth rate of carbon emissions is smaller than the economic growth rate. A decoupling value between 0.8 and 1.2 represents expansive linkage, which means that the economic growth rate is similar to the growth rate of carbon emissions. Finally, a decoupling value greater than 1.2 represents expansive negative decoupling, indicating that the growth rate of carbon emissions is faster than the economic growth rate (**Figure 1**).

To present a more visual image of the distribution of carbon emission decoupling in China, this study uses the indicator of point elastic carbon emission decoupling to make the spatial distribution for types of carbon emission decoupling before (2004–2010) and after (2011–2017) China launched the carbon trading policy.

Variable Selection and Data Sources

For carbon emissions (*carbon*), since China has not published data for CO_2 emissions, this study uses the IPCC's method for estimating carbon emissions. The formula is as follows:

$$carbon = \frac{12}{44} \times \left(\sum E_n \times \alpha_n \times \beta_n \right) \tag{3}$$

Here, *carbon* refers to carbon dioxide emissions with the unit of 10,000 tons. E_n denotes the terminal consumption of the nth energy, in which the types of energy include raw coal, washed coal, other washed coal, briquette, coke, coke oven gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, refinery dry gas, natural gas, and other petroleum (with 17 types in total). The unit of coke oven gas, other gas, and natural gas is 10^8 m^3, while the unit of other energy is 10,000 tons. α_n represents the standard coal coefficient of the nth energy, while β_n represents the CO_2 emission coefficient of the nth energy.

Regarding gray technological innovation (*gray*) and clean technological innovation (*clean*), referring to the Cooperative Patent Classification (CPC) jointly issued by the US and the UK in 2013, this study uses the number of Chinese patent applications in the Y02 classification to indicate innovation in low-carbon technology. In view of the internal heterogeneity of low-carbon technological innovation, Y02 patents are divided into two sub-categories: gray technology (*gray*) and clean technology (*clean*). Gray technology is aimed at improving energy efficiency; thus, it is not completely carbon-free. Clean technology, in contrast, aims to achieve zero-carbon production or consumption.

The industrial structure (*STR*) is the ratio of the proportion of tertiary industry to the proportion of secondary industry in the region. Advanced industrial structure and its upgrading are helpful to eliminate the crude economic development model that relies on high energy consumption and high pollution, providing impetus for low-carbon technological innovation.

Regarding opening up (*FDI*), the use of foreign direct investment (FDI) is used to indicate the extent of openness. There exists disagreement on the effect of the extent of openness on the ecological environment of the host country. The "pollution paradise" hypothesis suggests that FDI is accompanied by the transfer of highly polluting and energy-intensive industries, thus aggravating the damage to the ecological environment of the host country. In contrast, the "pollution halo" hypothesis indicates that foreign investment can upgrade the production technology and management level of the host country, thus improving its environmental quality.

The urbanization rate (*UR*) is the ratio of the regional urban population to the total population. Generally speaking, the rapid growth in population resulting from urbanization will lead to a substantial increase in carbon emissions; thus, the resulting agglomeration effect contributes to carbon decoupling to some extent.

For command-and-control environmental regulation (*IER*) and voluntary environmental regulation (*VER*), referring to the calculation method of domestic scholars (Ghisetti et al., 2015), environmental regulation is used to construct an inverse index of

TABLE 1 | Descriptive statistics.

Variable symbol	Variable meaning	Number of observations	Unit	Average value	Standard deviation
E_p	Point elastic carbon decoupling	420	%	0.5038	0.7924
E_a	Arc elastic carbon decoupling	420	%	0.4860	0.7700
lnGDP	Gross regional product	420	Million yuan	8.9472	0.9862
lncarbon	Carbon dioxide emissions	420	Million tons	5.4040	0.8295
gray	Gray technological innovation	420	Hundred pieces	14.5708	21.4916
clean	Clean technological innovation	420	Hundred pieces	5.2182	7.8323
lnFDI	FDI log value	420	Million yuan	6.1238	1.4484
IER	Command-and-control environmental regulation	420	Dimensionless	0.4877	0.5343
VER	Voluntary environmental regulation	419	Pieces	9.2819	1.5823
UR	Urbanization rate	420	%	0.5191	0.1426
STR	Industry structure	420	%	0.9780	0.5294

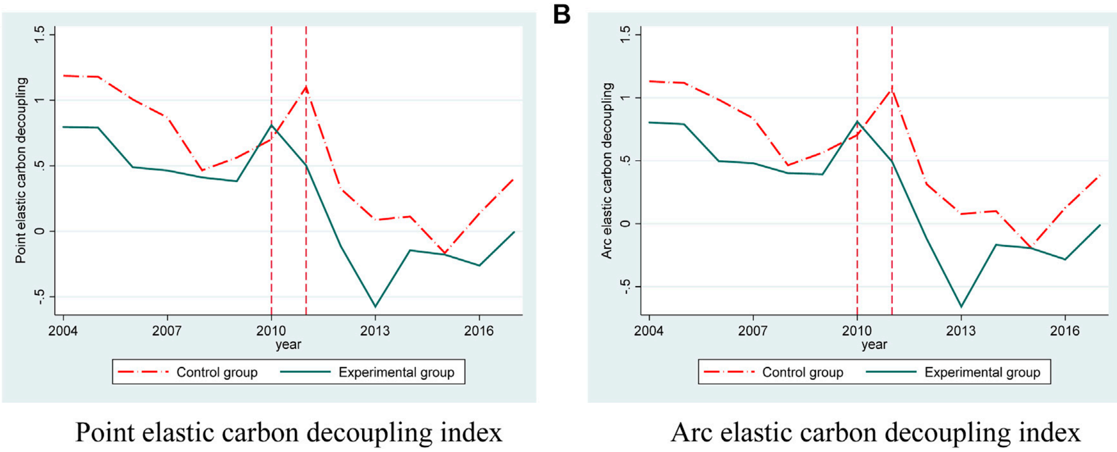

FIGURE 2 | Parallel trend test. **(A)** Point elastic carbon decoupling index. **(B)** Arc elastic carbon decoupling index.

comprehensive pollution. *VER* is measured by the number of environmental petitions in each province. Public environmental awareness induces technological innovation activities by exerting environmental pressure on governments and enterprises.

This study used the data from 30 provinces as the research objects (Tibet, Hong Kong, Macao, and Taiwan data are missing and therefore not included), with 2004–2017 being the research interval. Socioeconomic data were obtained from the China Statistical Yearbook as well as provincial and municipal yearbooks; Y02 patent data were obtained from the incoPat patent database; and energy consumption data were taken from the China Energy Statistical Yearbook. All variables for economic price were treated as constant prices to eliminate the effect of price fluctuations. Descriptive statistics are shown in **Table 1**.

EFFECT OF THE CARBON TRADING POLICY ON CARBON DECOUPLING

Parallel Trend Test

On the basis of the design of the DID model, the explanatory variables for the reference and experimental groups need to meet the parallel trend test before the implementation of the policy pilot. The parallel trend test plots in **Figure 2** show that the data both for the reference and experimental groups have relatively consistent trends in 2010, as well as the previous years, regardless of whether the indicator of point elasticity carbon emission decoupling or arc elasticity carbon emission decoupling is used as the explanatory variable. However, there was a wide divergence when the policy was implemented in 2011. The indicator for carbon emission decoupling in the experimental group continued to decline after 2011, while the indicator for carbon emission decoupling in the reference group still maintained an upward trend in 2011, compared to 2010, indicating that the hypothesis of the parallel trend test was met.

Effect of the Carbon Trading Policy on Carbon Decoupling

First, a benchmark regression on the effect of the carbon trading policy on carbon emission decoupling indicators was conducted, in which the explained variables include two types of carbon emission decoupling indicators: point elasticity and arc elasticity. The results are shown in **Table 2**.

TABLE 2 | Regression results for the carbon trading policy on two carbon emission decoupling indicators.

Variable	(1)	(2)	(3)	(4)
	E_p	E_p	E_a	E_a
ETS	−0.7034***	−0.3018*	−0.7306***	−0.3345**
	(−4.2511)	(−1.8425)	(−4.5608)	(−2.1076)
UR		−6.5278***		−6.2933***
		(−8.7096)		(−8.6654)
ln*FDI*		0.1434***		0.1218**
		(2.5977)		(2.2778)
STR		−0.2742*		−0.2520
		(−1.7052)		(−1.6173)
_cons	0.5741***	3.3127***	0.5590***	3.2867***
	(14.1657)	(8.4106)	(14.2461)	(8.6118)
Hausman	Fixed	Fixed	Fixed	Fixed
N	420	420	420	420

*p < *0.01;* **p < *0.05;* ***p < *0.01.*

TABLE 3 | Placebo test regression results.

Variable	(1)	(2)	(3)	(4)
	E_p	E_p	E_a	E_a
ETS_2008	−0.0893	−0.1184		
	(−0.5047)	(−0.6904)		
ETS_2009			−0.0915	−0.1166
			(−0.5409)	(−0.7103)
UR	−6.6110***	−6.3760***	−6.6111***	−6.3784***
	(−8.7643)	(−8.7141)	(−8.7725)	(−8.7253)
ln*FDI*	0.1324**	0.1101**	0.1333**	0.1112**
	(2.4007)	(2.0586)	(2.4121)	(2.0741)
STR	−0.3382**	−0.3191**	−0.3345**	−0.3153**
	(−2.1261)	(−2.0680)	(−2.0882)	(−2.0290)
_cons	3.4687***	3.4507***	3.4582***	3.4395***
	(8.9131)	(9.1410)	(8.8151)	(9.0384)
Hausman	Fixed	Fixed	Fixed	Fixed
N	420	420	420	420

*p < *0.01;* **p < *0.05;* ***p < *0.01.*

As shown in **Table 2**, the results of models (1) and (3) indicated that there was a significantly negative correlation between the ETS and the indicator of point elasticity carbon emission decoupling, and between the ETS and the indicator of arc elasticity decoupling, which meant that the pilot of carbon emission rights policy significantly promoted the carbon emission decoupling process in the pilot areas of China. After introducing control variables in models (2) and (4), the China's urbanization rate has a negative coefficient on both types of carbon emission decoupling indicators, passing the significance test at the 1% level. The results indicate that China's current urbanization can have a better control over carbon emissions and promote economic development to achieve a benign coordination between the aforementioned two indicators. On the contrary, opening up significantly inhibits China's carbon emission decoupling and pollutes the environment. The coefficients of the industrial structure on both types of carbon emission decoupling indicators are negative, but the coefficient of the point elasticity indicator only passes the significance test at the 10% level, while the coefficient of the arc elasticity indicator fails the significance test. Thus, the effect of China's economic structural transformation has not been fully revealed yet, and transformation from an industrial-based economy to a service-based economy is needed.

Robustness Tests

Most studies have used counterfactual tests for the robustness of the results of DID model (Ye, 2018). The main idea is to change the time of policy implementation through the "counterfactual" tests to generate new policy shock variables for regression analysis and to verify the results by comparison. If the policy shock variable is not significant in the new regression analysis, the original model passes the robustness test. In this study, the year of policy implementation is set to 2008, and the new policy shock variables are then put into the model for regression to judge the robustness of the original regression results.

Table 3 shows that both coefficients of the counterfactual policy shock variables in 2008 and 2009 do not pass the significance test. Thus, the counterfactual policy shock variables do not have an effect on carbon decoupling, indicating that the original policy variables are valid and that the original model passes the robustness test.

TABLE 4 | Interaction between carbon trading and command-and-control environmental regulations on carbon decoupling.

Variable	(1)	(2)	(3)	(4)
	E_p	E_p	E_a	E_a
IER	0.2321	0.2332	0.2081	0.2093
	(0.9690)	(0.9918)	(0.8878)	(0.9118)
ETS ∗ *IER*		−0.9123***		−0.9988***
		(−3.8852)		(−4.1384)
UR	−6.6914***	−6.5032***	−6.4668***	−6.2608***
	(−7.9604)	(−7.4089)	(−8.0137)	(−7.4246)
ln*FDI*	0.1302*	0.1385*	0.1072*	0.1163*
	(1.8808)	(1.9828)	(1.7457)	(1.8743)
STR	−0.4038**	−0.4007**	−0.3855**	−0.3821**
	(−2.4389)	(−2.4264)	(−2.5208)	(−2.5102)
_cons	3.4619***	3.3257***	3.4623***	3.3132***
	(8.0677)	(7.2918)	(8.1703)	(7.3618)
Hausman	Fixed	Fixed	Fixed	Fixed
N	420	420	420	420

*p < *0.01;* **p < *0.05;* ***p < *0.01.*

Interaction Between Carbon Trading and Other Environmental Regulations on Carbon Decoupling

As a market-incentive environmental regulation, a carbon trading policy is often implemented simultaneously with other environmental regulations as a policy portfolio; therefore, it is necessary to explore the interaction of heterogeneous environmental regulation on carbon emission decoupling in China. Based on the aforementioned literature review, regressions were conducted on the interaction between carbon trading policy and command-and-control and between carbon trading policy and voluntary environmental regulations, respectively. The results are presented in **Tables 4**, **5**.

TABLE 5 | Interaction between carbon trading and voluntary environmental regulation on carbon decoupling.

Variable	(1)	(2)	(3)	(4)
	E_p	E_p	E_a	E_a
AER	0.0538	0.0601*	0.0549*	0.0618*
	(1.5789)	(1.7606)	(1.6604)	(1.8695)
ETS ∗ *AER*		−0.0298*		−0.0328**
		(−1.9230)		(−2.1860)
UR	−6.4900***	−6.3335***	−6.2668***	−6.0945***
	(−8.6167)	(−8.3892)	(−8.5783)	(−8.3345)
ln*FDI*	0.1242**	0.1378**	0.1011*	0.1161**
	(2.2614)	(2.4969)	(1.8977)	(2.1712)
STR	−0.3608**	−0.2811*	−0.3474**	−0.2597*
	(−2.3300)	(−1.7593)	(−2.3133)	(−1.6780)
_cons	2.9664***	2.6971***	2.9512***	2.6546***
	(5.8311)	(5.1282)	(5.9810)	(5.2112)
Hausman	Fixed	Fixed	Fixed	Fixed
N	420	420	420	420

*p < 0.01; **p < 0.05; ***p < 0.01.

Before the introduction of the carbon trading policy, the coefficient of the effect of command-and-control environmental regulation (*IER*) on carbon emission decoupling is positive but not significant, indicating that it does not contribute to carbon decoupling. After introducing the carbon trading policy, the interaction with command-and-control environmental regulation remains insignificant. This suggests that the government often adopts a "one-size-fits-all" coercive approach to administrative regulation, and enterprises are forced to reduce production and emissions in the face of transition cost constraints, resulting in the loss of economic growth. Furthermore, the interaction with command-and-control environmental regulation is significantly negative, effectively promoting carbon decoupling. The carbon trading policy internalizes the cost of carbon emissions into the production cost of enterprises through market incentives. With the dual constraints of pollution control from mandatory environmental regulations and energy consumption from market-based environmental regulations, enterprises tend to invest in low-carbon technology R & D and upgrade management skills to achieve both economic benefits and emission reduction.

Before introducing carbon trading, the coefficients of the effects of voluntary environmental regulation on both kinds of carbon emission decoupling indicators pass the significance test at the 5% level. The results show the weak public awareness of environmental protection in most regions and insufficient pressure on enterprises for environmental protection. After the introduction of carbon trading, the interaction with voluntary environmental regulation has a significant negative effect on the carbon emission decoupling index. This indicates that the ETS, as a market-based incentive system, can guide the green transformation of enterprises and help regions in carbon decoupling through the dual paths of cost constraint of carbon excess fines and the incentive of carbon sale proceeds.

INNOVATION-DRIVEN MECHANISM OF CARBON TRADING PROMOTING CARBON DECOUPLING

Mediating Effect of Low-Carbon Technological Innovation

Referring to Fang et al. (2014), this study adopted a mediating effect regression model based on the DID model and the Sobel test to explore the driving mechanism of low-carbon technological innovation in the process of a carbon trading policy promoting carbon decoupling. The three-step regression model is set up as follows:

$$E_{it} = \alpha_0 + \alpha_1 DID_{it} + \alpha_2 X + \beta_t + \beta_i + \varepsilon_{it} \tag{4}$$

$$gray/clean_{it} = \gamma_0 + \gamma_1 DID_{it} + \gamma_2 X + \beta_t + \beta_i + \varepsilon_{it} \tag{5}$$

$$E_{it} = \mu_0 + \mu_1 DID_{it} + \mu_2 gray/clean_{it} + \mu_3 X + \beta_t + \beta_i + \varepsilon_{it} \tag{6}$$

The first step is to test path a: whether the coefficient $\alpha1$, the effect of the carbon trading policy on two indicators of carbon emission decoupling, is significant. The second step is to test path b: whether the coefficient $\gamma1$, the effect of the carbon trading policy on two types of low-carbon technological innovation, is significant. The final step is to test c: whether the coefficients $\mu1$ and $\mu2$, the interaction between carbon trading policy and low-carbon technological innovation on carbon decoupling indicators, are significant.

Based on the explanatory law of the mediating effect model, the regression coefficient $\alpha1$ in path a, $\gamma1$ in path b, and $\mu2$ in path c are all significant, which meets the prerequisite of the mediating effect. When the regression coefficient $\mu1$ in path c is not significant and the Z-value of the Sobel test is significant, the model is fully mediated. When the regression coefficient $\mu1$ in path a is significant but lower than the corresponding coefficient $\alpha1$, with a significant Z-value for the Sobel test, the model presents a partial mediation effect.

According to the regression results shown in **Table 6**, the coefficients $\alpha1$ for path a and $\gamma1$ for path b are both significant when the mediating variable is gray technological innovation, and the coefficients in path c and the Z-values of the Sobel test are consistent with a full mediation effect when the explanatory variable is the indicator of point elasticity decoupling. When the explanatory variable is the indicator of arc elastic decoupling, the coefficient in path c and the Z-value of the Sobel test show partial mediation effects. Both coefficients, $\alpha1$ in path a and $\gamma1$ in path b , are significant when the mediating variable is clean technological innovation. The coefficients in path c and the Z-values of the Sobel test show partial mediation when the explanatory variables are indicators of point elasticity decoupling and arc elasticity decoupling.

In summary, both gray and clean technological innovation can be considered critical mediating variables in the process of carbon emission decoupling boosted by the carbon trading policy. Based on the driving mechanism of low-carbon technological innovation, a carbon trading policy can encourage enterprises to increase their innovation efforts and then gradually achieve low carbon and clean

TABLE 6 | Mediating effects and Sobel test results.

	Path a: without mediating variables			
Independent variable	**ea**		**eb**	
ETS	−0.3055** (−2.13)		−0.3183** (−2.29)	
Control variables	Control		Control	
Observation samples	420		420	
Path b: mediating variable test				
Independent variable	Gray technological innovation		Clean technological innovation	
ETS	9.6442*** (3.15)		2.6668** (2.39)	
Control variables	Control		Control	
Observation samples	420		420	
Path c: with mediating variables				
Independent variable	ea	eb	Ea	eb
ETS	−0.2352 (−1.64)	−0.2539* (−1.82)	−0.2578* (−1.80)	−0.2750** (−1.98)
Gray technological innovation	−0.0072*** (−3.21)	−0.0067*** (−3.03)		
Clean technological innovation			−0.0179*** (−2.86)	−0.0162*** (−2.67)
Control variables	Control	Control	Control	Control
Observation samples	420	420	420	420
Absolute value of Sobel *Z*	0.0703**	0.0644**	0.0477*	0.0432*
p-value of Sobel *Z*	0.0247	0.0290	0.0667	0.0747

*p < 0.01; **p < 0.05; ***p < 0.01.

TABLE 7 | Emission reduction effects of two kinds of low-carbon technological innovations.

Variable	**(1)**	**(2)**	**(3)**	**(4)**
	Carbon emission	**Carbon emission**	**Carbon emission**	**Carbon emission**
Gray	0.0053*** (4.1279)		0.0133*** (3.7536)	0.0097** (2.4085)
Clean		0.0109*** (2.9486)	−0.0243** (−2.4137)	−0.0092 (−0.8036)
ETS∗gray				0.0059 (0.8874)
ETS∗clean				−0.0428** (−2.2150)
STR	−0.0327 (−0.3858)	−0.0161 (−0.1867)	−0.0121 (−0.1431)	0.0462 (0.5462)
ln*FDI*	0.0214 (0.8273)	0.0320 (1.2361)	0.0156 (0.6034)	0.0171 (0.6817)
ln*POP*	1.6383*** (4.2443)	1.7089*** (4.3263)	1.7969*** (4.6170)	2.5522*** (6.2726)
_cons	−8.1564*** (−2.6401)	−8.7942*** (−2.7806)	−9.4257*** (−3.0259)	−15.6534*** (−4.7912)
Hausman	Fixed	Fixed	Fixed	Fixed
N	420	420	420	420

*p < 0.01; **p < 0.05; ***p < 0.01.

production to reduce CO_2 emissions while ensuring economic development at the same time.

Effect Decomposition of Two Kinds of Low-Carbon Technological Innovations Boosting Carbon Decoupling

To further explore the intrinsic paths of low-carbon technological innovations to promote carbon emission decoupling in China and different mechanisms of heterogeneous technological innovations, this study examines the emission reduction effects and economic effects of two kinds of low-carbon technological innovations on the basis of the nature of carbon decoupling, in which the explanatory variables are carbon emissions (*carbon*) and the level of economic development (ln*GDP*).

The results of the regression model (1) in **Table 7** show that the coefficients of correlation between gray technological innovation and carbon emissions are negative. The results of

TABLE 8 | Economic effects of two kinds of low-carbon technological innovations.

Variable	(1)	(2)	(3)	(4)
	ln*GDP*	ln*GDP*	ln*GDP*	ln*GDP*
Gray	0.0120***		0.0200***	0.0193***
	(9.4409)		(5.7464)	(4.8230)
Clean		0.0286***	−0.0246**	−0.0169
		(7.6522)	(−2.4741)	(−1.4974)
*ETS * gray*				−0.0026
				(−0.3958)
*ETS * clean*				−0.0181
				(−0.9515)
STR	0.1842**	0.1990**	0.2049**	0.2377***
	(2.2061)	(2.2940)	(2.4585)	(2.8491)
ln*FDI*	0.0652**	0.0840***	0.0593**	0.0587**
	(2.5579)	(3.2227)	(2.3325)	(2.3728)
ln*POP*	1.9475***	1.9750***	2.1077***	2.8684***
	(5.1188)	(4.9582)	(5.4964)	(7.1406)
_cons	−7.7165**	−8.0460**	−8.9985***	−15.2341***
	(−2.5341)	(−2.5229)	(−2.9319)	(−4.7231)
Hausman	Fixed	Fixed	Fixed	Fixed
N	420	420	420	420

*p < 0.01; **p < 0.05; ***p < 0.01.

the regression model (2) in **Table 7** show that the coefficients of correlation between clean technological innovation and carbon emissions are also negative. The results of regression model (3) indicate that the coefficient of the effect of gray technological innovation remains negative and the coefficient of clean technological innovation is positive when both gray and clean technological innovations are put in the regression equation. Therefore, gray technological innovation improves energy efficiency and promotes more energy consumption, leading to an increase in CO_2 emissions instead of a decrease, i.e., the "rebound effect." In contrast, clean technological innovation is committed to zero-carbon production and consumption, which promotes an overall reduction in CO_2.

Model (4) introduces the interaction effect of the carbon trading policy and discovers that the interaction with gray technological innovation remains positive but not significant, whereas the interaction with clean technological innovation is negative and larger than the corresponding coefficient of model (3). The findings show that the "carbon-increasing" effect of gray technological innovation is effectively suppressed in the context of the carbon trading policy, and the "carbon-reducing" effect of clean technological innovation is further enhanced.

Table 8 illustrates the economic effects of the two kinds of low-carbon technological innovations. The results of models (1) and (2) suggest that the coefficients both of gray and clean technological innovation on economic development are positive when the two kinds of low-carbon technological innovation are examined separately. The results of model (3) imply that the coefficient of gray technological innovation on economic development is significantly positive and the coefficient of clean technological innovation on economic development is significantly negative. Therefore, under the premise that both kinds of technologies are applied simultaneously with production activities in real situations, gray technological innovation can significantly contribute to economic growth. In contrast, clean technological innovation cannot boost economic development in a short period of time, and it might inhibit the economic development due to high R & D investment and slow implementation.

After the introduction of the carbon trading policy, the interaction coefficient with both types of technological innovation is not significant, indicating that the carbon trading policy has no significant effect on the economic effect of both kinds of low-carbon technological innovation.

To sum up, the elements of the heterogeneous environmental regulatory portfolio can interact with each other. In addition, it is worth noting that innovation is an important mechanism for the carbon trading policy to boost carbon decoupling. The results of the mediating effect and the Sobel test reveal that the carbon trading policy significantly increases two types of low-carbon technological innovations; in turn, low-carbon technological innovation is a significant driver for the carbon trading policy. After decomposing the paths of the two kinds of technological innovation, gray technological innovation reveals an "economic effect" with the increase of CO2 emissions, while clean technological innovation shows an "emission reduction effect" but does not have advantages in terms of economic cost-effectiveness. The mechanism of gray technological innovation promoting carbon emission decoupling increases economic growth, but it triggers a "rebound effect" for CO2 emissions. Clean technological innovation has great potential for reducing carbon emissions, although it has not promoted GDP growth. Since the introduction of the carbon trading policy, the interaction with the two types of low-carbon technological innovations has significantly facilitated the carbon emission reduction effect but not the economic effect.

CONCLUSION AND SUGGESTIONS

The critical criteria for checking the effectiveness of implementing a carbon trading policy lie in whether the China's carbon emission trading market can help decouple carbon and achieve a win–win situation between economic development and carbon emission reduction. Based on the panel data for 30 provinces across China from 2004 to 2017, this study has analyzed the underlying mechanisms through which the China's carbon trading pilot policy facilitates carbon emission decoupling with the methods of a DID quasi-natural experiment, a mediating effect model, and the Sobel test. The main conclusions are presented as follows:

First, the carbon trading policy pilots can boost carbon emission decoupling in China. Regardless of whether using point or arc elasticity calculations, carbon trading policies have effectively promoted carbon emission decoupling in the pilot regions, with a significantly negative indicator for carbon emission decoupling.

Second, the elements of a heterogeneous environmental regulatory portfolio can interact with each other. Considering that the carbon trading policy has entailed for enterprises, the dual constraints of carbon costs and market incentives, both the underperforming command-and-control environmental regulation and voluntary environmental regulation, facilitate the decoupling of carbon emission.

Third, innovation is an important mechanism for the carbon trading policy to boost carbon decoupling. The results of the mediating effect and the Sobel test reveal that the carbon trading policy significantly increases two types of low-carbon technological innovations; in turn, low-carbon technological innovation is a significant driver for the carbon trading policy.

Fourth, after decomposing the paths for the two kinds of technological innovation, gray technological innovation revealed an "economic effect" with the increase of CO_2 emissions, while clean technological innovation showed an "emission reduction effect" but did not have advantages in terms of economic cost-effectiveness.

Based on the aforementioned findings, the following policy recommendations are suggested:

First, the construction of the China's carbon trading market is conducive to the win–win goal of carbon emission reduction and economic development. China should actively build a national unified carbon trading market and a scientific market trading system. Moreover, the focus should be on the synergistic coupling of emission reduction and economic growth and on the dynamic adjustment of the carbon market.

Second, the government needs to effectively manage different types of environmental regulations in a synergistic manner and actively guide both market-incentive environmental regulations and voluntary environmental regulations. Command-and-control environmental regulations should be prudently implemented. The conflicts among different environmental regulations need to be balanced in order to bring into play the synergy of the heterogeneous environmental regulatory portfolio.

Third, the carbon market should play an active role in promoting the progress of low-carbon technology and ensure a scientific carbon quota. China should speed up the construction of the national carbon emission trading market and guide enterprises in carrying out low-carbon innovation through reasonable carbon element costs and carbon trading income.

Finally, in developing countries such as China, it is necessary to encourage R & D in clean and low-carbon technology through various policy tools, such as tax, green finance, and financial subsidies. Moreover, it is also important to strive to reduce the R & D costs of, and barriers to, applying clean technological innovation in order to popularize the application of clean technology and achieve a boost to economic growth and the reduction of carbon emissions at an early date. For gray technological innovation, the government should gradually weaken the support to accelerate its transition to clean technology.

In conclusion, it must be noted that this study has some limitations, which suggest avenues for further research. It is reasonable to use patents as an index for innovation, which can bring convenience to research and reveal certain issues, but it is easy to ignore the complex relationship between patents and innovation, thus resulting in errors. Further research can broaden the meaning of innovation, especially green innovation, and explore the deeper impact of environmental policies such as carbon trading on one of the complex behaviors of innovation.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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The Green Bonus: Carbon Reduction Effect of Sulfur Dioxide Emissions Trading Pilot Scheme

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Market-oriented environmental policy has made an indelible contribution to promoting sustainable development in China. We consider the introduction of the Sulfur dioxide Emissions Trading Pilot Scheme (SETPS) as a quasi-natural experiment and adopt PSM-DID method to study the reduction effect of SETPS on corporate carbon emissions. We find that SETPS can effectively promote the carbon emission reduction of enterprises, which highlights the dual significance of market-based environmental regulation policies in the field of pollution reduction and carbon emission reduction. Considering the heterogeneity of enterprises, SETPS imposes a more significant effect on carbon emission reduction of enterprises with high energy consumption and high pollution. The mediation effect analysis indicates that the indirect reduction effects of SETPS on the carbon emission through the marketization process and the development of non-state-owned economy. In addition, results from the test of moderation effect suggest that both financing constraint and ownership are the moderation factors for SETPS to affect enterprise carbon emission reduction. The empirical results suggest that there exists such a green bonus: reduction effect of introducing the SETPS on firm level carbon emission and other pollutant discharges. It should be paid more attention by the authorities.

Keywords: sulfur dioxide emission trading pilot scheme, carbon emissions, PSM-DID, mediation effect, moderation effect

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INTRODUCTION

Global warming poses a serious threat to global sustainability. Excessive carbon emissions are the main cause of climate change (Lin et al., 2018; Xiang et al., 2021; Yang et al., 2022). Since China's reform and opening up, the Chinese government has accelerated the pace of industrialization and development at the expense of the environment (Zhang et al., 2021). China's energy consumption structure is dominated by traditional fossil fuels (Schreifels et al., 2012; Umar et al., 2021; Xiao et al., 2022). It is an important source of environmental pollution. Since 2006, China has been the world's number one emitter of carbon dioxide (Guan et al., 2021). In 2021, China's carbon dioxide emissions accounted for 30.7% of the world's total carbon dioxide emissions, and its share of pollution continues to grow. Achieving sustainable environmental development is a very important issue, especially for developing countries (Nawaz et al., 2021). In September 2020, Chinese President Xi Jinping announced that China would strive to achieve its carbon peak by 2030 and be carbon neutral by 2060. To sum up, China has been suffering from the greenhouse effect for a long time and has an urgent need to reduce carbon emissions. Therefore, it is necessary to measure the policy effects of environmental regulation policies.

TABLE 1 | Variable definition.

Variable symbol	Variable name	Definitions of variables
CO_2	Carbon emission	Carbon emissions are derived from the conversion of standardized coal, and the conversion formula is: $CO_2 = \log(1 + co_2)$; and co_2 = standardized coal *0.714*2.492
Did	The interaction term	*did* = *time* × *treat* time = 0 if time is before 2007, otherwise time = 1; treat = 1 if the firm located in the one of 11 pilot cities that with SETPS implemented, and treat = 0 otherwise
Fuel	Fuel consumption	Diesel consumption (ton)
Values	Gross industrial production value	Current price of industrial GDP (10,000 yuan)
Fee	Effluent charge	Effluent charge
Treatment	Exhaust gas treatment capacity	Exhaust gas treatment facility series (set)
Export	Firm exports	0–1 Dummy variable. If the export delivery value is >0, the value of export is 1; otherwise, it is 0
Growth	Enterprise growth	Logarithm of total assets (1,000 yuan)

The Chinese government has adopted two kinds of environmental regulation policies. One is command-and-control policies, such as environmental emission standards and non-tradable emission permits. The other is market-oriented policies, such as environmental taxes and emission trading schemes. In terms of environmental governance, traditional command-and-control environmental regulation policies may appear as "government failure." The single traditional command-and-control environmental regulation policy has been unable to achieve the ideal emission reduction effect, and the traditional environmental regulation policy may to some extent damage the economic benefits of enterprises (Gray et al., 1993).

Compared with traditional command-and-control environmental regulation policies, emissions trading schemes are regarded as effective policies to address global climate change (Coase, 1960; Jog & Kosmopoulou, 2014; Xiao et al., 2022). These schemes can control the cost of emission reduction (Montgomery, 1972; Tietenberg, 1985), technological incentives, and the advantages of political acceptability (Anke et al., 2020). The system entrusts enterprises with the right to discharge pollutants within the limits set by the government. And then economic entities can sell excess emission rights in the emission trading market, or buy additional emission rights from other enterprises. The scheme's ultimate purpose is to introduce a forced mechanism for enterprises through market means. It aims to maximize profits while achieving the best pollution control effect.

Our study aims to investigate the effect of sulfur dioxide emission trading pilot scheme (SETPS) on firm carbon emissions, that is, whether the introduction of SETPS will cause the enterprise to reduce carbon emissions. In 2007, Chinese government approved 11 pilot provinces[1] for emission right trading. In order to avoid the intervention of endogenous problems and other policies, we chose the propensity score matching difference-in-differences (PSM-DID) method to conduct quasi-natural experiments. Moreover, we also used the Annual Environmental Survey of Polluting Firms (AESPF) and the Annual Survey of Industrial Firms (ASIF) to collect pollution panel data from Chinese industrial enterprises span from 1998 to 2013. The results indicated that introduction of SETPS imposes a significant reduction effect on corporate carbon emission. This means that an SETPS not only can achieve pollution reduction, but can also achieve an additional carbon reduction effect.

The contribution of this paper can be summarized in the following three aspects. First, we enrich the literature on the effect and evaluation of market-oriented environmental regulation policies. Contrary to traditional environmental regulation policies, an SETPS is a market-oriented policy. Not only does it achieve an SO_2 emission reduction (Chang & Wang, 2010; Cheng et al., 2016; Wu et al., 2019; Chen et al., 2022), but it also achieves an additional carbon emission reduction effect. This highlights the importance of market-oriented policies in pollution reduction and carbon abatement.

Second, we further tested the moderation effect. The results demonstrated that both financial constraints and ownership are moderation factors of SETPS, affecting enterprise carbon emission reduction; the moderation effect of financial constraints is slightly greater than that of the ownership.

Third, we tested the influence mechanism of an SETPS on enterprise carbon emission reduction through a mediation effect analysis. The results indicated that SETPS can influence carbon emissions by promoting the marketization process and the development of the non-state-owned economy. The mediation effect of the marketization process is more significant.

Finally, we also conducted a variety of robustness tests, such as a placebo test, and all the results indicated robustness. Considering the heterogeneity of enterprises, an SETPS has a more significant effect on the carbon emission reduction of enterprises with high energy consumption and high pollution levels.

The remainder of the thesis is arranged as follows. Chapter 2 introduces the institutional background and describes the literature review. Chapter 3 discusses our model design and data sources. Chapter 4 reports the empirical results and tests. Finally, Chapter 5 summarizes the paper and provides policy implications.

[1]11 pilot provinces are: Tianjin, Hebei, Shanxi, Inner Mongolia, Jiangsu, Zhejiang, Henan, Hubei, Hunan, Chongqing, Shaanxi.

LITERATURE REVIEW

China's emission trading system has progressed through the initial, exploratory, and deepening stages. In the 1960s, Coase (1960) proposed the important role of property rights theory in public management, laying the foundation for the theoretical development of emission rights trading (Dales, 1968). It has been demonstrated that by incorporating the concept of property rights into pollution control. The emission trading system can reduce emissions through the commercialization of emission rights in a perfect competition market. With the gradual improvement of the domestic market economy, the decisive role of the market mechanism in the allocation of environmental factors has become an important idea to explore a new path for environmental governance.

In 2002, the former State Environmental Protection Administration initiated a pilot scheme of sulfur dioxide emission trading in seven provinces and cities. It passed a resolution to conduct pilot emission trading in 7 provinces and cities. In 2007, the Ministry of Finance, the Ministry of Environmental Protection, and the National Development and Reform Commission approved 11 provinces for pilot projects for trading of pollution discharge rights. The emission trading policy was officially launched, and now 28 provinces and cities in China have conducted pilot schemes in emission trading. The pilot schemes use SO_2 as the main component, and further include nitrogen oxides, chemical oxygen demand, and ammonia nitrogen.

Existing research on the policy effects of SETPS focus primarily on the schemes' effects on emission reduction, economic growth (Ramanathan et al., 2017), enterprise innovation, and total factor productivity (Ren et al., 2020; Tang et al., 2020; Peng et al., 2021). More researchers have focused on SO_2 about the emission reduction effect of SETPS. Many studies have concluded that an SETPS has a positive emission reduction effect on SO_2 (Loschel et al., 2019; Zhu et al., 2019; Wu et al., 2020; Zhang et al., 2020). Regardless of whether the research uses panel data of pilot provinces in China (Wu et al., 2019) or focuses on a specific province (Cheng et al., 2016), the SETPS has been demonstrated to achieve good emission reduction effects. At the same time, the policy effects of an SETPS have regional heterogeneity, that is, the results are different in different regions (Chen, 2022), and the results may be related to other conventional policies (Chang & Wang, 2010).

However, some studies have come to quite different conclusions, suggesting that China's emissions trading policies have not been effective in reducing sulfur dioxide emissions (Greenstone, 2004; Wang et al., 2004; Gerking & Hamilton, 2008). The reasons for the failure to implement China's emission trading system are that the pilot areas have not really institutionalized sulfur dioxide emission trading. Lacking domestic institutional innovation, it is difficult to adapt the scheme to China's national conditions (Shin, 2013). Furthermore, China has not formed a perfect emission trading market (Wang et al., 2004).

Sulfur dioxide and carbon dioxide are highly homologous. Their emissions are correlated (Agee et al., 2014). Therefore, it is feasible and necessary to consider the coordinated treatment of atmospheric pollutants and greenhouse gases (Labriet et al., 2009; Zhang & Wang, 2011). In fact, an introduction of SETPS may be able to promote the emission reduction of carbon at the same time as the emission reduction of SO_2. However, to date, in the process of studying the policy effect of SETPS, few studies have focused on the schemes' effect on carbon emission reduction.

To fill this gap, the PSM-DID model is adopted to estimate the effect of implementing the SETPS. Potential endogeneity problems are avoided and the results are more robust. Second, to better estimate the policy effects of an SETPS, we constructed an enterprise pollution dataset that included 13,314 observations span from 1998 to 2013.Third, historical research studies lack robustness tests and heterogeneity analyses. Various robustness tests, moderation effect tests, and heterogeneity analyses were conducted. Finally, few historical documents have analyzed the influence mechanism of the SETPS policy effect, whereas we tested the mediation effect.

METHODOLOGY AND DATA

Model Specification

Propensity Score Matching

On the basis of considering the effects of market-oriented environmental regulation policies, we selected fuel consumption, gross industrial production value, effluent charges, exhaust gas treatment capacity, firm exports, and enterprise growth as the characteristic variables to match the treatment group with the control group. The model is represented by the following equation:

$$Logit\,(du_{it} = \lambda) = \alpha + \beta X_{it} + \varepsilon_{it} \tag{1}$$

In **Eq. 1**, du_{it} is a dummy variable, $\lambda = 1$ when the firm is located in a province where an SETPS is implemented, and 0 otherwise. X_{it} is the characteristic variable. Using the PSM method, individuals within the same value range were matched.

Difference-In-Differences Estimation

To measure the impact of China's emissions permit system on carbon emissions, it was necessary to exclude the effect of other policies on carbon emissions. Therefore, we adopted the PSM-DID method to solve the endogeneity problem. Based on Beck et al. (2010), the model can be represented as follows:

$$CO2_{it} = \alpha_0 + \alpha_1 did + \beta Control_{it} + Year_t + Province_j + Ind_i + \varepsilon_{ijt}$$
$$did = treat \times time \tag{2}$$

In **Eq. 2**, i and t denote firm and year, respectively, $CO2_{it}$ represents the carbon dioxide emissions of firm i in year t. did represents the SETPS for a specific firm in a given year. $Control_{it}$ is a vector of the control variables, including the fuel consumption, gross industrial production value, effluent charge, exhaust gas treatment capacity, firm exports and

TABLE 2 | Descriptive statistics.

Variable	Obs	Mean	Sd	Min	P50	Max
CO_2	228622	6.332	3.629	0.000	7.286	16.53
Did	514280	0.312	0.463	0.000	0.000	1.000
Fuel	24273	4.488	1.911	0.000	4.585	7.822
Values	509952	8.391	1.859	0.000	8.343	12.81
Fee	514280	11.117	0.712	8.799	11.343	12.227
Treatment	229964	2.701	4.948	0.000	1.000	35.000
Export	514280	0.558	0.497	0.000	1.000	1.000
Growth	514215	11.099	1.608	7.711	10.96	15.33

enterprise growth. $Year_t$, $Province_j$, and Ind_i represent fixed effects for time, area and individual firm, respectively. ε_{ijt} is the error term.

Variable Definition

The definitions of variables used in the empirical analysis are listed in **Table 1**.

Dependent Variable

The dependent variable is carbon dioxide emissions, which are calculated using the carbon emission coefficient method. The conversion formula is: $CO_2 = \log(1 + co_2)$, and co_2 = standardized coal *0.714*2.492. China's energy consumption structure is dominated by traditional fossil fuels (Huang et al., 2011; Schreifels et al., 2012; Umar et al., 2021), which are an important source of environmental pollution. We therefore chose carbon dioxide emissions as the dependent variable.

Independent Variable

The independent variable is an SETPS. This means that by giving enterprises the right to discharge pollutants within the limits set by the government, they can sell excess emission rights in the emission trading market or buy additional emission rights from other enterprises. Marketization gives enterprises a forced mechanism to achieve the best pollution control effect. An SETPS is represented by the interaction term *did*, $did = time \times treat$. time = 0 if time is before 2007, otherwise time = 1; treat = 1 if the firm located in the cities that with SETPS implemented, and treat = 0 otherwise.

Control Variable

We selected enterprise-level control variables based on the existing literature in the field of environmental regulation (Hu et al., 2020; Du & Li, 2020; Bertarelli & lodi, 2019; Ouyang et al., 2020), that is, factors such as fuel consumption, gross industrial product, effluent charge, exhaust gas treatment capacity, firm exports, and enterprise growth. In the current international division of labor, China is still mainly at the lower end of the value chain. Enterprises can obtain advanced technology and management experience through exports and improve production efficiency (Clerides et al., 1998; Yang et al., 2017), thus influencing the energy conservation and emission reduction activities of the industry. In addition, the capital flow of enterprises restricts the updating of products or technologies (Yin et al., 2022). Companies with higher profitability tend to invest more in the introduction of environmental protection facilities and technologies, thus affecting the pollution emission intensity of these enterprises.

TABLE 3 | PSM-DID.

	(1)	(2)	(3)
Variables	CO_2	CO_2	CO_2
Did	−1.0045***	−1.7811***	−1.7811***
	(−38.97)	(−13.14)	(−10.97)
Fuel	—	−0.0785***	−0.0785***
	—	(−4.03)	(−2.98)
Values	—	0.2287***	0.2287***
	—	(11.40)	(9.55)
Fee	—	−0.2180*	−0.2180**
	—	(−1.82)	(−2.00)
Treatment	—	0.0956***	0.0956***
	—	(14.43)	(10.12)
Export	—	−0.7416***	−0.7416***
	—	(−8.55)	(−6.92)
Growth	—	0.3125***	0.3125***
	—	(10.84)	(8.22)
Constant	4.4654***	1.3669	1.3669
	(54.29)	(1.16)	(1.14)
Time effect	YES	YES	YES
Industry effect	YES	YES	YES
Regional effect	YES	YES	YES
Cluster at firm	NO	NO	YES
Observations	228,622	13,314	13,314
R-squared	0.260	0.494	0.494

Data Sources

Firm Pollution Data

Corporate carbon emission data are issued by the Annual Environmental Survey of Polluting Firms (AESPF) of China. Established in the 1980s by China's Ministry of Ecology and Environment, the AESPF records data on industrial emissions and how effectively companies are reducing emissions. The database mainly includes enterprise pollutant emissions (such as SO_2, nitrogen oxide, industrial waste water, industrial waste gas, smoke, and solid waste), the application of cleaning facilities and energy consumption (including fresh water, circulating water, coal, fuel, clean gas, etc.), and other indicators. Pollution data in the database are highly representative, with industrial enterprises included in the dataset accounting for approximately 85% of the total pollution. Sample enterprises need to report a large amount of environment-related information to environmental authorities every year. After verification, these data are compiled into standardized reports and then included in the database.

Other Firm-Level Data

Other firm-level data are issued by the Annual Survey of Industrial Firms (ASIF). The ASIF, compiled by the National Bureau of Statistics, is a micro enterprise data set widely used by scholars, both in China and internationally, and has strong representativeness with regard to studying enterprise issues. Its sample ASIF range includes all state-owned and non-state-owned industrial enterprises with sales of more than ¥5,000,000. The database includes two types of information

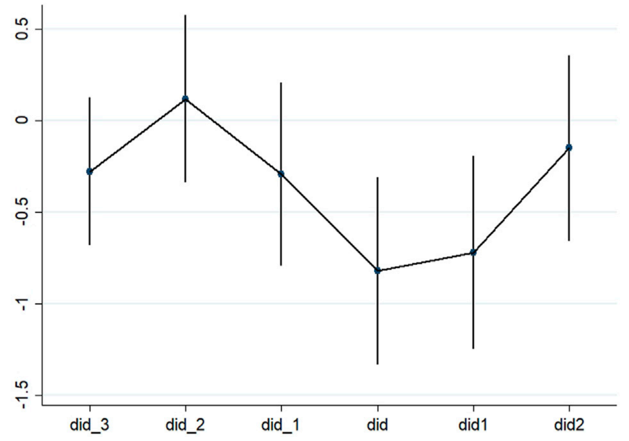

FIGURE 1 | Test for Assumption of parallel Trend.

regarding enterprises: One is basic information on the enterprise (including the legal person code, enterprise name, legal representative, and other indicators), and the other is financial data on the enterprise (current assets, accounts receivable, long-term investment, fixed assets, and other indicators). We matched the AESPF with ASIF based on the company names and then the corporate codes. After excluding outliers and eliminating records which violate the accounting standards, we obtained 13,314 observations between 1998 and 2013.

Descriptive Statistics

The descriptive statistics of variables is shown in **Table 2** including the number of observed values, the mean, the standard deviation, and the maximum and minimum values. The mean value of carbon emissions is 6.332, and the standard deviation is 3.629, indicating that there are huge differences among firms.

EMPIRICAL RESULTS AND DISCUSSION

Benchmark Regression

Of our central interest is to examine the carbon emission effect of SETPS on enterprises. With the choice of fixed effects that are used to absorb confounding unobservable at time, region or industry level, the regression results as presented in Column 1) of **Table 3**. Consistent with the conclusion of Wang et al. (2019) and Yu et al. (2022), there is a negative and statistically significant coefficient about *did*, indicating that an SETPS have a negative impact on the enterprise carbon emission. By including all the control variables, the regression results were determined, as presented in Column (2) of **Table 3**. The estimated coefficient absolute value becomes bigger and remains the statistically significant at the 1% level. In addition, Standard errors presented in the parenthesis are clustered at firm level, As shown in column (3) of **Table 3**, the estimated impact of SETPS on firm carbon emission is still negative and statistically significant at 1% level. These findings suggest that an SETPS can effectively reduce the enterprise carbon emissions.

TABLE 4 | Replacing dependent variables.

	(1)	(2)	(3)
Variables	**tgas**	**cod_discharge**	**fumes_emission**
Did	−0.2688***	−0.2239***	−0.2256***
	(−4.50)	(−3.29)	(−2.86)
Fuel	0.1765***	0.0824***	0.0952***
	(18.72)	(8.25)	(7.92)
Values	0.1710***	0.1108***	0.1666***
	(14.97)	(10.15)	(11.92)
Fee	−0.1538***	0.0854	−0.0358
	(−2.73)	(1.19)	(−0.47)
Treatment	0.0936***	0.0480***	0.0651***
	(41.71)	(16.03)	(18.62)
Export	−0.2193***	0.0516	−0.3992***
	(−5.71)	(1.19)	(−7.79)
Growth	0.4151***	0.4201***	0.3099***
	(28.86)	(27.78)	(17.13)
Constant	−6.4951***	−6.3868***	−4.8203***
	(−11.53)	(−8.87)	(−6.30)
Time effect	YES	YES	YES
Industry effect	YES	YES	YES
Regional effect	YES	YES	YES
Observations	16,295	13,790	13,597
R-squared	0.604	0.367	0.556

Test for Assumption of Parallel Trend

The key prerequisite for the DID model to effectively identify causality is the establishment of the common trend hypothesis. Before the implementation of an SETPS, the difference in carbon emissions between enterprises in the treatment group and the control group will not change systematically over time. Based on Beck et al. (2010), the dynamic model to test the common trend as follows:

$$CO2_{it} = \alpha + \sum_{\tau=-3}^{2} \beta_{\tau} * did^{\tau}{}_{it} + \lambda * Control_{it} + Year_t + Province_j + Ind_i + \varepsilon_{ijt} \quad (3)$$

In **Eq. 3**, $did^{\tau}{}_{it}$ is a series of dummy variables. The value is 1 if there are τ periods before the SETPS is executed in enterprise, and otherwise the value is 0.; When $\tau < 0$, it indicates that the enterprise has not implemented an SETPS. We conducted trend tests on the two phases after the implementation of an SETPS and the third lagged periods. In addition, $Year_t$, $Province_j$, Ind_i represent fixed effects referring to time, area, and individual firm, respectively. ε_{ijt} is the error term.

The results are presented in **Figure 1**. The figure illustrates that the parameters β_{τ} of did_1, did_2 and did_3 in the three stages before did, are all near 0, and the 95% confidence interval also contains 0 (not significantly different from 0). This means that there is no difference in the ex ante trend between the treatment group and the control group. So the common trend hypothesis is verified. Moreover, the emission reduction effect of the treatment group is obviously better than that of the control group. This result proves that an SETPS has a significant effect on corporate carbon emission reduction.

TABLE 5 | Heterogeneity test.

Variables	(1) High Energy Consumption and High Pollution Enterprises CO_2	(2) Low Energy Consumption and Low Pollution Enterprises CO_2
Did	−2.0555***	−1.6492***
	(−9.09)	(−10.05)
Fuel	0.1456***	−0.2812***
	(4.54)	(−12.00)
Values	0.3275***	0.1588***
	(7.88)	(7.35)
Fee	0.2805	−0.6116***
	(1.38)	(−4.36)
Treatment	0.0620***	0.1523***
	(6.76)	(15.67)
Export	−0.3033*	−0.9417***
	(−1.95)	(−9.12)
Growth	0.1690***	0.4274***
	(3.42)	(12.56)
Constant	−7.1095***	5.7390***
	(−3.58)	(4.19)
Time effect	YES	YES
Industry effect	YES	YES
Regional effect	YES	YES
Observations	5,450	7,864
R-squared	0.449	0.480

Robustness Checks

Replacing Dependent Variables

Considering the diversity of enterprise emissions, this study replaced the dependent variable carbon with total industrial gas emissions (tgas), chemical oxygen demand (cod_discharge) and industrial fumes emissions (fumes_emission), respectively. It examined whether an SETPS also imposes reduction effect on these emissions. As shown in **Table 4**, the results indicate that an SETPS has a strong inhibitory effect on the discharge of these pollutants and statistically significant at the 1% level. This indicates that SETPS achieved the dual significance of promoting carbon emission reduction and pollution emission reduction. The reason may be that SETPS significantly promotes enterprises adopting green innovation (Ren et al., 2020; Tang et al., 2020; Peng et al., 2021), forcing enterprises to transform and upgrade to clean enterprises, thereby reducing the overall level of enterprise pollution rather than specific emissions. In addition, it can be seen from the regression results that the emission reduction effect for other pollutants is better than that for carbon emission reduction. The reason may be that the main purpose of SETPS is to achieve SO_2 emission abatement by trading SO_2 emission permits. Although carbon emission discharged by enterprises together with pollutants in industrial production, an SETPS does not reduce carbon emissions as much as pollutants.

Placebo Test

Furthermore, we used a placebo test to solve the estimation error caused by missing variables. We randomly chose enterprises that implemented SETPS every year and repeated the regression to **Eq. 2** 1,000 times. As shown in **Figure 2**, the coefficients obtained based on the random sample estimation are all distributed near 0, which indicates that the influence of the SETPS on the carbon emissions of an enterprise is not affected by the missing variables.

Heterogeneity

The industry where an enterprise is located has a significant influence on its pollution emission levels. Industries with high energy consumption and high pollution levels will inevitably produce more carbon emissions, so it is necessary to further understand the impact of industry heterogeneity on the emission reduction effect. This study divided enterprises into high energy consumption and high pollution enterprises on the one hand, and low energy consumption and low pollution enterprises on the other hand. As shown in **Table 5** we report the results for enterprise carbon emission measured by pollution degree. In both columns, the estimated coefficients for *did* are consistently negative and statistically significant at the 1% level. It can be seen that introduction of SETPS imposes a significant reduction effect on enterprises carbon emission in both high and low-pollution industries. Specifically, an SETPS has a more significant effect on carbon emission reduction for enterprises with high energy consumption and high pollution levels. The reason may be that the pollution emission levels of low energy and low pollution enterprises are relatively lower. For enterprises with high energy consumption and high pollution levels, their own pollution emission base is large. The introduction of SETPS just provides a suitable platform to promote emission reduction.

Further Discussion

This study investigates whether financial constraints and ownership are moderation factors for SETPS to affect enterprise carbon emissions. The moderation effect has been tested according the following models:

(1) Moderation effect Model 1—Financial constraints (SA):

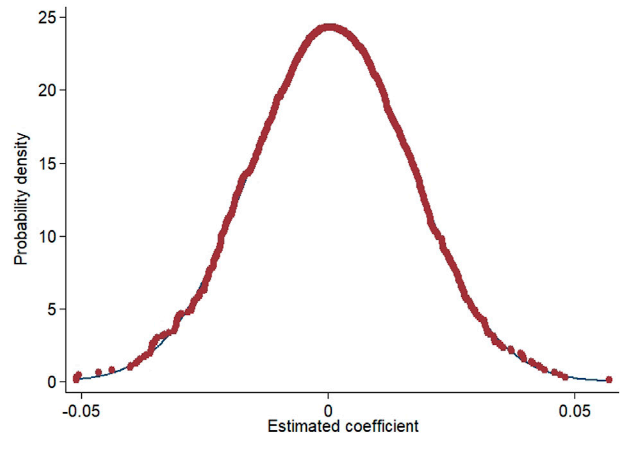

FIGURE 2 | Placebo Test.

TABLE 6 | Moderation effect.

Variables	(1) CO_2	(2) CO_2
Did	−3.5426***	−1.7112***
	(−7.44)	(−12.23)
SA	3.0348***	—
	(13.83)	—
State	—	1.2512***
	—	(12.13)
SA*did	−0.6771***	—
	(−3.99)	—
State*did	—	−0.5949**
	—	(−2.39)
Fuel	−0.0965***	−0.0812***
	(−4.96)	(−4.20)
Values	0.2092***	0.2295***
	(10.51)	(11.47)
Fee	−0.1763	−0.2203*
	(−1.48)	(−1.84)
Treatment	0.0812***	0.0851***
	(12.17)	(12.90)
Export	−0.7359***	−0.7143***
	(−8.53)	(−8.27)
Growth	−0.4477***	0.2520***
	(−7.54)	(8.67)
Constant	18.4552***	1.2495
	(11.21)	(1.06)
Time effect	YES	YES
Industry effect	YES	YES
Regional effect	YES	YES
Observations	13,309	13,314
R-squared	0.502	0.501

$$CO2_{it} = \alpha_0 + \alpha_1 did + \alpha_2 \times SA + \alpha_3 \times SA \times did + \beta Control_{it} + Year_t + Province_j + Ind_i + \varepsilon_{ijt}$$
$$did = treat \times time \tag{4}$$

(2) Moderation effect Model 2—Ownership (state):

$$CO2_{it} = \lambda_0 + \lambda_1 did + \lambda_2 \times \text{state} + \lambda_3 \times state \times did + \beta Control_{it} + Year_t + Province_j + Ind_i + \varepsilon_{ijt}$$
$$did = treat \times time \tag{5}$$

In terms of financial constraints (SA), this study divided enterprises into two categories according to whether they have financial constraints. With regard to the nature of the enterprises (state), this study classified enterprises according to their actual controllers. If the actual controllers are central or state organs, they were classified as state-owned enterprises, and the rest were classified as non-state-owned enterprises. When an enterprise is state-owned, state = 1; otherwise, state = 0.

As shown in **Table 6**, when it comes to the interaction term between *did* with financial constraints, we document the consistently negative coefficient and the coefficient is statistically significant at the 1% level, indicating that financial constraints can adjust the impact of SETPS on enterprise carbon emission. Similarly, when it comes to the interaction term between *did* with ownership. we find the coefficient is -0.5949 and the coefficient is also statistically significant at the 1% level. This indicates that the ownership influences the impact of SETPS on enterprise carbon emissions. Both financial constraints and ownership can be used as regulatory factors for SETPS to affect enterprise carbon emissions; the regulatory effect of financial constraints is slightly greater than that of the ownership.

Mechanism Analysis

Next, we analyzed the mechanism of SETPS's influence on carbon emissions using the mediation effect test. With the wide application of market-based environmental regulation policies, the marketization process is accelerated, and the trading market of emission rights becomes more mature. In addition, state-owned enterprises have problems with regard to principal-agent relationship (Zhang, 1997) and the policy burden (Lin et al., 1998), due to their nature. These problems can be solved by introducing non-state-owned capital into state-owned enterprises governance (Kornai et al., 2003). Therefore, we speculate that SETPS can influence carbon emissions by promoting the marketization process and the development of the non-state-owned economy. When testing, we controlled for time effect, industry effect, and region effect in all regressions. The estimated results are presented in **Table 7**.

The Marketization Process

It can be clearly seen from column 2) of **Table 7** that the marketization process is inversely related to the proportion of carbon emissions. The coefficient of market_score is −0.4436 and is statistically significant at 1% level, which demonstrates that SETPS can indeed reduce the enterprise carbon emissions by speeding up the process of marketization. Specifically, the effect of SETPS on enterprise carbon emission reduction by affecting the marketization process is 0.3431*(−0.4436) = −0.1522. In addition, according to the above basic regression results, the total effect of SETPS on enterprise carbon emission reduction is −1.78. This accounts for approximately 8.6% of the total effect, indicating that the mediation effect of the marketization process is relatively significant.

The Development of the Non-state-owned Economy

Based on column (4) of **Table 7**, we document that the coefficient of state_score is −0.3517 and is statistically significant at 1% level. This demonstrates that SETPS can reduce carbon emissions by promoting the development of the non-state economy. Specifically, SETPS has an effect of 0.3278*(−0.3517) = −0.1153 on the carbon emission reduction of enterprises by affecting the development of the non-state-owned economy. Its mediation effect is slightly smaller than that of the marketization process.

TABLE 7 | Mediation effect.

	The Marketization Process		The Development of Non-state-owned Economy	
	(1)	(2)	(3)	(4)
Variables	**Market_score**	**CO_2**	**State_score**	**CO_2**
Did	0.3431***	−1.6321***	0.3278***	−1.6755***
	(27.98)	(−12.16)	(23.29)	(−12.40)
Market_score	—	−0.4436***	—	—
	—	(−5.21)	—	—
State_score	—	—	—	−0.3517***
	—	—	—	(−5.04)
Fuel	0.0019	−0.0774***	0.0016	−0.0775***
	(1.13)	(−3.99)	(0.79)	(−3.99)
Values	0.0023	0.2305***	−0.0004	0.2290***
	(1.43)	(11.44)	(−0.17)	(11.39)
Fee	0.0909***	−0.1709	0.2238***	−0.1640
	(7.13)	(−1.42)	(10.94)	(−1.36)
Treatment	0.0004	0.0961***	0.0003	0.0958***
	(0.81)	(14.50)	(0.55)	(14.47)
Export	−0.0062	−0.7412***	−0.0104	−0.7442***
	(−0.82)	(-8.55)	(−1.34)	(−8.59)
Growth	−0.0063**	0.3097***	−0.0020	0.3123***
	(−2.52)	(10.74)	(−0.63)	(10.85)
Constant	7.5637***	4.6058***	6.9660***	4.0343***
	(57.79)	(3.46)	(37.20)	(3.20)
Time effect	YES	YES	YES	YES
Industry effect	YES	YES	YES	YES
Regional effect	YES	YES	YES	YES
Observations	16,935	13,314	16,935	13,314
R-squared	0.964	0.495	0.971	0.495

CONCLUSION AND POLICY IMPLICATION

This paper examines whether sulfur dioxide emission trading pilot scheme (SETPS) can help reduce the carbon emissions of enterprises. We hypothesize that the implementation of SETPS can negatively affect carbon emissions. Based on the pollution data of Chinese industrial enterprises from 1998 to 2013, we adopted the propensity score matching-difference in differences (PSM-DID) method to evaluate the impact of SETPS on enterprise carbon dioxide emissions in these pilot areas. The results demonstrate that the introduction of SETPS has a positive effect on the carbon emission reduction of enterprises, while the pollution emission differences in different industries lead to the heterogeneity of emission reduction effect. Specifically, SETPS achieves better emission reduction effect for enterprises in high pollution industries. We also find that SETPS reduces carbon emissions by promoting the marketization process and the development of the non-state-owned economy. In addition, both financial constraints and enterprise nature can regulate the impact of SETPS on carbon emissions.

Our research provides certain policy implications. First, faced with the “carbon neutrality” target, the command-and-control environmental regulation policy has been unable to achieve the desired emission reduction goal. the Chinese government should vigorously promote market-oriented environmental regulation policies such as SETPS. The emission rights could be distributed reasonably according to enterprise needs through market means. Implementation of SETPS can not only promote SO_2 emission abatement, but also impose a reduction effect on carbon emission and other pollutant discharges, which constitutes a green bonus for the policy.

Second, Industrial differences should be taken into account when controlling carbon emissions in China. Authority should, based on industrial particularity, introduce more targeted policies and supporting mechanisms to reduce carbon emissions. Enterprises from high-polluting industries should be allocated relatively more emission rights. This will assist in increasing the incentive for companies to reduce emissions.

Then, A perfect emission trading market need to be constructed, allowing market to display the decisive role in allocating resources. The government should continue to consistently deepen market-oriented reform and promote the development of the non-state-owned economy. Speeding the marketization process support the full operation of SETPS and improve the efficiency of emission rights allocation.

Eventually, Government should pay more attention to the moderation effect of financing constraints on enterprise emission reduction, to ensure that enterprises have sufficient funds for environmental protection. One effective measure is to reduce the financing constraints of enterprises, thus increasing the working capital of enterprises and giving enterprises more incentive to use capital for green innovation to improve air quality.

In addition, the article also has some limitations inevitably. This paper only analyzes the effectiveness of market policy on enterprise carbon emission. However, the marketization policy and the traditional environmental regulation policy complement each other, and the coordination of various policies will achieve better emission reduction effect. If data are available, future research can focus on exploring policy effects under the framework of constructing multiple policy combinations.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

YZ: methodology, writing—review and editing, supervision, and resources. SS: methodology, software, and visualization. YX: formal analysis, data curation, and investigation. LY: writing—review and editing, supervision, and project administration. SC: data curation, formal analysis and software. DJ: resources, software, and visualization. ZX: conceptualization, validation, resources, data curation, funding acquisition and writing original draft. All authors: contributed to the article and approved the submitted version.

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Why Are Households Willing to Pay for Renewable Energy? Lessons From Romania

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Renewable energy is seen as a key tool in addressing the dual issue of increasing energy demand and climate change mitigation. In the current geopolitical climate, it may also play a key long-term role in increasing energy security. In order to reach the ambitious green energy targets set for each European Union member state public support for fiscal and other support mechanisms is required. The purpose of this paper is to determine to what extent the population in the North-East region of Romania is willing to make financial sacrifices for further development of renewable energy. We also explore what lifestyle and socio-demographic factors influence willingness to pay. We applied a discrete choice experiment on a sample of 602 households from the populous North-East region of Romania. Our results show that the creation of new jobs and the increase of the national energy independence, followed by the reduction of pollution are societal benefits that would convince households to pay a premium in order to support renewable energy development. Increased local budgets for rural communities resulting from the taxation of new energy companies is not one of the desired outcomes of green energy development. The study is useful in the design of adequate fiscal and renewable support policies and serves companies by identifying willingness to pay influence factors, as well as by demonstrating a market segmentation procedure.

Keywords: renewable energy, willingness to pay, discrete choice experiment, lifestyle segmentation, energy independence

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1 INTRODUCTION

Satisfying the ever-growing energy demand, but at the same time reducing greenhouse gas emissions and mitigating climate change are some of the most challenging and ardent issues for the policymakers around the world. Renewable energy is perceived as an effective way to cope with the dual nature of these challenges, usually topping the list of meaningful changes that our society can implement. The new European Green Deal places the European Union (EU) on a path towards climate neutrality by 2050, a goal that requires a significant commitment towards developing the production of electricity from Renewable Energy Sources (RES). However, fiscal policies and financing schemes that promote RES, will not prove to be successful if governmental authorities do not take note of the local or national public opinions and perceptions. According to the 2019 Eurobarometer, the population in Romania is not significantly concerned with climate change, but rather believes that the most serious problems that the world is faced with are the overall economic situation and issues such as poverty and hunger (European Union, 2019). In the current geopolitical context, assuring long term energy security for the European Union is likely to be achieved both through a diversification of fossil fuel imports and, crucially, the large scale development of internal generation of electricity from non-fossil sources (Sauvageot, 2020; Mišík, 2022). The aim of this paper is to determine to what extent the population in the North-East region of Romania is willing to make financial sacrifices in order to support the development of RES. We have pursued three goals in order to reach our aim: determining the Willingness to Pay (WTP) of households in the North-East region of Romania for the development of RES, identifying the factors that influence WTP, and simulating the structure of the retail electricity market based on the preferences of household consumers.

The current paper makes several contributions to the field of knowledge. From a methodological standpoint, we provide demonstrations on how discrete choice experiments can be constructed in order to estimate preferences both in the short and in the medium/long term, as well as how to incorporate socio-demographic and lifestyle variables in the segmentation of the retail electricity market. Empirically, this is the first large scale experimental study of the WTP of households in the North-East region of Romania for renewable electricity. Finally, in terms of policy implications, our findings demonstrate that the public is willing to pay for fiscal and financing schemes for RES development to the extent in which it provides energy independence, creates new local jobs and reduces pollution. However, we find that they are opposed to additional taxation of newly established RES producers.

The literature review section presents the current status and debates around renewable energy policies and markets across the world and introduces the primary method used in the study. This is followed by the methodology section, in which we outline the data collection process, the validation of our energy knowledge scale, the market segmentation procedure and the discrete choice experiment. We then proceed to the results section, where we present the findings focusing on the three research goals outlined above: determining the WTP of Romanian households for RES development, identifying the factors that influence WTP, and simulating the future structure of the retail electricity market. Finally, we conclude with an outline of the theoretical, policy and practitioner implications of our study and discuss its limitations and future studies required.

2 LITERATURE REVIEW

2.1 Renewable Energy: Evolution and Debate

Renewable energy presents a complex set of advantages, besides those of being "green". The growing sector of renewables expands energy access in many developing countries and it can create jobs, and, in the long term, it can help lower energy bills, as well as improve environmental protection and the general health of the public.

The main types of RES currently utilized are hydro (including tidal energy), wind, solar, biomass and geothermal. Nuclear energy could also be considered "green", although the fuels used for energy production are non-renewable. The fact that, on one hand, nuclear power plants do not generate emissions of greenhouse gasses or other air pollutants during their operation, while, on the other hand, creating issues related to nuclear waste, investment costs and public acceptance makes this a disputed source of clean, sustainable energy (Suman, 2018; European Commission Joint Research Centre, 2021; US Department of Energy, 2021; Simionescu et al., 2022).

In terms of electricity generation, the latest data by the IEA shows that, in 2019, global production reached 25.8 TWh, out of which coal represented 36%, natural gas 23%, hydro 17%, nuclear 10%, wind 6%, solar 3%, biomass 3% and oil 3% (IEA, 2020a). It is worth noting that, in 2019, "low carbon" electricity generation (renewables and nuclear) surpassed coal sources, which decreased by 3.1% in 2019.

The pursuit and implementation of RES related policies around the world, as well as the proportion of RES energy production and consumption at macro-regional and national levels in the respective energy mixes are influenced by a series of geo-political and socio-economic factors such as type and level of resources available, energy dependency, economic development or public perception of environmental issues and RES. When it comes to some of these factors, the EU member states have been proven to be both more exposed to energy supply risks and more committed to reducing greenhouse gas emissions compared to the other countries in the world, determining the EU to provide significant support for the development of renewable energy. Due to its low reserves of oil and natural gas, the EU imports more than half of all the energy it consumes. In its path towards improving energy security the European Commission has sought to increase the integration of the EU energy markets and infrastructure, but also to increase domestic production of electricity (primarily through RES). As a result, in 2019, the electricity generation mix for the EU was: 36% RES (of which 11% hydro), 25% nuclear, 22% natural gas, 15% coal and 2% oil (IEA, 2020b). The data shows a remarkable 245% increase in non-hydroelectric RES by 2019 compared to 2010 (IEA, 2020b).

Renewable energy production and the pursuit of new technologies meant to solve de dilemma of satisfying the growing energy demand while protecting the environment are not without their critics. First of all, an issue of principle can be brought up: that of the poorer countries and regions of the world which face the challenge of having to grow their economies, alleviate poverty and increase electricity access for their citizens, whilst avoiding the carbon-intensive approach which was used for decades by the currently developed countries of the world. That said, according to the International Renewable Energy Agency, many countries in Africa have sought to support the RES development as a means of leapfrogging the traditional centralized-utility model of providing energy to households and businesses (International Renewable Energy Agency, 2015).

Other valid critiques of RES are related to the intermittent nature of some of the energy sources (such as solar or wind), the changes to the landscape and the disruption to ecosystems that dams, large solar plants or wind turbine fields create, the technology and maintenance costs, or the production of new types of waste and pollution (Levenda et al., 2021; Sayed et al., 2021). In terms of landscape integration and planning of renewables, the COST Action TU 1401 ("Renewable Energy and Landscape Quality"—RELY) performed extensive pan-European research and produced case studies, community events and toolkits that can support the synergy between landscape protection and management and renewable energy (RELY, 2022). The Action also generated a comprehensive guide on renewable energy sources with their production potential, advantages, disadvantages, as well as paths towards addressing these disadvantages with applied case studies across 33 European states, including Romania (Roth et al., 2022).

Wind turbines and solar photovoltaic panels do not generate greenhouse gas or other emissions during their operation. They both have a relatively short installation time (compared to all other conventional and renewable power plants) and can be placed in a variety of locations. Their main practical disadvantage is related to intermittency of generation, making them inadequate destabilizing components of the energy grid in the absence of rapid response units such as large hydroelectric plants or natural gas turbines. In the case of wind, there are several disadvantages that need to be considered, ranging from a limited negative impact on wildlife (birds in particular), potential micro-climate disruptions, as well as noise pollution and landscape disruption (Breeze, 2005; Genoud and Lesourd, 2009). The last of these has been addressed in detail by the RELY COST Action mentioned previously. The disadvantages of solar photovoltaic panels relate to excessive land use, potential negative visual impact (e.g., when placed on historical buildings) and a notable risk of pollution and greenhouse gas emissions during the production process (Maxim, 2015a). Notably, solar panels are one of the most effective methods of supplying electricity for a dwelling that is not connected to the grid, a fact that has been recognized by a funding scheme by the Romanian Environment Fund Administration, through which 5,000 euro subsidies were offered for the installation of photovoltaic panels on isolated homes. This scheme along with other current renewable energy support mechanisms in Romania are discussed in more detail in **Section 2.3**.

Biomass is overall much closer to conventional fossil fuel technologies, in the sense that electricity is generated using steam turbines, but using a sustainable carbon neutral fuel. The crops used in the process can be regrown locally every year, thus increasing energy security and re-capturing the equivalent carbon from the atmosphere and soil as is emitted during the generation process. The burning of biomass does contribute to carbon emissions, which can be offset by the crops of the following year, but it also generates nitrous oxides, particulate matter and ash. It also requires large land surfaces for cultivation, thus limiting the areas available for growing food crops and amplifying the pollution of the water table with fertilizers. Some grassy and wood energy crops (e.g., poplar) can have the positive effects such as soil stabilization and underground water filtration (Breeze, 2005; Genoud and Lesourd, 2009).

Hydroelectric power has become a somewhat controversial energy source over the last decades due to its significant socio-environmental disadvantages coupled with its undeniable socio-economic and technical benefits. Large hydroelectric projects have numerous benefits, such as low generation costs, rapid and on-demand response to peak demand. The reservoirs have also been used to facilitate irrigation, prevent floods and to boost local economic development through the establishment of water-centric recreation amenities that attract tourists. However, there are complex issues that arise from the establishment of large hydroelectric power-plants. These range from the unforeseen complications that can appear during the dam construction phase to the social and environmental impact that the newly established reservoir creates. For example, any population living in the area to be flooded must be moved, while any significant locales, such as worship sites and historical landmarks will be submerged and become inaccessible. From an environmental standpoint, the reservoir reduces the natural habitat of fauna and flora in the area, severely changes the local landscape and it may also lead to greenhouse gas emissions resulting from the decomposition of the organic matter that becomes submerged. The dam itself can affect the flow of fish and sediments along the river and could lead to erosion and even drought downstream—generating the need for internationally coordinated management of strategically important transnational rivers, such as the Nile (Heggy et al., 2021).

It is due to the significant disadvantages such as those outlined above, but also due to the fact that much of the large hydroelectric potential has generally been exploited across the European Union that renewable energy support schemes do not focus on providing support for such developments. In Romania, the vast majority of the large hydropower projects have been developed before 1990 and are now owned and operated by the state-controlled company Hidroelectrica SA. Under these circumstances, the initial law outlining the green certificate support scheme adopted in 2008 mentions power plants with an installed capacity of at most 10 MW (Nazare, 2020). There are currently 245 small hydroelectric plants (below 10 MW) that are connected to the national grid according to Transelectrica, the grid operator (Transelectrica, 2022). While small hydropower plants can have many of the same benefits as their larger counterparts, they generally do not have the same flexibility in the generation process, as they cannot rely on the availability of a large reservoir of potential energy. In addition, as many of these plants have been developed along remote mountainous regions, environmental activists, as well as mass media outlets and local communities have condemned these projects for their destructive impact on picturesque local ecosystems, making small hydropower plants a rather controversial option (Pavlakovič et al., 2022).

The pros and cons of renewable energy have a differentiated impact on the public, based on their perception of the advantages and disadvantages encompassed, on their personal beliefs and preferences, all influenced by a complex set of economic, demographic, social and cultural factors.

2.2 Development of Renewable Energy: Policies and Public Support

In order to develop the willingness to make an effort (financial, visual, personal convenience) so as to support RES development, the public in general and consumers in particular need to accept that renewable energy is desirable and has a predominantly positive impact on society and their lives. Without this type of support, any inconvenience that arises from the implementation of RES support policies will be met with protests and disobedience. Thus, issues regarding how RES are perceived and to what extent they are accepted by citizens has been the topic of several studies. One innovative piece of research concerns how renewable energy is perceived by young schoolchildren in Latvia, Lithuania and Romania. The authors find that the label "clean" and the colours "yellow" and "white" are prevalent in the mind of first to fourth graders, compared to the label "green" and the colour "green" in older children (Tsagarakis et al., 2018). This finding has implications on the entire manner of communicating about renewable energy in schools in order to develop awareness from a young age.

Paravantis et al. find that the social acceptance of renewable energy has been affected primarily by institutional shortcomings (bureaucracy, inefficient legal frameworks, planning issues), economic factors, such as higher electricity costs paid by consumers, as well as more complex societal issues (lack of trust in investors, lack of information and awareness regarding the new technologies) (Paravantis et al., 2018). In the case of Greece, these problems are prevalent among lower income societal groups, with a lower level of formal education or information on the topic, who live far away from existing renewable energy projects. A different study applied in Italy also found that the desirability of renewable electricity generation facilities depends significantly on the energy source used, with agricultural biomass being the least desirable (lowest WTP) out of the set presented to the respondents (Vecchiato and Tempesta, 2015). In the case of Saudi Arabia, researchers found that the level of education, income and age have a significant impact on the willingness to adopt renewable energy technologies (Mosly and Makki, 2018). Similarly, from the perspective of willingness to invest in renewable energy generation, aside from the profitability of such projects, respondents' attitudes were impacted by environmental values and their preference for specific energy sources (Karasmanaki et al., 2019).

The main types of fiscal policies and RES support schemes used across the globe are Feed-In-Tariffs and Tradable Green Certificates. Some of these have evolved into Renewable Portfolio Standards and the more recently introduced Renewable Obligations or the tender based Erneuerbare Energien Gesetz. Most studies discussing these policies tend to either assess the impact of these policies in various countries or seek to optimize and propose revisions to the traditional policies already in place (Shen et al., 2020). Mezősi et al. conducted a cost-efficiency benchmarking of RES support schemes across Europe over two decades and identified significant differences in the cost-benefit ratio of different national mechanisms (Mezősi et al., 2018).

The design of policies regarding RES is highly dependent on a thorough analysis of public perceptions and attitudes. This is why concepts such as "social acceptance" or "community acceptance" are becoming more prevalent in studies, whilst policymakers around the world acknowledge that analyses that focus solely on technical and economic factors are not sufficient for the successful implementation of these policies. Wűstenhagen et al. propose a typology of renewable energy acceptance frameworks which includes a political level, a market level and a societal and community level of acceptance (Wűstenhagen et al., 2007). The social acceptance of RES is influenced by several factors, identified usually in the literature as "local externalities", amongst which we find aesthetics, noise and impact on local ecosystems.

Studies aimed to assert the willingness to accept/adopt RES for the consumers in various countries/regions of the world, the willingness to pay (WTP) for RES, as well as people's preferences concerning different energy sources and the factors that drive these preferences have grown in number in recent years. The methodology used in the studies is also varied. In the case of Knapp et al. a mixed method approach is used to correlate standardized national surveys in the United States with data regarding voluntary participation in green energy support programmes offered by utility companies (Knapp et al., 2020). Gao et al. implement a meta-regression analysis based on several previous studies in order to determine WTP, which they deem crucial for establishing adequate levels of investment subsidies (Gao et al., 2020). Ntanos at al. apply a survey among Greek citizens in order to identify the factors that influence consumers' WTP for and their willingness to invest in renewable energy (Ntanos et al., 2018). Balezentis et al. as well as Lee and Heo use contingent valuation in surveys of Lithuanian household consumers and Korean consumers respectively (Lee and Heo, 2016; Balezentis et al., 2021).

2.3 Renewable Energy in Romania

In the case of Romania, the chosen RES support scheme has been a combination of tradable green certificates and a renewable energy quota imposed on electricity suppliers (Zamfir et al., 2016). The price of the certificates could fluctuate within a pre-established interval, depending on market demand. The scheme entered into force in 2011, leading to a rapid expansion of renewable energy projects in the country, as well as a significant increase in electricity prices. As a result, the government decided to implement a downward revision of the support scheme, reducing the number of certificates awarded to green energy producers, thus reducing the overall subsidies offered to the RES sector. This approach seems to have transformed the policy into one of the most cost effective in the EU (Mezősi et al., 2018). Given that the green certificate system was only aimed at medium and large scale producers of electricity, governmental authorities also set up legislation to subsidize the procurement and installation of photovoltaic solar panels by households (Cristea et al., 2020).

Currently, we can identify four avenues of support for renewable energy development in Romania. First, the green certificate and quota system implemented since 2011 is still in force until 2032, albeit in an adjusted format, and it applies for installations that were set up before the end of 2016. Other large scale projects benefit indirectly from both the quota of renewable energy imposed on suppliers, as well as priority transmission to the grid. Second, for smaller producers of renewable energy, Law

184/2018 regulated that "prosumers", with an installed capacity of up to 27 kW (increased to 100 kW in 2020), can sell the energy they produce to their contractual supplier, who is obligated to purchase the energy at the average weighted price of the Day-Ahead market in the previous year. Third, the Romanian Environment Fund Administration (AFM) launched two programs, with budgets of 115 million euros and 47 million euros respectively, which provided subsidies of up to 4,000 and 5,000 euros respectively for the installation of photovoltaic panels primarily by households (Nazare, 2020). Finally, for larger producers, the Ministry of Energy has recently launched a call for the construction of new wind and solar power plants worth 457.7 million euros financed through the National Recovery and Resilience Plan (Ministry of Energy, 2022). Eligible projects need to have a minimum capacity of at least 0.2 MW and be completed and connected to the network by the middle of 2024. The maximum available funding per applicant is 15 million euros. One noteworthy aspect is that applicant companies do not need to be primarily registered as energy producers. They only have the relevant NACE code (3511—"Electrical energy production") as one of their registered activities. Thus, the program is also presented as a valuable opportunity for entities, such as farms and factories, which have enough real estate which can be used to install solar panels or wind turbines in order to reduce their energy costs and diversify their revenue streams.

As part of the EU 20-20-20 climate and energy package, the target set for Romania in terms of gross final consumption of energy from renewable sources has been 24%. The country managed to reach this target in 2015, coinciding with a significant decrease in regulatory incentives for RES investments. In the perspective of 2030, Romania has assumed a target of 30.7%, below the 34% level recommended by the European Commission (Nazare, 2020). The current level of development of the RES sector in Romania can be described through dimensions such as installed capacity, production and consumption. In terms of installed capacity, in May 2022, out of a total of 18 542 MW, 35.8% were hydroelectric plants, followed by 16.3% wind, 7.5% solar and 0.6% biomass (a total of 60% of installed capacity is RES). Other production sources include 16.7% coal, 15.4% hydrocarbons (almost all of which is natural gas), and 7.6% nuclear. Negligible capacities of biogas, geothermal and other technologies also exist (ANRE, 2022a). In terms of actual production, given the intermittency of renewables, their total contribution to electricity output in 2021 has been approximately 44.8% (30.8% hydroelectric and 14% non-hydro: 12.1% wind, 1.5% solar and 0.4% biomass), from a total of 54.02 TWh delivered to the grid (ANRE, 2022b). Finally, in terms of consumption, renewable energy represented 24.5% of gross final energy consumption in 2020 (Eurostat, 2022).

The price paid by Romanian households for electricity is determined both by the free market, as well as the regulated tariffs established by the Romanian Energy Regulatory Authority (ANRE) (ANRE, 2021; Pack Energy, 2022). After the energy is produced, the generator sells it to a supplier through one of the various types of transactions available on the market. The energy is then introduced into the national grid owned by the state-controlled company Transelectrica SA. Next, it is sent through the regional networks of the six distributor companies (only one of which is state owned) and is delivered to the end user either through high, medium or low voltage distribution lines. The market based price of the electricity sold to consumers encompasses the cost of generation and the margins of both the producer and the supplier. This component of the tariff is sometimes called active energy and is the component that can be negotiated or adjusted based on the pricing strategy of the supplier. There are also several regulated components of the electricity tariff related to transportation, distribution, green certificates and other taxes. The transportation components include the system price (TS) and the prices for introducing and extracting the energy from the national grid (TG and TL, respectively). The distribution tariffs depend on whether the customer is connected to the high, medium or low voltage lines (low voltage incurs a higher tariff per unit of energy) and is abbreviated as IT, MT or JT, respectively. Finally, other regulated tariffs include the green certificates, the excise and the tax for supporting high efficiency cogeneration. Based on the commercial offers provided to household customers in May 2022 by two of the largest suppliers and the regulated tariffs currently in effect, the green certificates currently represent approximately 4% of the overall electricity bill—between 5 and 10 lei per month for an average household (Electrica Furnizare, 2022; E.; ON, 2022).

Studies of Romanian household consumers' WTP for renewable energy are very rare in Romania. Most of the research that we have identified is focused on presenting the evolution of the electricity market from a policy and energy mix perspective. Dragomir et al. present the impact that the roll-back of the green certificate scheme had on wind farm investments (Dragomir et al., 2016). Năstase et al. provide an overview of the development of solar photovoltaic energy production in Romania over the last decade (Năstase et al., 2018). We can also find more complex energy system modelling studies, which provide guidelines on how the gradual transition from conventional power generation towards RES can be achieved while maintaining the stability and sustainability of the market and the energy system as a whole (Koltsaklis et al., 2020). The only WTP focused research that we are aware of has been the set of papers developed and published by the authors of the current study over the last six years.

One of the most surprising findings regarding renewable energy in Romania was that RES projects do not seem to have any significant positive impact on rural development in terms of employment, increased revenues to the local budgets, demographics or agriculture (Cebotari et al., 2017). This is in spite of the fact that much of the existing literature presents the socio-economic development of rural communities as one of the positive benefits of RES development (hence our inclusion of rural development as one of the positive societal benefits of renewable energy in the discrete choice experiment). In fact, our findings also seem to confirm that consumers do not consider increased revenues for the local budgets of rural communities as a relevant or desirable benefit of RES.

2.4 Discrete Choice Experiments and Public Preference

Discrete choice experiments (DCEs) have grown in popularity over the last decade due to their versatility and the level of insight they provide on the topics being studied. A DCE works by simulating a choice task that a consumer could make in a real-life scenario. For example, one such study could ask respondents to choose from a set of three vacation packages, each defined by a specific destination, duration, type of activity and price. The packages themselves are called profiles, the four different traits are called attributes, while the specific value of each attribute (e.g., duration of 2, 7 or 10 days) is called a level. The choices are repeated across several such sets of 2–4 profiles, called "choice sets", in which the attribute levels assigned to each profile vary according to the experimental design. After analysing the data, researchers are able to estimate the utility that respondents assign to each attribute and/or level and thus predict the probability with which a profile/product/offering "i" would be chosen from any specific set of "n" profiles.

As discussed in this section, WTP studies do not need to rely on a DCE. There are several revealed preference methods (hedonic pricing, travel costs) or stated preference methods (contingent valuation, conjoint analysis variants) which can be used to estimate WTP (Accent and RAND Europe, 2010). However, due to the realistic simulation of a real-life choice, DCEs have increasingly been used by researchers in fields such as marketing, healthcare, tourism, public goods, non-marketable environmental goods and ecosystem services, urban green space design and product design and several others (Rakotonarivo et al., 2016; Van Dogen and Timmermans, 2019; Guo et al., 2021; Kemperman, 2021; McPhedran and Toombs, 2021; Rusmevichientong et al., 2021).

DCEs are also used in studies covering the topic of energy and renewable energy development. Some researchers use them in order to determine public preferences for specific attributes of RES projects or electricity services (e.g., location, type of energy, size or even electricity tariff preferences) (Srivastava et al., 2021; Oehlmann et al., 2022). Other studies use DCEs to calculate consumer WTP for the development of RES (Longo et al., 2008; Ku and Yoo, 2010).

3 METHODOLOGY

Our study is centred on a discrete choice experiment conducted through the use of an instrument that included both the experimentally designed question items and a series of survey questions. The data was collected from a sample of 602 households from the North-East development region of Romania (the most populous of the country). The sampling procedure was based on two quotas: rural/urban residence and county of residence, considered highly relevant given that the surveyed population is composed of households. The resulting sample insures a proportional spread of the respondents across the region. Data collection and analysis were performed during Q4 2020—Q1 2021. The data was collected online using the Sawtooth Software Lighthouse Studio 6.6 platform. The statistical analyses were performed using IBM SPSS 25 and STATA MP16.

Aside from providing the first large scale implementation of a choice experiment in the field of renewable energy in Romania, the current work is able to provide more layers to the existing DCE and RES literature through unique econometric modelling techniques applied to data concerning the preferences of energy consumers. First, we are able to demonstrate the implementation of a choice modelling approach with two distinct temporal horizons: short term versus medium/long term. Secondly, we have tested and incorporated an energy knowledge scale in the analysis in order to identify whether awareness regarding the functioning of the energy sector impacts consumer preferences. Thirdly, we have also demonstrated the use of an innovative market segmentation procedure using a mix of lifestyle and socio-demographic variables, thus increasing the practical utility of the resulting clusters. Finally, we are able to further expand the results of the study by demonstrating of the use of market simulations in the retail energy sector based on choice preferences.

3.1 Choice Experiment Variables and Design

The attributes chosen for the choice experiment were identified based on an extensive literature review and filtered through the use of a survey among a sample of academics and specialists from the energy field. The full process through which the attributes were chosen is described in (Maxim, 2015a). Our experiment uses a set of five attributes. Four of these refer to societal benefits that can result from an increased share of renewable electricity being produced and consumed at the national level. We also included a price attribute that allows us to determine the WTP of household consumers for these benefits.

The process of establishing adequate levels for the attributes required a specific approach for each of the five items, as described in (Maxim et al., 2021). The cost attribute was scaled based on the average monthly electricity bill for households, the energy independence levels were designed based on the projected substitution of energy imports with internally produced renewable electricity, the number of new jobs is estimated based on current numbers of employees in the energy sector and projected employment increases, pollution effects were evaluated based on the externalities generated by each type of electricity production technology and the increased tax revenue was estimated based on the projected revenue generated by locally based renewable electricity companies and projects. We decided to set a number of four gradual levels of increase from the status quo values of each of the five attributes. The full set of attributes and levels is presented in **Table 1**.

Based on the number of attributes and levels, the experimental design could incorporate up to 45 offering profiles. In order to generate a high quality fractional factorial design, we utilized the "Balanced Overlap" approach provided by Sawtooth Software's Lighthouse Studio. Based on the recommendations of Orme, we decided to use a design that incorporates 3 distinct profiles in each choice set, plus an additional status quo option, through which respondents may decide to not pay any additional fees, resulting in no additional societal benefits (Orme, 2014). The use of a status quo option in choice experiments is recommended in order to avoid overestimation of preferences and WTP (Maxim and Roman, 2019).

TABLE 1 | Summary of the attributes and levels included in the discrete choice experiment.

Attribute	Status quo	Level 1	Level 2	Level 3	Level 4
Additional cost of the monthly electricity bill	0 RON	5 RON	15 RON	25 RON	35 RON
Romania's independence from energy imports (coal, gas, oil etc.)	77%	78%	80%	82%	84%
New jobs created at the county level	0	2	6	12	16
Reduction of pollution effects (air, water, soil)	0%	10%	15%	20%	25%
Increased revenue for rural localities from taxes paid by new energy companies	0%	1%	3%	5%	7%

However, each choice set in the experiment also required respondents to choose their favourite option out of the non-status-quo profiles. This approach is an original contribution that the current study brings to the choice experiment methodological design, and it has been used to generate two different WTP models, a short-term one and a medium/long-term one.

The results of the experiment were analysed through a Conditional Multinomial Logistic regression (cMNL), also known as Conditional Logit, which is based on calculating the utilities of profiles—sets of attributes or traits that a product or service offering provides to consumers (Hauber et al., 2016). The utility is estimated using a linear predictor function, as seen in **Eq. 1**.

$$U_m = V_m + \varepsilon_{in} = \alpha_i + \beta_1 X_{1i} + \beta_2 X_{2i} + \ldots \beta_K X_{Ki} + \varepsilon_{in} \quad (1)$$

where:

U_{in}—the utility of profile i perceived by respondent n; V_{in}—the systematic, explainable component of utility of profile i perceived by respondent n; ε_{in}—the random, unexplained component of the utility of profile i perceived by respondent n; x_{ki}—the level of attribute k in the case of profile i.

It is assumed that a respondent will choose the profile or offering that provides the highest level of utility out of a set of n profiles. The probability (P) of choosing a specific profile (i) out of a set (n) is shown in **Eq. 2**. We will later use this formula to generate simulations regarding the retail electricity market.

$$P_{in} = \Pi_{in} = \frac{\exp(V_{in})}{\sum_{j=1}^{n} \exp(V_{in})} = \frac{e^{\alpha i + \beta 1x1i + \beta 2x2i + \ldots + \beta kxki}}{\sum_{j=1}^{n} e^{\alpha j + \beta 1x1j + \beta 2x2j + \ldots + \beta kxkj}} \quad (2)$$

One of the risks associated with using the cMNL model, is the assumption that respondents' preference for one profile is independent of all other profiles. This is called the Independence from Irrelevant Alternatives (IIA) assumption, also referred to in practice as the "Red Bus/Blue Bus" problem (Orme, 2014). This issue can only be mitigated through the use of other modelling approaches, such as mixed logit, which relaxes the IIA assumption. However, given that the current experiment uses generic societal benefits and electricity price as attributes (all of which have levels designed on a continuous scale), we expected that the IIA assumption will not have a major influence. After rerunning the analysis using the mixed logit model, we only observed a notable increase in the preference impact of "pollution reduction" compared to the cMNL model. The differences are discussed in **section 4.1**.

The marginal WTP of respondents for an attribute (or for a distinct attribute level in some cases) is determined by dividing the regression coefficient of that attribute to the negative of the cost coefficient (Orme, 2014).

$$WTP = -\frac{\beta_{attribute\ or\ attribute\ level}}{\beta_{cost}} \quad (3)$$

Thus, in the case of attributes with levels that qualify as continuous intervals (such as price), if a linear relationship is assumed along the different levels, a single regression coefficient will be attributed and used in determining WTP.

Hypothetical bias, taking the form of overestimated WTP values being measured primarily due to respondents providing what they perceive to be socially desirable answers, is an issue that can affect stated preference surveys. In order to avoid the overestimation of respondents' willingness to commit financial resources for specific goods and services, several ex-ante and ex-post measures can be taken by researchers (Loomis, 2014). We have taken steps to limit hypothetical bias, although it may still have an effect on the presented results. In the case of our study, the approach meant to limit the hypothetical bias falls primarily within the ex-ante category. We use dual questions in the choice experiment component of the survey and provide a choice set model demonstrating the acceptability of the "status quo" answer. The two questions asked to respondents for each choice set are: "Out of A, B and C, I prefer . . . " and "If I had to sign a new contract today, I would choose:", as illustrated in **Table 2**. In a previous study on this topic where this approach was used, we were able to calculate an average WTP level which was approximately one third lower compared to forcing respondents to choose their initially preferred contract (from the first question), rather than the status quo selected in the second question (Maxim and Roman, 2019). In support of this method, before starting the choice experiment, respondents were presented with a pre-filled choice set model that presented the case of a hypothetical respondent and the options chosen by them. Our hypothetical respondent choose to remain subscribed to their current electricity contract in the case of the second question (status quo), thus demonstrating to the respondents that the status quo option is an acceptable answer. This example also served as a method of ex-post validation of the collected data. One of the profiles in the choice set example included a perfect (unrealistic) combination of at-tributes (i.e., the highest possible benefits for the lowest possible price). Any respondent who did not choose this profile may be flagged as not understanding the choice set or not being attentive when responding to the survey.

TABLE 2 | Example of choice set used in questionnaire.

	Offer A	Offer B	Offer C	Current offer
Romania's independence from energy imports (coal, gas, oil etc.)	78%	82%	84%	77%
New jobs created at the county level	16	6	6	0
Additional cost of the monthly electricity bill	35 lei	15 lei	5 lei	0 lei
Reduction of pollution effects (air, water, soil)	10%	20%	20%	0%
Increased revenue for rural localities from taxes paid by new energy companies	+5%	+7%	+3%	0%

Out of A, B and C, I prefer: Offer A Offer B Offer C
If I had to sign a new contract today, I would choose: Offer A Offer B Offer C Current offer

The results of logit analyses have been proven to be intrinsically robust even when omitting relevant variables (Cramer, 2007). Specialists in the field do not make any specific recommendations on robustness tests for logit models beyond the mitigation of the IIA assumption vulnerability discussed above (Train, 2009; Lancsar et al., 2017).

3.2 Validation of Energy Knowledge Scale

The data was collected using a questionnaire that, aside from the discrete choice experiment, includes several other questions and scales that are meant to identify factors that influence the WTP of household consumers for renewable energy development. We included a series of socio-demographic questions that are meant to test various hypotheses regarding factors that influence consumers' WTP, as well as two more complex sections: a test of energy sector knowledge and a scale for lifestyle segmentation.

The first of these is a 10 item True/False/Do not know scale that seeks to measure whether the respondent is knowledgeable regarding the energy sector and the electricity market. We hypothesize that the WTP level can be correlated with the respondents' awareness regarding the issues and inner workings of the energy sector. The 10 items included in the scale were:

- Carbon dioxide is a greenhouse gas;
- Over 80% of the electricity produced in Romania comes from fossil fuels (e.g., coal, natural gas, oil);
- During the process of generating electricity, nuclear power plants do not produce carbon dioxide;
- Production of electricity from renewable sources (wind, solar, hydroelectric, etc.) does not cause significant carbon dioxide emissions;
- Currently, from a legal standpoint, household consumers in Romania can change their electricity supplier;
- The electricity supplier is a company that owns the physical infrastructure through which the home is supplied with electricity;
- The electricity distributor is a company that owns the physical infrastructure through which the home is supplied with electricity;
- The companies E.On, ENEL, CEZ, Electrica, Engie are electricity distributors;
- Tariffs for electricity supplied to homes are set by state authorities;
- Some electricity suppliers offer the possibility of purchasing electricity produced only from renewable sources.

The Cronbach α indicator was used to verify the confidence of the proposed scale, in accordance with the recommendations in the literature on exploratory scales with dichotomous responses (Pallant, 2011). The analysis was performed for two distinct methods of coding the answers: "all or nothing" (the correct answers are marked with 1, and the incorrect ones or "I don't know" with 0), and "intuitive response", that acknowledges respondents, who selected the "I don't know" option in instead of opting for the wrong answer (correct answers are marked with 1, "I don't know" are marked with 0.5, and incorrect ones are marked with 0). Following the analysis, we determined a Cronbach α value of 0.474 for the "intuitive response" coding with an average inter-item correlation below the minimum level of 0.2 recommended in the reference works. Instead, for the "all or nothing" approach we obtained a Cronbach α value of 0.51, with an average inter-item correlation of 0.204 for a grouping of statements 1, 3, 4 and 6 (three related to greenhouse gasses and one related to the definition of electricity supplier). Despite the relatively low value of the scale confidence indicator, we can say that the combined answers provided in the case of the 4 statements tend to measure the same construct—the level of knowledge about the energy sector. By summing up the answers for each statement, we obtain an interval scale, with values between 0 and 4. This was used in subsequent analyses to verify the impact of "knowledge" on WTP.

3.3 Market Segmentation

Aside from socio-demographic variables and the level of knowledge regarding the energy sector, we hypothesize that WTP is also influenced by the consumer lifestyle. In order to assess whether a lifestyle-based market segmentation can be used to determine groups of consumers with distinct preferences and WTP levels, we used the 19 item life practices scale used successfully in a previous market segmentation study of household electricity consumers (Maxim, 2015b).

After the data collection stage, the 19 lifestyle practices were reduced to a more compact set of dimensions using Principal Components Analysis. The analysis was conducted through several iterations and, in accordance with existing literature on the subject (Malhotra and Birks, 2007; Field, 2009; Pallant, 2011), we identified that "Planning household expenses" and "Religious and spiritual activities" have weak correlations with all other practices. We settled on an optimal solution that could be clearly interpreted, consisting of 6 components. The factor loading matrix presented in **Table 3** illustrates how these variables were grouped within the components.

TABLE 3 | Lifestyle components resulting from the Principal Components Analysis applied to the life practices scale (Factor loading matrix).

Life practices (short format)	Component					
	1	2	3	4	5	6
Hobbies	0.758					
Cultural activities	0.741					
Career development	0.731	–0.371				
Sports and physical activities	0.689		–0.334	–0.329		
Vacations	0.683					
Spending time in nature	0.652		–0.398			
School/Education	0.650	–0.415				
Protecting the environment	0.650					
Volunteering/Charity	0.638					
Online entertainment	0.620			0.386		0.302
Non-food shopping	0.579			0.414		
Spending time with family	0.566		–0.446	0.306		
Watching TV		0.694		0.337		
Following energy news		0.667	0.498			
Home repair/improvement	0.371	0.442	0.384			
Study/test new technologies	0.484		0.496			
Religious/spiritual activities	0.338		–0.326		0.605	
Socializing	0.351	0.425			–0.500	
Planning household expenses	0.362	0.345		0.362		–0.586
Variance explained	22.1%	11.6%	9.5%	9.1%	7.4%	6.5%

TABLE 4 | Segmentation of the household consumer market based on lifestyle and socio-demographic traits (average or median values).

Segmentation value	Cluster 1	Cluster 2	Cluster 3	Cluster 4
Urban/Rural	urban	rural	rural	rural
Income (RON)	1,500–2,999	3,000–5,999	3,000–5,999	1,500–2,999
Education	University	High-school	High-school	Post-secondary
Age (years)	31.4	65.7	21.3	45.2
Active careerism	0.15	−1.40	0.38	−0.43
Proletarianism	0.01	0.20	−0.07	0.07
Introverted technologism	0.19	−0.36	0.03	−0.18
Domestic sedentarism	0.00	0.22	−0.15	0.34
Religiosity	−0.09	0.28	−0.04	0.03
Spontaneity	0.26	0.47	−0.27	0.03
No. of members	158	71	289	83

In order to be able to use these components more effectively in the market segmentation analysis, we assigned suggestive labels, which result from the direct and inverse correlations they have with different life practices:

- Component 1: Active careerism;
- Component 2: Proletarianism;
- Component 3: Introverted technologism;
- Component 4: Domestic sedentarism;
- Component 5: Religiosity;
- Component 6: Spontaneity.

The six components provide an eloquent picture of the types of activities which are practiced concurrently or distinctly by the population of the North-East region of Romania. The results of this analysis can also be used to issue future hypotheses in explaining the market behaviours of consumers from the studied population.

In order to identify market segments (groups of respondents with somewhat homogeneous preferences with regard to the electricity market), we utilized the hierarchical cluster analysis. The initial iterations based solely on the 6 lifestyle components mentioned above yielded market segments which were very similar in terms of socio-demographic traits. In order to improve the practical utility of the study, we also incorporated four socio-demographic variables in the analysis: age, education level, income level and rural/urban residence.

Table 4 provides a descriptive illustration of the four clusters generated. The values shown represent the mean or median value of each variable, depending on the type of scale used. The six lifestyle components have values between −2 and +2, depending on the intensity with which that specific component is practiced by each individual. In order to facilitate the identification of the segments during the data analysis process, they were assigned descriptive labels according to the mean/median values of the segmentation variables. The names chosen are: "urban middle

TABLE 5 | Descriptive statistics of independent variables.

Variable	All available profiles					Choices applicable to main model				
	N	Min	Max	Mean	S.D.	N	Min	Max	Mean	S.D.
INDEP	18,060	78.00	84.00	81.00	2.29	6,020	78.00	84.00	81.27	2.38
JOBS	18,060	2.00	16.00	9.13	5.38	6,020	2.00	16.00	10.37	5.24
COST	18,060	5.00	35.00	19.33	11.16	6,020	5.00	35.00	16.83	11.13
POL	18,060	10.00	25.00	17.17	5.58	6,020	10.00	25.00	16.97	5.52
RURAL	18,060	1.00	7.00	4.13	2.23	6,020	1.00	7.00	4.02	2.23

TABLE 6 | Main utility model (medium and long term).

Variable	B coefficient	Std. Error	Standardized B	Sig
INDEP	0.045	0.007	0.102	0.000
JOBS	0.047	0.003	0.249	0.000
COST	–0.021	0.002	–0.233	0.000
POL	0.008	0.003	0.042	0.018
RURAL	–0.016	0.007	–0.036	0.027

–2 Log likelihood = 13,227.29; –2 Log likelihood = 12,506.7; Chi-square 703.5 (df = 5, sig = 0.000).

TABLE 7 | Short-term utility model.

Variable	B coefficient	Std. Error	Standardized B	Sig
INDEP	0.047	0.009	0.105	0.000
JOBS	0.050	0.003	0.262	0.000
COST	–0.018	0.002	–0.200	0.000
POL	0.005	0.004	0.030	0.181
RURAL	–0.005	0.009	–0.012	0.550

–2 Log likelihood = 8428.6; –2 Log likelihood = 8000.7; Chi-square 415.1 (df = 5, sig = 0.000).

class" (Cluster 1), "senior rural" (Cluster 2), "entry level" (Cluster 3), "rural middle class" (Cluster 4).

4 RESULTS

The results of the study will be outlined progressively, starting with the estimated values of the households' willingness to pay, continuing with the factors that influence these values and closing with a simulation of the evolution of the market based on the preferences expressed by the respondents.

4.1 Determining the WTP of Households for Renewable Energy

The descriptive statistics for the five independent variables are presented in **Table 5** in two groups: those applicable to all profiles presented to the respondents and those applicable to the profiles chosen by the respondents. As seen in **Table 6**, after 18,060 experimental observations of choices made by respondents, all five attributes of RES development were found to have a statistically significant impact on consumer choice. This is our main regression model, which takes into consideration all respondents. These results are likely to hold true in the medium to long term, as they are based on a formulation that does not include the "status quo" option, in which consumers can refuse to opt for any of the alternative offerings presented in the experiment.

INDEP (Romania's independence from energy imports—coal, gas, oil etc.), JOBS (new jobs created at the county level) and POL (reduction of pollution effects—air, water and soil) have a positive influence on the perceived utility of the electricity supply offerings. COST (additional cost of the monthly electricity bill) and RURAL (increased revenue for rural localities from taxes paid by new energy companies) have a negative impact on utility.

Although the negative sign of the COST variable is natural, the result obtained for the RURAL variable is surprising. One possible explanation is that respondents may have a negative perception regarding the taxation of newly established enterprises. Thus, it is possible that respondents perceive this final attribute more as an obstacle in the path of RES development, rather than a societal benefit of the sector's expansion. In fact, the findings of Cebotari et al. show that, in those rural communities in North-West Romania where RES projects were developed, there were no significant improvements in employment, size of the local budget, population or agriculture (Cebotari et al., 2017).

In order to estimate the short-term preferences and WTP of consumers, we excluded those respondents who are currently renting or who do not own their current dwelling, and thus are much less likely to have a say in the type of energy contract signed by the household in the short term. The model presented in **Table 7** did provide respondents with a "status quo" option that does not increase monthly electricity bills and does not generate any societal benefits. This is likely to be a realistic option only in the short term, given the ambitious RES development targets assigned to Romania by the European Commission for the year 2030 (which will require new investments and, consequently, higher costs with green certificates).

In the case of the short-term model, the number of experimental observations of choice drops to 11,508. In this formulation, we observe that only INDEP, JOBS and COST have a statistically significant impact on choice. The POL and RURAL variables do not significantly influence the utility of the electricity offerings.

The estimations of households' marginal WTP for the development of the RES sector are illustrated in **Table 8**. The values presented assume a linear preference across the various attribute levels—a realistic assumption given that the experimental design used equal distances between these levels.

TABLE 8 | Households' marginal WTP for the societal benefits attributable to the development of the RES sector.

Resulting benefit	Marginal WTP (RON/month)	Marginal WTP (RON/month) in the short term
1% increase of energy independence	2.1 (CI 95%: 1.3/3.3)	2.6 (CI 95%: 1.2–3.5)
1 additional job created at the county level	2.2 (CI 95%: 1.7/2.9)	2.8 (CI 95%: 1.8–3.1)
1% reduction of pollution	0.4 (CI 95%: 0.1/0.8)	–
1% increase of the local budgets of rural communities	−0.8 (CI 95%: −1.3/−0.1)	–

CI 95% represents the 95% confidence interval (lower value/upper value)

The overall results show a significant increase (up to five times) in absolute terms for JOBS and INDEP compared to a similar study that we conducted six years ago on a smaller and more localized sample of households (Maxim, 2015b). There is also a 15% increase in the WTP for pollution reduction compared to the results of the same study. The results presented in **Table 8** also show that the WTP of households for job creation and energy independence is higher in the short term, while the WTP for pollution reduction is not significant within the same time frame. The increased WTP in the short term is a surprising result, given that the inclusion of a non-payment "status quo" option usually leads to a decrease in WTP, as some respondents are allowed to not choose a profile that requires, for example, an increase in the electricity bill.

As mentioned in **section 3.1**, a mixed logit model can eliminate the IIA assumption issue specific to cMNL and provide more practically valid results. After running the analysis using a mixed logit procedure, we saw a notable increase of 37% in the marginal WTP for pollution reduction and a 22% decrease in the marginal WTP for jobs in the long term, while rural budget increases lose their statistical significance. In the short term, WTP for pollution reduction becomes statistically significant and is calculated at 0.5 RON/month, while WTP for jobs decreases by 23% compared to the cMNL short term model.

4.2 Identifying the Factors That Influence the WTP of Households for Renewable Energy

All of the variables included in the research instrument that are not part of the choice experiment have been evaluated with regard to their impact on WTP. One common approach of determining influence factors is to include them in the regression model as interaction effects. However, the process of identifying and reporting the results in the case of over 20 variables each potentially impacting one of the four RES attributes would have proved cumbersome to report and interpret. For this reason, we have decided to run the regression analysis on sub-samples of respondents, obtained by filtering the respondents based on each tested variable. By utilizing this approach, we can identify and report the impact on WTP in a clear and comprehensible manner. The results in **Table 9** present the relative differences between the WTP for each attribute in the case of the variable filtered sub-sample and the complete sample used for the main regression model. The data only includes those cases for which the regression coefficients or the regression model itself have a statistical significance above 0.05.

The results presented in **Table 9** are meant to indicate influence tendencies and should not be analysed strictly from the perspective of the illustrated values. Based on the table results, we are able to identify those factors which determine increases in WTP for the different societal benefits that can be attributed to RES development. Some of the results can be explained by mediators that are not difficult to intuit. For example, income levels in Iași county are higher compared to the rest of the North-East region, which explains the lower WTP of Bacău, Neamț and Suceava counties. However, other results can help us identify potential causal factors. For example, the much higher WTP of Iași county residents for pollution reduction compared to the rest of the sample is correlated, and likely caused, by the high level of air pollution encountered especially in the area of Iași city.

4.3 Simulating the Retail Electricity Market Based on Consumer Preferences

In order to estimate the market share potential of an electricity offering on a hypothetical market, we can employ the standard probability estimation formula for the cMNL model illustrated in **Equation 2**. In order to create a hypothetical marketplace for the North-East region of Romania, we constructed a series of realistic electricity offering profiles that focus on different RES benefits. The level of the price attribute was adjusted in order to match the other attributes (i.e. a profile with high levels of benefits has a high cost level). The results of the hypothetical market simulation are illustrated in **Table 10**.

In the hypothetical market presented in **Table 10** we can observe the high impact that the price of the offering has on its potential market share. The level of the RURAL attribute was maintained at its lowest level, given its inverse correlation with utility. It is recommended that such an attribute be excluded from the commercial messages constructed by electricity suppliers for households. It should be noted that the "preference share" presented in **Table 10** is not a guarantee of the attainable market share, but rather an indication of the probability that a specific offering will be chosen by customers in a specific, simulated, market context.

In spite of maximizing two of the benefits, the "Energy independence + Pollution reduction" offering has the worst share on the market, due to its high price. Contrarily, an average price level combined with the highest level of new jobs obtained the best result on the hypothetical market.

TABLE 9 | Identification of factors that have a significant influence on WTP and their estimated impact.

Benefit	Influence factor	Impact on WTP
Romania's independence from energy imports—coal, gas, oil etc.	Urban resident	109%
	Dwelling type—apartment	108%
	Male	51%
	"Senior rural" segment	28%
	"Urban middle class" segment	14%
	Age below sample average	9%
	Income above sample average	4%
	"Entry level" segment	−7%
	Education above sample average	−19%
	Knowledgeable about energy	−23%
	Residence: Suceava county	−27%
	Residence: Neamț county	−34%
	Residence: Bacău county	−52%
New jobs created at the county level	Dwelling type—apartment	80%
	Urban resident	57%
	Male	44%
	"Entry level" segment	9%
	"Rural middle class" segment	8%
	Age below sample average	3%
	Parent	2%
	"Senior rural" segment	−4%
	"Urban middle class" segment	−13%
	Knowledgeable about energy	−23%
	Income above sample average	−25%
	Education above sample average	−26%
	Residence: Suceava county	−27%
	Residence: Bacău county	−34%
	Residence: Neamț county	−47%
Reduction of pollution effects—air, water, soil	Residence: Iași county	179%
	Dwelling type—apartment	154%
	Income above sample average	91%
	"Entry level" segment	79%
	Age below sample average	27%
	Education above sample average	13%
	Knowledgeable about energy	6%

Average results are observed in the case of the "Maximum benefits and cost" and the "Minimum benefits and cost" offerings, as well as in the case of maintaining the "Status quo".

The preference of the population for electricity offerings which provide a high number of new jobs is perhaps not surprising if we take into account the socio-economic realities of the North-East Development Region of Romania. Statistical data regarding economic development and income show that the region is well below EU-27 average levels, but also national levels. In fact, over the last decade, the North-East region has constantly had the lowest GDP per capita (purchasing power standard) out of the 8 development regions of Romania, comprising just 46% of the EU average in 2020 (Eurostat, 2022). In terms of net disposable income at the household level, in 2019, the North-East region was ranked 236th out of 242 NUTS 2 territorial units in the EU-27, below all other regions in Romania—a situation that has not changed since 2015, when the region was ranked 240th. Economic difficulties for households are also evidenced by poverty statistics, with 41.4% of the North-East population at risk of poverty or social exclusion. Surprisingly, between 2015 and

TABLE 10 | Market/preference share simulation for competing electricity offerings.

Electricity offering profile	INDEP (%)	JOBS	COST	POL (%)	RURAL (%)	Preference share (%)
High number of new jobs	78	16	15 RON	10	1	17.7
Minimum benefits and cost	84	16	35 RON	25	1	11.7
Energy independence + New jobs	84	16	35 RON	10	1	11.7
Pollution reduction + New jobs	78	16	35 RON	25	1	11.7
Status quo	77	0	0 RON	0	0	11.4
Maximum benefits and cost	78	2	5 RON	10	1	11.3
Reduced pollution	78	2	15 RON	25	1	9.2
High energy independence	84	2	15 RON	10	1	9.2
Energy independence + Pollution reduction	84	2	35 RON	25	1	6.1

2020, the region had both the lowest unemployment rate among youths (15–29 years of age) and overall unemployment rate out of all regions in Romania. Unemployment among youths has seen an overall downward trend from 7 pp. in 2015 to 6.1 pp. in 2020 (between 40–50% below the national level), while the overall unemployment rate has decreased slightly from 3.9 pp. in 2015 to 3.2 pp. in 2020 (consistently around 40% less than the national average). An overall underdeveloped economy, with low disposable household income and a low unemployment rate could explain the observed household preference for the creation of new jobs in a high income sector such as energy.

Consumers have shown a somewhat limited preference for national energy independence and even less so for the reduction of pollution effects. However, price hikes caused in part and accelerated by energy imports may result in a shift in consumer preferences in the near future. Throughout 2021, Europe has faced rising energy prices, in line with a global upward trend. According to Eurostat (2022) data, the Harmonised index of consumer prices for electricity, gas and other fuels has reached the level of 126.26 at the EU-27 level (with 2015 prices being the base reference of 100). EU Member States have managed to react the situation by agreeing that coordinated and urgent action is needed in order to mitigate the impact of this growth, especially on the most vulnerable households and businesses.

The invasion of Ukraine by Russia in 2022 followed by an ample set of economic and trade sanctions has amplified these trends on the energy markets, leading to further increases in energy prices and genuine concerns about the EU's security of energy supply. The above mentioned index soared to 138.7 at the EU level by February 2022, with values above 170 in countries such as Italy, Netherlands and Belgium. Russia is currently the main supplier of crude oil, natural gas and solid fossil fuels to the EU, which depends on Russia for about 40% of its natural gas needs. In addition, in 2019, almost a third of crude oil imports from outside the EU came from Russia (27%). Although in Romania the import needs are lower, the talks around the topic of securing energy independence have intensified in the new geopolitical context.

If, in the autumn of 2021, the long-term plans of the EU and Romania regarding the energy future of the European bloc were built around the European Green Pact, the transition to the green economy, the current geopolitical context seems to postpone, at least for the time being, the measures announced in this direction. As a result, the European institutions, as well as the individual Member States, are looking for solutions to limit their energy dependence on Russia, a challenge that overlaps with that which involves protecting consumers from price increases. An agreement with the United States for the supply of liquefied natural gas (LNG) in the EU, the postponement of plans to close coal-fired power plants in some European countries are just some of the solutions currently being developed.

In Romania, one of the solutions discussed during this period to reduce energy dependence on Russia is the exploitation of Black Sea gas deposits, with a new law regarding offshore facilities and exploitation currently under the review of the Parliament. On the other hand, the production capacity of coal-fired power plants has recently been increased. Nuclear power is also a viable alternative, so the completion of the Cernavodă reactors is needed, and the development of other similar capacities could become a priority. At the same time, the import of LNG from the United States, Qatar or the Caspian area are being considered and the discussions have intensified around the need to finalize the BRUA pipeline projected to transport gas from Azerbaijan to Austria, a pipeline which traverses Greece, Bulgaria, Romania and Hungary (Romania Insider, 2022).

Renewable energy seems to have taken a back seat in the immediate strategic planning, or at least in the current political discourse. However, locally produced renewable energy from wind, solar and, crucially, large hydroelectric projects for peak demand, coupled with baseline nuclear production may prove to be the long-term solution given the long-term outlook for the current turn of events in Europe. Regardless of the source, energy prices are likely to remain high for a prolonged period, whilst securing energy independence becomes a new imperative for the countries of the European bloc and a fervent topic of public debate, which will undoubtedly raise the profile of this subject among consumers. As a result, energy independence is likely to become a factor of more significant weight in the coming years within the preferences of the households.

A solid conclusion that can be extracted from the results is that public opinion in the North-East Region of Romania supports renewable energy policies. The support is expressed at both perceptual and attitudinal level. A willingness to pay is expressed and measured. Thus, central authorities should feel more at ease considering the financial burden that the shift towards renewable energy sources requires. Extra taxation for companies that produce energy from renewable sources appears not to be a supported option given the tendency of the associated attribute to generate negative utility, as perceived by the public opinion. Besides, the domain is expected to create new jobs and contribute in a relevant manner to the development of the region. Thus, central authorities could feel encouraged to address rather fiscal facilities to encourage employment and professional reconversion instead.

5 CONCLUSIONS AND DISCUSSION

Our findings show that the creation of new jobs and the increase of the country's energy independence, followed by the reduction of air, water and ground pollution are societal benefits that would realistically convince households to pay a premium on their electricity bill in order to support RES development. Increased local budgets for rural communities resulting from the taxation of newly established energy production companies is seen as having a negative utility and is not one of the desired outcomes of ESR development. As expected, respondents with higher than average income and those living in urban areas or apartments have a higher WTP for renewable energy across all attributes. Males have a higher WTP for RES, but only in the case of the new job creation and energy independence attributes. Interestingly, respondents with an above average education level are willing to pay less for new jobs and energy independence, but are willing to pay more for pollution reduction, compared to the WTP of the complete sample of households. Pollution reduction does not have a significant impact on preferences and WTP in the short term.

Theoretically, this study advances existing knowledge primarily from a methodological standpoint. Firstly, by demonstrating the implementation of a choice modelling approach with two distinct temporal horizons: short term versus medium/long term. The approach illustrated in our study is especially useful in designing adequate policies (e.g., fiscal and financial support schemes) after the general strategic direction has already been established (e.g., the share of renewable energy in consumption needs to reach a specific level by 2030). Secondly, we have also demonstrated the use of a market segmentation procedure using a mix of lifestyle and socio-demographic variables, thus increasing the practical utility of the resulting clusters for marketing specialists. Finally, a minor contribution is the demonstration of the use of market simulations in the retail energy sector based on choice preferences.

The policy implications of the study are primarily related to the design of adequate fiscal and support policies. Thus, from the perspective of governmental authorities, outlining the policies that can support the development of renewable energy production may be achieved within the limits of the financial sacrifice that consumers are willing to make, but should be focused on providing those benefits that households are interested in. For example, they should encourage the development of production units that generate a higher number of job-years per GWh, such as solar photovoltaic and thermal, biomass and hydroelectric. According to the results obtained in the current study, as well as the exploratory study conducted in 2015 by the research team, it is likely that a policy based on supporting the development of rural areas by taxing the new energy companies may not be attractive to consumers—in fact it may lead to a rejection of renewables.

The practitioner implications of our study stem primarily from the market segmentation procedure and the identification of WTP influence factors. Our results show that there is a willingness of consumers to pay more for an electricity supply contract, if it will provide a series of societal benefits, such as an increase in the number of local jobs, the reduction of fossil fuel imports and the reduction of pollution (all of which are correlated with an increase in production from renewable sources). These indirect benefits can be used in promotional campaigns for the contract offerings and they can provide avenues through which public relations events and strategies can be developed. Furthermore, by identifying the socio-demographic and behavioural factors that influence WTP, electricity suppliers are able to fine-tune their offerings, advertising and targeting based on the traits of the decision-makers in the households.

Some of the limitations of our study result from the data collection method and, to some extent, the sampling procedure. With regard to data collection, we believe that the online administration of an instrument that contains a set of choice tasks can generate reliability issues. Ordinary respondents may assume that the choice experiment is a regular survey, during which they are not confronted with this type of task. The unusual nature of the request may seem complex or even overwhelming for some respondents, resulting in unreliable responses which cannot be easily identified ex-post. With regard to sampling, although we did use the quota method to insure a diverse set of respondents, the fact that the sample is not representative within the target population makes the absolute WTP values less reliable. Finally, as stated in the paper, one of the risks associated with using the cMNL model is generated by the IIA assumption, which can lead to results that are less valid from a practical standpoint. By using a mixed logit model, which relaxes the IIA assumption, we were able to identify a notable increase in MWTP for pollution reduction, although its impact on overall WTP did not change dramatically. However, we believe that the absolute marginal WTP values for pollution reduction and even job creation resulting from the cMNL model should be used with caution.

Some of the results, such as the fact that males have a higher WTP or the fact that rural development does not have a significant impact on choice are somewhat surprising and should be further explored through more extensive studies on the same population in order to see if the same results apply. Finally, we believe that the overall findings need to be taken into consideration by policy-makers in order to improve public acceptance of the renewable energy transition.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

AM contributed to the conceptualization, methodology, data analysis, validation and manuscript writing. D-TJ contributed to the methodology, validation, data collection and manuscript writing. TR contributed to the conceptualization, methodology, validation and supervision of the research.

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Dynamic Effects of CO_2 Emissions on Anticipated Financial Development of European Countries

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This study investigates the motives behind the degrees of molecular pollution during the COVID-19 pandemic, which persisted from first walk 1 January 2020 to 31 December 2020. A spatial Durbin file model is used linked to an edge backslide model in this article to find the widely inclusive and nearby consequences of present-day plan and urbanization on nonrenewable energy source by things. The outcomes are discussed next: both were available in modern-day plan and urbanization from a generally inclusive standpoint. The geological consequences of CO_2 emissions were concentrated on utilizing information from 22 European countries somewhere in the range of 1990–2020, and all through the examination cycle, the Durbin spatial model was discovered. Although factors such as gross domestic product per capita, urbanization, and energy power impact CO_2 emissions, exchange receptivity stays unaltered. The findings will fill in as critical repercussions for state-run administrations, wellbeing experts, and regulators in the war against the return of COVID-19 in Europe. The great number of suggestions were worthless since the concept integrated six money-connected creation assessments into a coordinated arrangement. There is information to indicate that CO_2 emissions are associated with money-related events in neighboring nations.

Keywords: financial development, CO_2 emissions, European countries, spatial econometrics, Europe

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INTRODUCTION

There is an increase in global temperature due to the addition and collection of ozone-draining substances in the environment which all contribute to a constant state of flux. The concept of natural *SPE,* methane, nitrous oxide, and CO_2 are common ozone-depleting gases emitted by mechanical processes, such as those found in power plants and vehicles. Approximately 75% of ozone-depleting chemical emissions come from CO_2 emissions (Abbasi, 2016), and global temperatures have already reached 1.5°C, which is extraordinarily high. According to the findings, financial development stimulates money-related development, which boosts oil premiums and results in increased CO_2 emissions (Sadorsky, 2010; Islam et al., 2013; Tang and Tan, 2015; Le et al., 2020). By decreasing incoming expenses and increasing liquidity for reported ventures, cash-related advancement lowers credit focus and allows them to construct yield. As a result, financial regard develops, resulting in increased energy consumption and CO_2 emissions. Furthermore, there is a strong link between monetary growth and ecological degradation, implying that monetary improvement is linked to a baseline expansion in CO_2 emissions, followed by a decline as the economy grows, resulting in an EKC with a swapped U-shape(Orubu and Omotor, 2011). There are two approaches to understand the link between cash-related activities and money development, as represented by hypothetical strategies: first, the money-related advancement of a region is triggered by monetary development. In addition, the development of cash provides a fundamental framework for the growth of money (Goldsmith, 1969). While most experts agree that monetary progress is essential for mechanical advancement, it also allows businesses and governments to acquire earth-useful innovations, and finance also stimulates interest in energy-efficient advances capable of minimizing the negative impact of petrol subordinates, so improving the air quality or environmental quality (Jalil and Feridun, 2011; Tang and Tan, 2015; Acheampong, 2019; Sun et al., 2021). In order to reduce Chile's dependence on imported nonrenewable energy sources, the country's policymakers should actively encourage the development of low-carbon technologies and renewable energy investments, particularly in sectors that are more energy-intensive and are causing an increase in consumption-based CO_2 emissions (Kirikkaleli et al., 2021). Ongoing commitments in this sector have advised against using biological review strategies to investigate air pollution and COVID-19 credulously. In light of the pandemic's astonishing progress, strategic isolation and lockdowns have been imposed around the globe, resulting in crucial global and local financial disruptions. Air quality improvements have been declared in several urban communities where strategic isolation and lockdowns have been required, in accordance with the reverse relationship between money, mobility, and air quality. CO_2 emissions and renewable energy are mutually exclusive. However, CO_2 emissions correlated positively with nonrenewable and actual GDP growth. The circumlocutory and geographical flood effects of monetary change on CO_2 emissions are missed by the standard board econometric approaches; thus, spatial econometric models are more vital and capable (Meng et al., 2017; You and Lv, 2018). Geopolitical risk has a direct impact on carbon emissions in India. Geopolitical risk increases environmental deterioration in the intermediate quantiles while decreasing environmental degradation in the lower and higher quantiles. Demand for nonrenewable energy is driving up emissions, while demand for renewable energy is driving them down. The economic development and renewable and nonrenewable energy uses are linked via a feedback mechanism in the panel causality analysis (Bekun et al., 2018). Several studies have already combined data from ground-based equipment and satellites to estimate SO_2 levels. We were expecting a mixed or even inconsistent evaluation, given that most research projects in this sector use a standard and unambiguous board data assessment that ignores the geographical dependence of the data (Lv and Li 2021). Tourism, GDP, and foreign direct investment all degrade the natural environment. According to the causality study, tourism and carbon dioxide emissions are linked in a one-way causal relationship. FDI and carbon dioxide emission share a similar causation pattern with urbanization and carbon dioxide emission. Our next step is to look at the numerous heterogeneous effects of monetary policy on CO_2 emissions using various financial movement signals. In regard to global air quality, the lockdowns are the "largest scale trial of all time." They also serve as models for what to expect in future arrangements. The Eurozone's environment deteriorates as a result of financial inclusion. Both economic expansion and the use of renewable energy contribute to environmental damage (Fareed et al., 2020). According to these findings, earlier studies have only considered short-term changes in CO_2 emissions caused by changes in the value of a country's currency while neglecting its longer-term flooding effect on CO_2 emissions. Several additional financial and environmental requirements have been added to the content of this study According to our research, this is the first piece to examine the influence of financial expansion on CO_2 emissions from a local standpoint. As a result, we are investigating the relationship between financial development and CO_2 emissions from a board-level viewpoint. The ongoing and fresh COVID-19 epidemic has had a significant impact on our day-to-day activities and financial planning. Legislators have imposed lockdown measures to stop the spread of the disease, such as closing down workplaces, educational institutions, restaurants, and other places where people congregate to communicate, and all conditions of the European Association had imposed some form of developmental restriction (Sun and Razzaq, 2022).

Below is an explanation of the rest of this article's structure. A writing study on the impact of monetary growth on CO_2 emissions can be found in **Section 2**, while the evidence test and trial templates used in **Section 3** are shown in **Section 4**, and the scientific findings are presented in **Section 5**, which wraps up the investigation and makes several recommendations for the framework.

LITERATURE REVIEW

There is growing evidence that money-related changes have an impact on CO_2 emissions, and this section summarizes some key results on the impact of increased financial resources on CO_2 outflows and regular contamination. In addition, the previous tests appear to be substantially comparable on the basis of the fact that geographical dependence on information and nations using conventional board data as well as other econometric methodologies was ignored. While no nation is truly isolated, geographic econometric models should be considered as relying on data from several regions to avoid skewed findings. Renewable energy is hailed as a cure for reducing pollution since it has a statistically significant negative correlation with CO_2 emissions throughout the time period under study (Bekun et al., 2021a). To cope with the challenges caused by spatial dependency between credits, standard procedures like ordinary least squares (OLS) and summary methodology for second (GMM) are ineffective. When GDP development is prioritized over environmental quality, we get the EKC phenomena. In terms of causation, GDP growth and carbon emission follow a feedback Granger causality, whereas energy intensity and carbon emission follow a similar causality (Bekun et al., 2021b). The momentum research will next use spatial econometric approaches to look at the impact of money-related improvements on CO_2 emissions. GMM was used by Yuxiang and Chen (2011) to examine the impact of money-related improvements on petroleum derivative side effects in China, and results revealed that financial progress, as controlled by the extent of bank credits to GDP, the extent of private advances to GDP, and the extent of non-private GDP, reduces the impact of fossil fuel byproducts. According to the most recent statistics, there were 67,618,431 confirmed COVID-19 cases worldwide, with 1,544,985 deaths thus far. The United States has declared the most positive cases so far, followed by India, Brazil, Russia, France, and Italy. There is evidence that the amount of petroleum derivative side effects in Pakistan decreases when the amount of fluid liabilities and private area advances to GDP increases, as determined by Jalil and Feridun (2011), using the ARDL method. In the first place, the positive shocks of innovation disrupt CO_2 emissions' harmful ramifications, while the negative shocks impair the ecological quality. Second, globalization and REC reduce CO_2 emissions, which improves ecological quality. Third, FDI and FFC demonstrate the direct link between CO_2 emissions and the pollution issue, making the pollution issue even more worrisome (Weimin et al., 2021). In regard to working on money-related events and financial new developments, energy use plays a significant role. It also produces large emissions that countries might increase their energy production even more by improving energy efficiency. The presentation of oil venture subsidy programs, energy steadiness, and energy base movement can be modified to achieve monetary alterations and GDP growth in Sub-Saharan African countries. Positive and negative shocks have a considerable impact on environmental quality in both the short and long terms, according to the results from NARDL's method. Shahbaz et al. (2013a) investigated in Indonesia the link between financial activities and nonrenewable energy source outcomes using ARDL and Granger causality considerations. According to their findings, money-related change is necessary to spur environmentally friendly innovation, which reduces CO_2 emissions and enhances natural utility. Although globalization, energy use, commerce, and GDP development all have positive short-term correlations, a review of fuel importation also reveals a negative association with the ecological imprint of the global economy (Rehman et al., 2021a). Shahbaz et al. (2013b) used the cutoff points to look at the technique to deal with, examining the co-integration between monetary events and CO_2 increases in Malaysia, and found that CO_2 release, monetary events, energy consumption, and monetary development have had significant run links for a long time, as evidenced. There is a positive correlation between Pakistan's economic development and nuclear energy, according to short-run estimates, whereas the remaining factors revealed a negative correlation. In order to deal with the issue of GHG emissions, it is essential to have a conservative policy and financial assistance (Weimin et al., 2021). A decrease in CO_2 emissions is also seen from the data. An increased use of power and increased financial resources destroy CO_2 pollution. Air pollution poses substantial health risks to humans, such as heart and lung diseases and a variety of other ailments. Ziaei (2015) found that stock return rate staggers affect energy use, particularly in long-horizon situations with East Asian-Pacific countries present. It takes a long time for positive shocks to the output of cereal crops to have a detrimental influence on air quality because they increase carbon dioxide emissions, but negative shocks have no effect at all. China's carbon dioxide emissions are unaffected by shocks to forests, ironically (Rehman et al., 2021b). Additionally, Al-Mulali et al. (2015) used co-integration tests and FMOLS to discover that homegrown credit to the private sector raises the production of fossil fuel byproducts in 129 different countries. Furthermore, it is possible that air pollution is directly linked to the number of sickness cases. According to Abbasi and Riaz, (2016), the economic growth in Pakistan resulted in decreased CO_2 emissions because of the use of ARDL and VAR. They used hard and quick credit, private area credit, security, market capitalization, and trade protections to deal with the new financial development. CO_2 emissions induced the environmental Kuznets curve theory for each of the four sectors of the economy In addition, financial development and urbanization have been shown to increase CO_2 emissions, whereas technical innovation is needed to reduce sector-based CO_2 emissions (Murshed et al., 2022a). The causality test was used to determine if there was a two-way causation between the local acknowledgment of private space and CO_2 pollution by who also used a measurement of BRIC economies' financial progress as a proxy. They have rigged things such that the growth of the banking sector increases CO_2 emissions. Ahmad et al. (2018) achieved a similar outcome by extending local loans to the private sector to address money-related issues. They used the ARDL and ECM techniques to find that China's nonrenewable energy outcome was energized by financial development. The country's long-term growth is negatively impacted by CO_2 emissions from the transportation industry. It was revealed that positive shocks to CO_2 emission statistics from the transportation sector slowed the long-term economic growth in Pakistan, whereas negative shocks were shown to speed up both short- and long-term economic progresses in this example (Rehman et al., 2021c). Ehigiamusoe and Lean (2019) examined in 122 nations the impact of monetary change on fossil fuel byproducts, discovering that financial progress ruined petroleum derivative results over time. Analyzed station-based data on air quality in 34 countries and discovered that NO_2 and PM2.5 concentrations have increased by 60 and 31%, respectively, due to increased centralization. The long-term relationships between renewable power generation, economic globalization, economic growth, and urbanization, as well as emissions of carbon dioxide due to energy production, were confirmed by the econometric analysis (Murshed et al., 2022b). Most recently, monitored a 9.1% drop in NO_2 convergence 90 days after the lockout using an example of 174 nations. While petroleum product outcomes have fallen in high-paying countries, as the research shows, they have increased in low- and mid-paying countries. An investigation in 24 MENA nations was conducted by Charfeddine and Kahia (2019) to investigate the causative link between energy consumption that is safe for the ecosystem and monetary activities such as CO_2 emissions, and the financial turn of events. Rehman et al. (2022) have observed that the variable population growth, economic growth, rural population growth, and livestock output had a positive correlation with CO_2 emissions in the short-term inquiry. The increase in both animal production and energy use have a favorable impact on long-term CO_2 emissions, as does population growth, economic growth, rural population expansion, and livestock production. On a board vector autoregressive approach, the review's findings show that activities involving money and the use of environmentally friendly electricity have tight ties with CO_2 release. Adebayo et al. (2022a) observed that monetary development and nonrenewable energy usage add to the debasement of the climate, while globalization and sustainable power use help to control the corruption of the climate. The most obvious link in the epidemic is the sharp decline in emissions, which corresponds to a decline in the overall interest and consumption compared to the situation when GDP and outflows were separated. When looked at the reasons for population growth and urbanization as well as their links to CO_2 emissions, they uncovered a wealth of information. They discovered that the adverse impacts of petroleum products had enormously favorable links with various parameters. For the second technique to break down the influence of financial market development on nonrenewable energy source result power in 83 countries between 1980 and 2015, Acheampong et al. (2020) used the instrumental variable summary method (GMM). Important issues include the definition of health endpoints and recurrence metrics to define and quantify COVID-19 in the population. The FDI affects CO_2 emissions in both good and bad ways, and as a result, the costs rise and the problem of pollution resurfaces (Rehman et al., 2021d). Adebayo (2022b) found that i) REC improves environmental quality, ii) fossil fuels harm environmental quality, and (iii) FDI inflows improve environmental quality at all frequencies. Air pollution's potential negative impact on the COVID-19 pandemic is the cause for grave concern. Zhao and Yang (2020) used a static and dynamic inquiry to look at the relationship between financial events and CO_2 emissions at the Chinese public level. The stunning findings show that the progress made in regional money has had little effect on CO_2 emissions, as a result of lowering environment friendliness standards and narrowing the scope of environmental requirements in the United States (Utility Jump 2020). There is a strong correlation between CO_2 emissions and globalization, tourist arrivals, economic expansion, and energy consumption in the majority of quantiles, according to quantile causality results. Lv and Li (2021) used a board data spatial econometric approach for 97 countries from 2000 to 2014 to explore the impact of financial change on CO_2 pollution and concluded that there is a geographical association between CO_2 emissions *via* countries during this period. They also demonstrated that the CO_2 emissions of a country may be affected by the financial progress of its neighbors. A worldwide integration of economic and financial factors for natural resource-related and environmentally friendly goods and services is supported by the study's findings (Adebayo et al., 2022c). Researchers from studied the regional distribution of CO_2 emissions that when energy productivity improved, all six financial development metrics became more significant, resulting in increased CO_2 emissions despite their negative flood implications. According to the EU27 and UK saw an emanation decay of 12.7% in the first half of 2020, largely due to changes in ground transportation, with France, Spain, and Italy seeing the largest declines. Between 1 January and 31 July 2020, CO_2 outflow decreases in Europe were around 10.3%, with the bulk of declines coming from ground transportation and air travel, according to a study by Guevara et al. (2020).

METHODOLOGY AND DATA ANALYSIS

Empirical Model

In this research, the logarithm of the carbon emission ($lnCO_2$) is measured to be a purpose of some illuminating variables counting the logarithm of GDP per capita ($lnGDPP$), the rectangle form of GDP per capita ($lnGDPP^2$), urbanization ($lnURB$), trade openness ($lnOPE$), energy intensity ($lnENER$), and financial development ($lnFD$) so that the experimental model of the CO_2 emission model is as follows:

$$\begin{aligned} lnCO_{2it} &= \beta_1 + \beta_2 lnGDPP_{it} + \beta_3 lnENER_{it} + \beta_4 lnOPE_{it} \\ &\quad + \beta_5 lnURB_{it} + \beta_6 FD_{it} + c_i\,(optional) + \alpha_t\,(optional) \\ &\quad + v_{it}. \end{aligned} \tag{1}$$

When we regard monetary growth as a free factor, the ecological efficiency is turned U-shaped, so the negative coefficient of the squared kind of gross domestic product per capita in the CO_2 emanation situation is hypothetically discussed and should be investigated, according to the natural Kuznets (EKC) conjecture. In either case, as the economy develops, the condition of the atmosphere first deteriorates and then changes (Grossman and Krueger, 1995; Lee et al., 2010). Other factors such as urbanization, energy force, and trade openness are often used as illustrative factors for CO_2 emissions in the literature (Epule et al., 2012; Chakravarty and Tavoni, 2013; Solarin et al., 2017; Acheampong, 2019; Kayani et al., 2020).

$$\begin{aligned} lnCO_{2it} &= \beta_1 + \beta_2 lnGDPP_{it} + \beta_3 lnENER_{it} + \beta_4 lnOPE_{it} \\ &\quad + \beta_5 lnURB_{it} + \beta_6 FD_{it} + \beta_7 \left(lnFD_{it} \times lnENER_{it}\right) \\ &\quad + c_i\,(optional) + \alpha_t\,(optional) + v_{it}. \end{aligned} \tag{2}$$

To surface the different accepts of the effectiveness of financial development on CO_2 emission in depth, the interaction terms of energy intensity and financial development are entered in the new form of the CO_2 emission model of Equation-2, where ($lnFD_{it} \times lnENER_{it}$) shows the interaction term, while the coefficient for ($lnFD_{it} \times lnENER_{it}$) indicates the relationship between financial growth and energy use. On the one hand, financial development will reduce CO_2 emissions by encouraging firms to adopt environmentally friendly technologies (Tamazian

TABLE 1 | Creations of new variables.

Variable	Variable constructed	Source
$lnCO_{2it}$	$lCO_{2it} = log(CO_{2it})$ CO_{2it} = CO_2 emissions (metric tons per capita) in the country i in period t	SDG
$lnGDP_{it}$	$lGDPP_{it} = log(GDPP_{it})$ GDP_{it} = GDP per capita in 2010 prices$ in the country i in period t	WDI
$lnURB_{it}$	$lURB_{it} = \log(URB_{it})$ URB_{it} = urban population (as a %age of the total population)	WDI
$lnOPE_{it}$	$lOPE_{it} = log(OPE_{it})$ OPE_{it} = trade openness (total exports and imports as a %age of GDP (	WDI
$lnENER_{it}$	$lENER_{it} = \log(ENER_{it})$ $ENER_{it}$ = energy intensity (energy use as a %age of GDP)	SDG
$lnFID_{it}$	$lnFID_{it} = \log(1 + 100 \times FID_{it})$ FID_{it} = the development of financial institution depth	IMF
$lnFIA_{it}$	$lnFM_{it} = \log(1 + 100 \times FIA_{it})$ FIA_{it} = the development of financial institution access	IMF
$lnFIE_{it}$	$lnFIE_{it} = \log(1 + 100 \times FIE_{it})$ FIE_{it} = the development of financial institution efficiency	IMF
$lnFMD_{it}$	$lnFMD_{it} = \log(1 + 100 \times FMD_{it})$ FMD_{it} = the development of financial market depth	IMF
$lnFMA_{it}$	$lnFMA_{it} = \log(1 + 100 \times FMA_{it})$ FMA_{it} = the development of financial market access	IMF
$lnFME_{it}$	$lnFME_{it} = \log(1 + 100 \times FME_{it})$ FME_{it} = the development of financial market efficiency	IMF

WDI, World Development Indicators; https://datacatalog.worldbank.org/dataset/world-development-indicators.
SDG, The Asia-Pacific SDG Gateway; https://data.unescap.org/.
IMF, International Monetary Fund; https://data.imf.org/.

TABLE 2 | Summary statistics over the years 1990–2020.

Variable	Mean	Median	Maximum	Minimum	Std. dev	Observations
$lnCO_{2it}$	1.755	1.836	3.205	-0.790	0.606	989
$lnGDP_{it}$	9.674	9.804	11.626	7.022	1.101	989
$lnURB_{it}$	4.212	4.226	4.585	3.676	0.201	989
$lnOPE_{it}$	4.520	4.476	6.012	3.113	0.440	989
$lnENER_{it}$	1.687	1.596	3.285	0.428	0.482	989
$lnFID_{it}$	3.304	3.392	4.615	0.637	0.949	989
$lnFIA_{it}$	3.897	4.062	4.615	1.615	0.617	989
$lnFIE_{it}$	4.131	4.205	4.488	2.044	0.294	989
$lnFMD_{it}$	2.912	3.187	4.606	0.102	1.322	989
$lnFMA_{it}$	2.788	3.505	4.615	0.001	1.560	989
$lnFME_{it}$	2.606	3.258	4.615	0.001	1.841	989

TABLE 3 | LR statistics in the spatial and time-period fixed-effect model.

	Spatial fixed effects		Time-period fixed effects	
Model A1	237.678	(0.001***)	2,950.312	(0.001***)
Model A2	238.356	(0.001***)	2,945.925	(0.001***)
Model A3	245.222	(0.001***)	2,963.600	(0.001***)
Model A4	237.193	(0.001***)	2,952.929	(0.001***)
Model A5	237.031	(0.001***)	2,920.111	(0.001***)
Model A6	237.540	(0.001***)	2,928.476	(0.001***)
Model A7	245.856	(0.001***)	2,891.977	(0.001***)
Model B1	317.246	(0.001***)	2,887.574	(0.001***)
Model B2	269.565	(0.001***)	2,875.251	(0.001***)
Model B3	238.945	(0.001***)	2,947.536	(0.001***)
Model B4	268.006	(0.001***)	2,900.667	(0.001***)
Model B5	261.394	(0.001***)	2,911.839	(0.001***)
Model B6	224.749	(0.001***)	2,850.826	(0.001***)

p *values, ***, **, and * show significance at 1, 5, and 10% levels, respectively.*
****shows significance at 1% level.*

et al., 2009; Tamazian and Rao, 2010), but, on the other hand, improved financial sector leads to cheaper access to credit for the purchase of new machinery and equipment (Sadorsky, 2010; Sadorsky, 2011; Acheampong, 2019). The following is how energy intensity impacts carbon emissions:

$$\frac{d(lnCO_{2it})}{d(lnENER_{it})} = \beta_6 + \beta_8 lnFD_{it}. \quad (3)$$

Higher-energy intensity is supposed to have a positive impact on CO_2 emissions because energy intensity is a metric of energy quality, and a higher value of this index equals more CO_2 emissions, so the coefficient six should be positive. However, if the financial market develops to stimulate pro-environmental infrastructure, the coefficient seven is negative, and the energy intensity's initial positive effects are diminishing. The consequences of CO_2 emissions are

TABLE 4 | The spatial lag in the spatial and time-period fixed-effect model.

	Pooled OLS		Spatial fixed effects		Time-period fixed effects		Spatial and time-period fixed effects	
Model A1	46.777	(0.001***)	55.075	(0.001***)	2.729	(0.099)	14.469	(0.001***)
Model A2	42.704	(0.001***)	56.020	(0.001***)	2.254	(0.133)	13.740	(0.001***)
Model A3	38.029	(0.001***)	55.883	(0.001***)	1.116	(0.291)	14.101	(0.001***)
Model A4	45.511	(0.001***)	55.814	(0.001***)	2.653	(0.103)	14.932	(0.001***)
Model A5	64.137	(0.001***)	56.308	(0.001***)	5.873	(0.015)	14.089	(0.001***)
Model A6	67.220	(0.001***)	56.093	(0.001***)	5.910	(0.015)	14.786	(0.001***)
Model A7	35.773	(0.001***)	55.630	(0.001***)	1.419	(0.234)	14.983	(0.001***)
Model B1	36.912	(0.001***)	61.579	(0.001***)	3.004	(0.083)	13.162	(0.001***)
Model B2	39.377	(0.001***)	61.199	(0.001***)	3.194	(0.074)	16.006	(0.001***)
Model B3	51.075	(0.001***)	54.669	(0.001***)	3.472	(0.062)	13.352	(0.001***)
Model B4	71.782	(0.001***)	56.102	(0.001***)	9.774	(0.002***)	9.628	(0.002***)
Model B5	77.867	(0.001***)	56.626	(0.001***)	13.781	(0.001***)	12.946	(0.001***)
Model B6	16.593	(0.001***)	47.859	(0.001***)	0.001	(0.974)	13.794	(0.001***)

p *values, ***, **, and * show significance at 1, 5, and 10% levels, respectively.*
Authors' estimations.
****shows significance at 1% level.*

TABLE 5 | Spatial error in the spatial and time-period fixed-effect model.

	Pooled OLS		Spatial fixed effects		Time-period fixed effects		Spatial and time-period fixed effects	
Model A1	1.929	(0.165)	13.960	(0.001***)	0.732	(0.392)	4.710	(0.030**)
Model A2	1.768	(0.184)	14.567	(0.001***)	0.668	(0.414)	4.356	(0.037**)
Model A3	1.710	(0.191)	10.522	(0.001***)	0.798	(0.372)	3.178	(0.075*)
Model A4	2.167	(0.141)	15.031	(0.001***)	0.812	(0.367)	5.217	(0.022**)
Model A5	3.999	(0.046**)	14.977	(0.001***)	2.004	(0.157)	4.601	(0.032**)
Model A6	5.335	(0.021**)	14.445	(0.001***)	3.277	(0.070*)	4.838	(0.028**)
Model A7	4.032	(0.045**)	15.970	(0.001***)	2.290	(0.130)	6.484	(0.011**)
Model B1	2.860	(0.091*)	15.632	(0.001***)	1.780	(0.182)	1.891	(0.169)
Model B2	12.365	(0.001***)	10.226	(0.001***)	10.486	(0.001***)	1.987	(0.159)
Model B3	2.163	(0.141)	14.225	(0.001***)	0.895	(0.344)	4.005	(0.045**)
Model B4	1.133	(0.287)	14.909	(0.001***)	0.494	(0.482)	1.861	(0.172)
Model B5	3.191	(0.074*)	15.015	(0.001***)	2.128	(0.145)	3.730	(0.053*)
Model B6	2.503	(0.114)	12.035	(0.001***)	1.088	(0.297)	5.607	(0.018**)

p *values, ***, **, and * show significance at 1, 5, and 10% levels, respectively.*
Authors' estimations.

TABLE 6 | Hausman test results.

	Model A1	Model A2	Model A3	Model A4	Model A5	Model A6	Model A7
Hausman test statistic for the spatial lag	309.862	152.682	149.066	239.757	226.023	174.785	136.632
	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
Hausman test statistic for the spatial Durbin	85.572	210.674	7.622	108.805	88.954	90.537	107.444
	(0.001***)	(0.001***)	(0.867)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
—	—	Model B1	Model B2	Model B3	Model B4	Model B5	Model B6
Hausman test statistic for the spatial lag	—	144.3372	108.8459	355.8821	630.5623	299.4728	124.9457
	—	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
Hausman test statistic for the spatial Durbin	—	187.6312	38.13154	110.46	228.7036	503.6572	150.9935
	—	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)

p *values, ***, **, and * show significance at 1, 5, and 10% levels, respectively.*
Authors' estimations.
****shows significance at 1% level.*

TABLE 7 | Results of the spatial Durbin model.

	Model A1	Model A2	Model A3	Model A4	Model A5	Model A6	Model A7
Wald test for the spatial Durbin model against the spatial lag model	53.977	67.466	66.441	51.173	56.863	55.208	69.922
	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
Wald test for the spatial Durbin model against the spatial error model	70.553	83.685	82.717	67.122	72.871	72.144	87.087
	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
LR test for the spatial Durbin model against the spatial lag model	54.698	68.189	67.533	51.297	57.396	56.026	70.683
	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
LR test for the spatial Durbin model against the spatial error model	63.852	76.803	77.752	60.308	66.096	65.106	77.750
	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
—	—	Model B1	Model B2	Model B3	Model B4	Model B5	Model B6
Wald test for the spatial Durbin model against the spatial lag model	—	80.295	83.304	68.857	76.893	64.806	71.825
	—	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
Wald test for the spatial Durbin model against the spatial error model	—	89.469	96.804	84.376	87.267	78.820	87.566
	—	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
LR test for the spatial Durbin model against the spatial lag model	—	76.166	79.114	69.852	77.992	65.292	72.466
	—	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
LR test for the spatial Durbin model against the spatial error model	—	88.034	93.671	78.808	85.364	73.695	79.667
	—	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)

*p values, ***, **, and * show significance at 1, 5, and 10% levels, respectively.*
Authors' estimations.
****shows significance at 1% level.*

investigated using a spatial econometric model, with a focus on financial growth metrics. A spatial panel model could have a lagged dependent variable or adopt a spatially autoregressive mechanism in the error word, according to the spatial Durbin model, which involves spatially lagged independent variables, was developed by LeSage and Pace (2009). The spatial lag model, the spatial error model, and the spatial Durbin model are all written as follows:

$$y_{it} = \lambda \sum_{j=1}^{N} w_{ij} y_{jt} + \varphi + x_{it}\beta + c_i\,(optional) + \alpha_t\,(optional) + v_{it}, \tag{4}$$

$$y_{it} = \lambda \sum_{j=1}^{N} w_{ij} y_{jt} + \varphi + x_{it}\beta + c_i\,(optional) + \alpha_t\,(optional) + u_{it},$$

$$u_{it} = \rho \sum_{j=1}^{N} w_{ij} u_{jt} + v_{it}, \tag{5}$$

$$y_{it} = \lambda \sum_{j=1}^{N} w_{ij} y_{jt} + \varphi + x_{it}\beta + \sum_{j=1}^{N} w_{ij} x_{ijt}\theta + c_i\,(optional) + \alpha_t\,(optional) + v_{it}. \tag{6}$$

Here, y_{it} represents a dependent variable for the cross-sectional unit $i = 1, 2, \ldots$ N at time $t = 1, 2, \ldots. T$. Also, x_{it} stands for a 1 × K vector of exogenous variables, while β represents a K×1 vector of parameters. It should be noted that $\sum_{j=1}^{N} w_{ij} y_{jt}$ accounts for the interaction effects of dependent variables in the adjacent units on the dependent one, w_{ij} denotes element *i, j* of an N×N matrix of spatial weights, λ denotes the endogenous interaction effect response parameter, v_{it} stands for an error term of independent and identical distribution, c_i is a spatial sectionicular effect, and α_t accounts for the time-period sectionicular effect. A spatial sectionicular effect accounts for all time-invariant space-specific variables, the absence of which would lead to skewed estimates in a typical cross-sectional study. A time-period-specific effect, on the other hand, accounts for all time-specific effects, the exclusion of which could lead to skewed estimates in a common time-series analysis (Baltagi, 2005). Unit *i* error word in the spatial error model **Eq. 3** (i.e., $u_{it} = \rho \sum_{j=1}^{N} w_{ij} u_{jt} + v_{it}$) and centered on matrix W and an idiosyncratic component is considered reliant on the error terms of adjacent units j. Furthermore, LeSage and Pace (2009) suggested that the spatial Durbin model in **Eq. 4** be used (2009). It will add individual spatial lag variables to the spatial lag model, where θ is a vector of $K \times 1$ parameters.

Data Collection

To analyze the effects of CO_2 emissions and conduct an experimental analysis, data from 22 European countries are compiled from 1990 to 2020. Moran's I is a more remarkable insight. A positive Moran's esteem shows the spatial amassing of comparative quality in the field, while a negative worth demonstrates the spatial collection of no virtual qualities. **Table 1** shows a list of the constructed variables used in the research, and the effect of CO_2 emissions, spatial econometric models are utilized.

The data related to all variables are collected from three websites: 1) World Development Indicator; https://datacatalog.worldbank.org/dataset/world-development-indicators, 2) The Asia-Pacific SDG Gateway; https://data.unescap.org/, and 3) International Monetary Fund; https://data.imf.org/

RESULTS AND DISCUSSION

The model with synchronous spatial and time-frame fixed impact is against models with time-frame fixed impact and additionally models with spatial fixed impact. The model of concurrent spatial and time span fixed impacts is picked if the invalid theory is rejected, and the subsequent model is picked if the invalid Speculation is acknowledged. **Table 2** also provides access to the data's summary statistics showing Moran's I more remark measurements.

Two autonomous likelihood ratio (LR) investigations are utilized to inspect the probability of the presence of time span

TABLE 8 | Results of the estimation of Equation (1).

	Model A1	Model A2	Model A3	Model A4	Model A5	Model A6	Model A7
lnGDPP	1.452	1.481	1.413	1.226	1.481	1.461	1.506
	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
lnGDPP^2	-0.027	-0.030	-0.029	-0.026	-0.029	-0.028	-0.031
	(0.002***)	(0.001***)	(0.001***)	(0.002***)	(0.001***)	(0.001***)	(0.001***)
lnURB	0.720	0.668	0.659	0.717	0.711	0.727	0.760
	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
lnOPE	0.028	0.039	0.040	0.030	0.029	0.030	0.036
	(0.159)	(0.058*)	(0.047**)	(0.137)	(0.147)	(0.140)	(0.069*)
lnENER	0.887	0.883	0.879	0.889	0.889	0.888	0.893
	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
lnFID	—	-0.002	—	—	—	—	—
	—	(0.863)	—	—	—	—	—
lnFIA	—	—	0.033	—	—	—	—
	—	—	(0.004***)	—	—	—	—
lnFIE	—	—	—	0.017	—	—	—
	—	—	—	(0.231)	—	—	—
lnFMD	—	—	—	—	-0.005	—	—
	—	—	—	—	(0.605)	—	—
lnFMA	—	—	—	—	—	-0.008	—
	—	—	—	—	—	(0.368)	—
lnFME	—	—	—	—	—	—	-0.019
	—	—	—	—	—	—	(0.003***)
W × lnGDPP	-0.336	-0.466	-0.353	-0.283	-0.344	-0.345	-0.357
	(0.156)	(0.051*)	(0.134)	(0.238)	(0.149)	(0.148)	(0.133)
W × lnGDPP^2	0.029	0.034	0.027	0.027	0.029	0.029	0.029
	(0.026)	(0.009***)	(0.035**)	(0.039**)	(0.029**)	(0.025**)	(0.025**)
W × lnURB	0.427	0.400	0.261	0.381	0.223	0.413	0.423
	(0.024**)	(0.035**)	(0.167)	(0.052*)	(0.022**)	(0.030**)	(0.024**)
W × lnOPE	0.062	0.074	0.095	0.054	0.062	0.057	0.048
	(0.060*)	(0.027**)	(0.004***)	(0.100)	(0.063*)	(0.086*)	(0.141)
W × lnENER	-0.025	-0.008	0.048	-0.019	-0.022	-0.028	-0.063
	(0.693)	(0.894)	(0.453)	(0.761)	(0.735)	(0.658)	(0.320)
W × lnFD	—	0.071	0.092	-0.031	0.023	0.009	0.034
	—	(0.001***)	(0.001***)	(0.257)	(0.146)	(0.448)	(0.001***)
W × lnCO$_2$	0.057	0.056	0.045	0.054	0.057	0.060	0.069
	(0.138)	(0.145)	(0.246)	(0.160)	(0.144)	(0.124)	(0.071*)

p *values, ***, **, and * show significance at 1, 5, and 10% levels, respectively.*
Authors' estimations.

fixed impacts and spatial fixed impacts in the model. **Table 3** shows the LR test insights for each model (3). The test outcomes show that the LR test figures are critical and that the invalid speculation is dismissed for all models. Subsequently, the model of covering spatial and time span fixed impacts is the better model for proceeding onward with the assessment technique in these situations.

Another evaluation, seen in **Tables 4**, **5**, looking at whether using the spatial lag or spatial error in the model with no spatial interaction effects improves the model significantly. LM experiments for a spatially lagged dependent variable and spatial error autoregressive model are used for this purpose, using the residuals of a non-spatial model. The test statistic is based on the chi-square distribution. The existence of the spatial lagged model and the spatial error model would be verified if the null hypothesis of the LM test is dismissed. We only consider the Lagrange multiplier (LM) statistics for this model since the results of the LR test verified the presence of the model with simultaneous spatial and time-period fixed effects. The test results indicate that the sum of test statistics is substantial at the 1% level in **Table 3** and 5% level in **Tables 4**, indicating that the presence of the spatial lagged in all models and the spatial error for the majority of models is not ruled out. As a result, the inclusion of spatial interaction effects in the model highlights the importance of including such effects in laboratory experiments to explore the factors causing CO_2 emission.

Table 6 shows the findings of the Hausman test, which was used to see whether the fixed effects model should be replaced with a random-effect model. In this test, the null hypothesis stresses the presence of random effects in the model. The Hausman test results reveal that the presumption of random effects in the spatial lag model is dismissed for all simulations, whereas the presence of fixed effects is verified at a 1% significance stage.

Finally, we examine two separate hypotheses H_0: $\theta = 0$ and H_0: $\theta + \lambda\beta = 0$ in **Eq. 3**. The spatial Durbin model is simplified to the spatial lag model if the first hypothesis is valid. Furthermore, if the second argument is true, the spatial Durbin model may be reduced to a spatial error model. To test if the presence of the spatial lagged independent variable in the model is important, we use the LR or Wald test. The findings of the test are shown in **Table 7** for fixed

TABLE 9 | Marginal effects of the CO_2 emissions.

	Direct		Indirect		Total	
	Coefficient	p value	Coefficient	p value	Coefficient	p value
lnGDPP	2.520	(0.001***)	-0.153	(0.593)	2.367	(0.001***)
lnGDPP²	-0.084	(0.001***)	0.024	(0.133)	-0.060	(0.001***)
lnURB	0.502	(0.001***)	0.022	(0.827)	0.545	(0.011**)
lnOPE	0.035	(0.084*)	0.012	(0.719)	0.047	(0.192)
lnENER	1.307	(0.001***)	0.144	(0.107)	1.451	(0.001***)
lnFID	0.275	(0.001***)	0.110	(0.051*)	0.385	(0.001***)
lnFIA × lnENER	-0.146	(0.001***)	-0.036	(0.196)	-0.183	(0.001***)
lnFIA	0.282	(0.001***)	0.136	(0.032**)	0.418	(0.001***)
lnFIE × lnENER	-0.140	(0.001***)	-0.023	(0.512)	-0.163	(0.001***)
lnFIE	0.113	(0.032**)	0.450	(0.001***)	0.563	(0.001***)
lnFMD × lnENER	-0.041	(0.061*)	-0.206	(0.001***)	-0.247	(0.001***)
lnFMD	0.109	(0.001***)	0.109	(0.005***)	0.218	(0.001***)
lnFMD × lnENER	-0.058	(0.001***)	-0.053	(0.007***)	-0.111	(0.001***)
lnFMA	0.072	(0.001***)	0.066	(0.033**)	0.137	(0.001***)
lnFMA × lnENER	-0.051	(0.001***)	-0.041	(0.032**)	-0.092	(0.001***)
lnFME	-0.044	(0.001***)	-0.002	(0.926)	-0.046	(0.099*)
lnFME × lnENER	0.015	(0.019**)	0.020	(0.093*)	0.035	(0.011**)

*p values, ***, **, and * show significance at 1, 5, and 10% levels, respectively.*
Authors' estimations.

effects models. For both models, the statistical significance of the two experiments, the LR or the Wald test, is important, and the spatial Durbin model cannot be transformed to a spatial error or spatial lag model. As a result, the presence of the spatial lagged independent variable is established, and the spatial Durbin model is used to analyze the estimation results.

Most of the model variables had a major impact on CO_2 emissions, according to the coefficients of the model variables in **Table 8**, and CO_2 emissions increased by around 1.45% with every % growth in GDP per capita. However, the GDP per capita coefficient of the squared words is negative, illuminating the EKC hypothesis and resulting in an inverted U-shaped association between GDP growth and CO_2 emissions. In addition, each percentage increase in urbanization results in a 0.7% increase in CO_2 emissions. While trade openness has a positive impact on CO_2 emissions, most simulations do not find this effect to be significant. The energy intensity has a favorable impact on CO_2 emissions, with each percentage increase in energy intensity resulting in an increase in CO_2 emissions by around 0.88%. **Table 8** shows that the estimation results for the coefficients of the logarithm of financial institution access and financial market efficiency are substantially positive and negative, respectively, when considering various components of the financial growth index.

The calculation results of equation (2) are provided in **Table 8** to understand the impact of financial growth spillover effects on energy production. The findings show that all aspects of financial growth have significantly important consequences. However, for financial market performance, all aspects of financial growth have a clear positive impact on CO_2 emissions. The addition of the interaction word improved the estimation results significantly, indicating that not using such effects might lead to misleading results. Except for financial market performance, the indirect effects are negative, according to the findings. The spillover effects of the various components of financial growth on energy intensity are measured using **Eq. 3**:

$$\frac{d(lnCO_{2it})}{d(lnENER_{it})} = 1.307 - 0.146 \times lnFID_{it}, \tag{7}$$

$$\frac{d(lnCO_{2it})}{d(lnENER_{it})} = 1.382 - 0.141 \times lnFIA_{it}, \tag{8}$$

$$\frac{d(lnCO_{2it})}{d(lnENER_{it})} = 1.029 - 0.039 \times lnFIE_{it}, \tag{9}$$

$$\frac{d(lnCO_{2it})}{d(lnENER_{it})} = 1.030 - 0.057 \times lnFMD_{it}, \tag{10}$$

$$\frac{d(lnCO_{2it})}{d(lnENER_{it})} = 0.987 - 0.050 \times lnFMA_{it}, \tag{11}$$

$$\frac{d(lnCO_{2it})}{d(lnENER_{it})} = 0.869 + 0.014 \times lnFME_{it}. \tag{12}$$

Table 9 shows the direct and spatially indirect effects of all model B_2 variables, as well as the variables specific to model B_3 on B_7's financial growth. Specific effects measure the influence of independent variables on a special country's dependent variable, while spatially indirect effects measure the effect of independent variables in neighboring countries on a special country's dependent variable. The direct results are significantly different from the approximate values when **Tables 8**, **10** are compared. Since the primary effects involve feedback effects from crossing adjacent states and returning to the states themselves, the indirect effects include feedback effects to investigate the impact of adjacent countries' independent variables on a country's CO_2 emissions concentrate on the spatially indirect effects.

DISCUSSIONS

According to the findings, while control independent variables in neighboring countries have no major effects on CO_2 emissions in other countries, the direct and spillover effects of neighboring

TABLE 10 | Eq. 2's estimated results.

	Model B2	Model B3	Model B4	Model B5	Model B6	Model B7
lnGDPP	2.516	2.035	1.485	1.629	1.635	1.451
	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
lnGDPP^2	-0.084	-0.063	-0.029	-0.034	-0.036	-0.028
	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
lnURB	0.505	0.622	0.678	0.677	0.690	0.735
	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
lnOPE	0.034	0.022	0.030	0.032	0.023	0.042
	(0.074)	(0.264)	(0.139)	(0.103)	(0.245)	(0.036)
lnENER	1.307	1.382	1.029	1.030	0.987	0.869
	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)	(0.001***)
lnFID	0.275	—	—	—	—	—
	(0.001***)	—	—	—	—	—
lnFID × lnENER	-0.146	—	—	—	—	—
	(0.001***)	—	—	—	—	—
lnFIA		0.282	—	—	—	—
	—	(0.001***)	—	—	—	—
lnFIA × lnENER	—	-0.141	—	—	—	—
	—	(0.001***)	—	—	—	—
lnFIE	—	—	0.107	—	—	—
	—	—	(0.034**)	—	—	—
lnFIE × lnENER	—	—	-0.039	—	—	—
	—	—	(0.072*)	—	—	—
lnFMD	—	—		0.107	—	—
	—	—	—	(0.001***)	—	—
lnFMD × lnENER	—	—	—	-0.057	—	—
	—	—	—	(0.001***)	—	—
lnFMA	—	—	—	—	0.071	—
	—	—	—	—	(0.001***)	—
lnFMA × lnENER	—	—	—	—	-0.050	—
	—	—	—	—	(0.001***)	—
lnFME	—	—	—	—	—	-0.044
	—	—	—	—	—	(0.001***)
lnFME × lnENER	—	—	—	—	—	0.014
	—	—	—	—	—	(0.020**)
W × lnGDPP	-0.151	-0.342	-0.170	0.123	-0.079	-0.412
	(0.622)	(0.183)	(0.479)	(0.656)	(0.772)	(0.096*)
W × lnGDPP^2	0.024	0.034	0.018	0.008	0.017	0.031
	(0.136)	(0.011**)	(0.176)	(0.594)	(0.251)	(0.020**)
W × lnURB	0.047	-0.232	0.244	0.082	0.340	0.420
	(0.809)	(0.267)	(0.218)	(0.673)	(0.071*)	(0.024**)
W × lnOPE	0.013	0.016	0.022	0.023	0.037	0.073
	(0.701)	(0.642)	(0.192)	(0.508)	(0.306)	(0.031**)
W × lnENER	0.148	0.206	0.692	0.095	0.069	-0.106
	(0.122)	(0.157)	(0.001***)	(0.237)	(0.363)	(0.118)
W × lnFD	0.110	0.132	0.425	0.105	0.060	0.001
	(0.048**)	(0.037**)	(0.001***)	(0.004***)	(0.035**)	(0.957)
W × lnFD × lnENER	-0.036	-0.022	-0.196	-0.052	-0.038	0.018
	(0.206)	(0.542)	(0.001***)	(0.006***)	(0.036**)	(0.105)
W × lnCO$_2$	-0.003	0.007	0.049	0.020	0.039	0.062
	(0.934)	(0.856)	(0.203)	(0.612)	(0.314)	(0.106)

p *values, ***, **, and * show significance at 1, 5, and 10% levels, respectively.*
Authors' estimations.

countries' financial growth on CO_2 emissions in other countries are significant. The direct effects of financial growth in neighboring countries' economies and organizations on a country's CO_2 emissions are positive, although spillover effects are negative. In terms of financial market performance, the effects are opposite. The sign of the coefficient is very similar to the non-spatial direct results of countries. The results of neighboring countries' financial growth are close to the effects of a country's own internal financial development.

CONCLUSION

The research is conducted with data from 22 European nations spanning the years 1990–2020; the study looked at the impact of CO_2 emissions on the physical location of people and places. For reasons that are not clear, the model's selection resulted in a biased estimation and unsatisfactory results. In the COVID-19 lockdowns, we studied the financial performance of companies and CO_2 emissions in Europe. The COVID-19 pandemic wave in

Europe had a significant impact on passenger transportation emissions. Trade transparency appears to have no influence on CO_2 emissions, according to the study's results. Between 1 March 2020 and 31 December 2020, emissions were decreased under the COVID-19 emergency. It will be impossible to meet the European Green Agreement emission reduction objectives unless the existing pattern of increasing private and decreasing public passenger transportation is modified. Most linear findings of financial growth are worthless, except for the logarithm coefficients of financial institution access and financial market performance, both of which are positive. In most cases, increased energy quality has a positive and considerable influence on CO_2 emissions, although this has the opposite effect on energy intensity. CO_2 emissions in a neighboring region are not affected by GDP growth or other control factors.

Suggestions for Future Research

Financial indicators from neighboring nations have similar impacts on CO_2 emissions, which suggests major consequences. According to this claim, reducing greenhouse gas emissions would necessitate global policy convergence. A comparison might be drawn between European industrial manufacturing processes and the production of harmful gases such as SiO_2 and NO_2.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

XL: Conceptualizing, writing, drafting-Original draft. KZ: Conceptualizing, writing, drafting-Original draft. HT: Data and methodology. CL: Review and editing. YS: Review and editing.

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The Relationship Between Economic Growth and CO_2 Emissions in EU Countries: A Cointegration Analysis

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This paper explores the dynamics of the relationship between economic growth and CO_2 emissions in the 27 EU member states in a panel setting for the period 2000–2017. We use qualitative sequential methodology, involving empiric analysis that provides coherence and viability for our study, but also quantitative methods, including Dynamic Ordinary Least Squares (DOLS), unit root tests and cointegration techniques. The results suggest the existence of a long run cointegrating relationship between growth and CO_2 emissions in EU countries and the DOLS method indicates a statistically significant effect of economic growth on CO_2 emissions for both versions of estimators, revealing that on average, a 1% change in GDP leads to 0.072 change in CO_2 emissions. The study also exhibits that higher income levels lead to increased demand for environmental protection and underline the need for designing environmental policies, capable to reduce emissions during periods of economic growth. Moreover, we find that the status of economic growth does not automatically diminish climate vulnerability in EU countries, only the correct type of growth does, thus being necessary that EU policymakers be aware of the energy cost pressure and to achieve economic growth in relationship with appropriate tools in terms of climate risk management.

Keywords: environmental degradation, CO2 emissions, economic growth, cointegration analysis, climate risk

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1 INTRODUCTION

Climate change and environmental degradation influence the status of the sustainable economy, being affected both financial and non-financial institutions (Haigh 2011; Sullivan 2014; Ozili, 2020). The potential negative implication of climate change on economic activity is revealed by the climate risk which leads to adverse impacts on human livelihoods and well-being. Managing climate risks and facing up to losses and damages, implies societal decisions, proactive management, and the capacity to predict climate dynamics related to the future greenhouse gas emission and of course, to the entire pattern of socio-economic development and equality. Emissions from human industry represent a key factor in climate change and exhibit one of the world's most pressing challenges. Year by year increase the concentration of carbon dioxide in the atmosphere and even if energy is a fundamental engine of economic development, the evolution of demand at different stages of economic development requires a viable solution for environmental problems. According to the literature insights, there are different types of approaches and different hypotheses related to the relationship between economic growth and environmental pollution. On the one hand, it is revealed that the status of environmental quality is influenced by the level of per capita income, which generate changes in environmental policies and legitimize the assumption that the higher is per capita income, the higher will be environmental deterioration. On the other hand, it is assumed that the ability to manage climate stress depends on the level of economic growth and is strongly influenced by the status of the financial sector, well-designed institutions, health sanitation system and the levels of education. At the EU level, environmental problems have escalated and even if the implemented environmental policies have brought some benefits, the use of natural resources linked to economic growth continued to pressure the environment and lead to new challenges and vulnerabilities in climate change areas.

Though there are numerous studies analyzing the dynamics of the relationship between growth and CO_2 emissions, only few focus on the profile of EU countries, losing sight of the largest contribution of the European Union to the global greenhouse gas emissions. EU strategies intend to remove more carbon emissions from the air, but the efforts are even harder and more demanding considering that in the year 2020 the European Union produced approximately 2.54 billion metric tons of carbon dioxide emissions.

Even if the EU has adopted ambitious climate law frameworks, such as Paris Climate Agreement, the Kyoto protocol for EU 15 or the European Climate Law from 2021 which promote the goals set by the European Green Deal, still remains the group of countries with a large contribution to the global greenhouse gas emissions. Paris Climate Agreement of 2015, entered into force in 2016 and impose limits in terms of global warming, Kyoto protocol for EU 15 aimed to reduce greenhouse emission and the European Climate Law from 2021 promote the goals set by the European Green Deal which stipulate the necessity to achieve climate neutrality by 2050 an to reduce CO_2 emissions by 55% by 2030 compared to 1990. However, according to statistics of the European Commission, in most EU Member States, in the third quarter of 2021, it is highlighted an increase in greenhouse gas emissions compared with the same quarter of 2020. Therefore, in the light of concerns related to the economic growth framework and due to the fact that the growth of many national economies cannot be delimited by an increase in greenhouse gas emissions, we investigate a vital issue related to climate change, respectively, the relationship between real GDP and CO_2 emission across EU countries. We use panel data from the 2000 to 2017 and we document that there is a positive correlation between real GDP and CO_2 emission. The results suggest that higher income levels lead to increased demand for environmental protection and underline the need for designing environmental policies, capable to reduce emissions during periods of economic growth. We exhibit that the status of economic growth does not automatically diminish climate vulnerability in EU countries, only the correct type of growth does.

The methodological approach includes qualitative sequential methodology, involving empiric analysis that will provide coherence and viability for our study, but also quantitative methods such as Dynamic Ordinary Least Squares (DOLS), unit root tests and cointegration techniques. As a first step, we establish the state of affairs and based on the content analysis we build a concrete image in terms of key characteristics of green infrastructure research and the correlation between growth and CO_2 emission by focusing on the countries of the European Union. Second, we focus on empirical analysis of the relationship between carbon dioxide (CO_2) emissions and economic growth. And as a final step, we establish the status of convergence to global policy incentives, and we identify new mechanisms and instruments for the purpose of reducing CO_2 emissions while attaining economic growth in EU countries.

The study provides new evidence on a panel of EU countries and based on Dynamic Ordinary Least Squares (DOLS), unit root tests and cointegration techniques, empirically analyzed the relationship between economic growth and CO_2 emissions. The study has a broader coverage and represents an important contribution to the extant literature based on three important contributions: First, it adds to the growing body of empirical investigations on the determinants of reducing CO_2 emissions while attaining economic growth, especially to the literature studying the impact of economic growth on environmental degradation. Second, we identify the literature gap, and we highlight that only a few studies focus on the profile of EU countries, losing sight of the largest contribution of the European Union to the global greenhouse gas emissions and we disentangle the implication of economic growth on CO_2 emissions on the profile of EU countries. We document a statistically significant effect of economic growth on CO_2 emissions for both versions of estimators and we emphasize that this effect is driven especially by the energy cost pressure and inefficiency in working with appropriate tools in terms of climate risk management. Third, we provide more insights into the relationship between higher income levels and the demand for environmental protection and we underline the need for designing environmental policies, capable to reduce emissions during periods of economic growth. The study also offers a clearer picture of EU energy cost pressure and represents a valuable framework for academics, practitioners, decision-makers and governments from the EU level. The remainder of the paper is structured as follows: In **Section 2** we review the current discussion on the relationship between CO_2 emissions and economic growth, in **Section 3** we present the sample, data and econometric framework; in **Section 4** we discuss the empirical results and in **Section 5** we conclude.

2 LITERATURE REVIEW

During the last two decades, has increased the interest in analyzing growth policies in relation to climate change, global warming and the greenhouse effect being the core of the analysis. The economic literature on CO_2 Emissions and growth is becoming abundant but decreased when we consider the studies that analyse the relationship between economic growth and CO_2 emissions in EU countries. Despite the large number of studies that have examined the status of climate change and global warming, there are only a few studies that have investigated the relationship between economic growth and CO_2 emission, especially in the profile of EU countries. The energy growth paradox is usually analyzed from the perspective of damage to the biosphere and although there are studies suggesting that energy contributes to economic growth (Shahbaz et al., 2013; Azam et al., 2020; Baz et al., 2021; Magazzino et al., 2021; Zhang et al., 2021) we also find studies demonstrating that energy has a negative impact on economic growth (Garcia1 et al., 2020).

In the debates carried out under the rubric of creating a "correct type of growth" that should be related to the objective of reducing CO_2 emissions, most of the papers analyzed the relationship between economic growth and CO_2 emissions. Azam et al. (2016) analyse the environment degradation proxied by CO_2 emission on the profile of selected higher CO_2 emissions economies and conclude that there is a positive relationship between CO_2 emissions and economic growth in China, Japan, and the USA. For BRIC countries, Li 2022 and Pao and Tsai (2010) reveal that in the long-run equilibrium, energy consumption has a positive and statistically significant impact on CO_2 emissions. A number of studies examined the relationship between CO_2 emission and economic growth at the country level, an example is Yousefi-Sahzabi et al. (2011) who investigate the relationship between CO_2 emission and economic growth of Iran and confirms a positive strong correlation between CO_2 emission and economic growth and related to this point of view, Bouznit and María del (2016) also confirm the same results on the profile of Algeria and Lešáková and Ondřej (2018) on the profile of Czech Republic. For Israel, Magazzino (2015) highlights that the real gross domestic product (GDP) drives both energy use and CO_2 emission. Some studies such as those of Kluschke et al. (2019) and Delgado and Lutsey (2015) analyse the status of CO_2 emission and related costs for various technology. Song and Xu (2012) compare the emissions from two alternatives, more exactly, analyse the emission between direct and feeder liner services and conclude that shipping companies should be useful to consolidate policy merits and service route design from a CO_2 emissions perspective.

Performing a literature overview, we find few studies examined the major factors affecting CO_2 emission or analysed the instruments for the purpose of reducing CO_2 emissions while attaining economic growth in EU countries. Recent studies validate the existence of a global interrelationship between economic growth and carbon dioxide emissions (Fávero et al., 2022; Khan et al., 2022). Bengochea-Morancho et al. (2001) explores the relationship between economic growth and CO_2 emission on a panel of ten European Union countries for the period 1981–1995 and conclude that there are major differences in terms of strategies to control emissions, indicating the necessity to manage the reduction of emissions by considering the economic situation of each EU countries. However, Acaravci and Ozturk (2010) admit the heterogeneity of EU countries and based on autoregressive distributed lag (ARDL) bounds test the approach of cointegration for nineteen European countries revealing that there is a causal relationship between CO_2 emissions, energy consumption and economic development in only seven from nineteen countries. Bilan et al. (2019) analyse the implication of renewable energy sources and CO_2 emission on GDP and confirms the existence of the relationship between the analysed variables, linked to this point of view, Halicioglu (2009) also validate that economic growth is closely related to energy consumption and the increase in growth leads to higher CO_2 emissions. In terms of instruments to reduce greenhouse emissions, according to Dogan and Seker (2016), it is highlighted that environmental pollution can be reduced by increasing the share of renewable energy. Other studies such as those of Breed et al. (2021) emphasize that based on the fact that one-quarter of the energy-related greenhouse gas emissions are from transport, fuel economy regulation can be a powerful instrument to reduce CO_2 emissions. At the global level, Jiang and Guan (2016), analyse the determinants of CO_2 emission growth and conclude that the CO_2 emissions from coal use grew the most rapidly and the growth in final demands has led to significant CO_2 growth worldwide.

Energy represents an essential engine of progress and economic development, which directly affect our essential well-being (Mendonç et al., 2020). Therefore, the ability to consolidate environmental sustainability and manage climate stress depends on the public agenda strategies and the entire itinerary of economic development. Economic activity and the technology status influence, of course, the energy demand and even if energy is an essential engine of economic growth, the negative implication on wellbeing can be managed by reducing vulnerability and promoting the right type of growth. A study conducted in 2017 on 31 developing countries, aimed to identify the effect of economic growth on CO_2 emission. Using a dynamic panel threshold framework, the authors show that there is a significant link between growth and CO_2 emission, highlighting that economic growth has a negative effect on CO_2 emission in the low growth regime but a positive effect in the high growth regime (Goodness and Prosper, 2017). Moreover, the study identifies methods to consolidate sustainable economic growth without increasing the level of emission, by highlighting the need to switch away from non-renewable energy to renewable energy. Linked to these results, many researchers have agreed that imposed mechanisms for increasing renewable energy had decreased CO_2 emissions (Cosmas et al., 2019; Toumi and Toumi, 2019). Moreover, the most recent studies examine if it is tough for CO_2 emission reduction to be compatible with the goal of economic growth and conclude that energy contributes to economic growth (Shahbaz et al., 2013; Azam et al., 2020; Baz, Khan et al., 2021; Magazzino et al., 2021; Zhang et al., 2021) and contrary to this point of view, we also find studies demonstrating that energy has a negative impact on economic growth (Garcia1 et al., 2020). Overall, the stream of the literature review reveals on the one hand, that growth per se could reduce climate vulnerability and economic vulnerability to disasters decreases as income increases, on the other hand, it is highlighted that CO_2 emissions depend on the amount of money we have, meaning that the richer we are, the more CO_2 we disengage. By retrospective analyze the existing literature, we can conclude that few studies focused on the profile of EU countries and this gap in the literature inspired the itinerary of this study, meaning to investigate a vital issue related to climate change, respectively, the relationship between real GDP and CO_2 emission across EU countries.

3 SAMPLE, DATA, AND METHODOLOGY

3.1 Sample and Data

We study the dynamics of the relationship between economic growth and CO_2 emissions in the 27 EU member states in a panel setting for the period 2000–2017. We use qualitative sequential methodology, involving empiric analysis that provides coherence and viability for our study, but also quantitative methods, including Dynamic Ordinary Least Squares (OLS) (DOLS), unit root tests and cointegration techniques. Gaining insight into what literature gives us, we find that the main advantage of the panel cointegration approach is its focus on the long-run relationships, and the format of the models limits the number of the accounted variables typically to CO_2 emissions and GDP per capita (Martinez-Zarzoso and Bengochea-Morancho, 2004; Lean and Smyth, 2010; Arouri et al., 2012; Kapusuzoˇglu 2014; Zhang et al., 2021). Therefore, given that economic growth is one of the most-watched economic indicators and usually is the core of the economic research analysis, it has been included in the analysis. Besides, represent an indicator that can be related to the trend in the capacity of an economy to produce goods and services in a period compared to another one. To measure the increase in the production of goods and services in EU economies, we use the most common indicator GDP Per Capita (constant U.S. $). Additionally, the growth process requires energy consumption and leads to rising atmospheric concentrations of carbon dioxide, that's why we include in the analysis the status of carbon emissions, measured by CO_2 Emissions (metric tons per capita).Other variables included in the analysis are: the rate of population growth, gross savings which represent the difference between disposable income and consumption and gross fixed capital formation (formerly gross domestic fixed investment) which includes land improvements (fences, ditches, drains, and so on); plant, machinery, and equipment purchases; and the construction of roads, railways, and the like, including schools, offices, hospitals, private residential dwellings, and commercial and industrial buildings. The main source of data is the database of the World Bank, World Development Indicators. The conceptual framework is explained in the next part of the study.

3.2 Econometric Framework

3.2.1 Panel Unit Root Tests—Methodology

According to the literature, there are two types of panel unit root tests. The first one can be classified as first-generation, has as particular limit the assumption of cross-sectional independence and incorporate Levin-Lin-Chu test-LLC (Levin A. et al., 2002), Im-Pesaran and Shin test-IPS (Persan et al., 2003) and Fisher-type tests. The second one is named the second generation and rejects the cross-sectional independence hypothesis. The previously mentioned tests represent the extension of the classical ADF unit root test (Augmented Dickey-Fuller) and can be expressed by the following equation:

$$\Delta y_t = \rho y_{t-1} + \sum_{p=1}^{P} \phi_p \Delta y_{t-p} + \gamma_l' D_l + \varepsilon_t, t = 1, ..., T \tag{1}$$

The Augmented Dickey-Fuller tests the null hypothesis that $\mathcal{Y}t$ has the unit root, versus the alternative that $\mathcal{Y}t$ is stationary (H_0: $\rho = 0$ against H_1: $\rho < 0$). For panel case, the Augmented Dickey-Fuller test is accomplished by running the following equation:

$$\Delta y_{i,t} = \rho_i \mathcal{Y}_{i,t-1} + \sum_{p=1}^{P_i} \phi_{ip} \Delta y_{i,t-p} + \gamma_{li}' D_{li} + \varepsilon_{i,t}, t = 1, \ldots, T, \quad i = 1, \ldots, N \tag{2}$$

Eq. 2 develop the first equation, and it considers that the errors $\varepsilon_{i,t} \sim N(0, \sigma^2)$ are assumed to be independent across the individuals. The Levin-Lin-Chu test assume the null H_0: $\rho_i = \rho = 0 \ \forall_i$ against *the alternative*H_1: $\rho_i < 0 \ \forall_i$. The Im-Pesaran and Shin test-IPS (Persan et al., 2003), in contrast to LLC test, admit the probability of varying autoregressive processes across individuals and can be expressed by the following equation:

$$\bar{t}\,NT = N^{-1} \sum_{i=1}^{N} t_{iT} (P_i, \phi_{i1}, \ldots, \phi_i P_i) \tag{3}$$

In which case t_{iT} $(P_i, \phi_{i1}, \ldots, \phi_i P_i)$ represent the t-statistic for assessing the unit root in the ith individual process. P_i represent the lag order which is generally selected based on some info criterion and $\bar{t}\,NT$ is included to test the null hypothesis H_0: $\rho_i = \rho = 0 \ \forall_i$, against the alternative H_1: $\exists i \in \{1, \ldots, N\}$, $\rho_i < 0$.

With reference to second generation unit root tests, we follow the assumption of the Cross-sectional Im-Pesaran-Shin test (CIPS), proposed by Pesaran (2007), which alternatively to standard ADF, adds lagged cross-sectional means of individuals $\bar{\mathcal{Y}}_t$ and is accomplished by running the following equation:

$$\Delta y_{i,t} = \rho_i \mathcal{Y}_{i,t-1} + \varphi_i \bar{\mathcal{Y}}_{t-1} + \psi_i \Delta \bar{\mathcal{Y}}_t + \gamma_{li}' D_{li} + \varepsilon_{i,t}, t = 1, \ldots, T, \quad i = 1, \ldots, N \tag{4}$$

The Cross-sectional Im-Pesaran-Shin statistic is estimated as group mean of t statistics obtained from Cross-sectional Augmented Dickey-Fuller equations, the rationale being explained in **Eq. 3**.

3.2.2 Cointegration Analysis—Methodology

To explore the relationship between CO_2 emission and economic growth in EU countries we follow the empirical literature, and we perform cointegration tests, thus investigating the existence of long run relationship among the variables (Pedroni 1999; Kao, 1999; Pedroni 2000; Pedroni 2001; Pesaran 2004; Pesaran 2007; Narayan and Smyth, 2008; Al-Mulali, 2011; Al-Mulali, 2012; Mitic et al., 2017). Comparable to panel unit root tests, panel cointegration tests are more effective and powerful than the traditional time series cointegration. First, we follow cointegration testing and Granger causality testing and then based on literature validation we develop a clear modelling approach based on panel Dynamic Ordinary Least Squares (DOLS) estimation methods in the existence of cointegration (see. Mikayilov et al., 2018; Zoundi, 2017). According to literature insights, the granger causality test represents an important instrument for detecting the dynamic interrelationships between two groups of variables (Bai et al., 2018), the methodology being applied at the institutional level, and being used in evidence from Linear and Nonlinear Panel and Time Series Models (see Chow et al., 2018).

The panel cointegration tests of Pedroni (Pedroni, 2004) is given by **Eq. 3**.

$$\mathcal{Y}_{i,t} = \beta_i' x_{i,t} + \gamma'_{li} D_{li} + \varepsilon_{i,t}, \text{ where } x_{i,t} \textit{ is equal to } x_{i,t-1} + \varepsilon_{i,t} \quad (5)$$

Panel Dynamic Ordinary Least Squares (DOLS) represents a measurement tool for predicting a particular cointegrating vector in the panel, the rationale of DOLS model requires that the variables be cointegrated. The model has the following specification:

$$\mathcal{Y}_{i,t} = \beta_i' x_{i,t} + \sum_{j=-q}^{q} \zeta_{ij} \Delta x_{i,t+j} + \gamma'_{li} D_{li} + \varepsilon_{i,t} \quad (6)$$

Where q denoting the number of lags normally chosen based on some info criterion. The effectiveness of these methods is given by the advantage of controlling the endogeneity in the model, thus providing robust correction of endogeneity in the explanatory variables (Mark and Donggyu, 2003; Dritsaki and Dritsaki, 2014). To test the general notion from Solow growth model theory and to assess the implication of general theory which admits that high population growth leads to lower per capita output, we used ordinary least-squares regression model (OLS) analysis with the following specification:

$$GDPCAP_{it} = c_0 + c_1 \times POPGR_{i,t} + u_{i,t}, \quad (7)$$

Where i and t indicate the country and year for each variable. The dependent variable $GDPCAP_{it}$ represents a key metric for assessing the increase in the production of goods and services in EU economies. The independent variable includes the rate of population growth, $POPGR_{i,t}$. Moreover, to evaluate the theoretical determinants of economic growth, the following models include relevant explanatory variables that influence the level of economic growth:

$$GDPCAP_{it} = c_0 + c_1 \times POPGR_{i,t} + c_2 \times CO2_{i,t} + c_3 \times GS_{i,t} + c_4 \times GFCFS_{i,t} + u_{i,t}, \quad (8)$$

Where i and t indicate the country and year for each variable. The dependent variable $GDPCAP_{it}$ and the first independent variable are analogous to those indicated in **Eq. 7**. Other independent variable includes the status of carbon emissions, measured by CO_2 Emissions (metric tons per capita), $GS_{i,t}$ which measure gross savings and represent the difference between disposable income and consumption, $GFCFS_{i,t}$, which measure gross fixed capital formation (formerly gross domestic fixed investment) and includes land improvements (fences, ditches, drains, and so on); plant, machinery, and equipment purchases; and the construction of roads, railways, and the like, including schools, offices, hospitals, private residential dwellings, and commercial and industrial buildings.

The fixed-effects model has the following form:

$$Y_{i,t} = \alpha_i + X_{i,t} \times \beta + \varepsilon_{i,t}, \quad (9)$$

$Y_{i,t}$ represents the dependent variable for country i at time t, α_i represents an unknown country-specific constant, $X_{i,t}$ indicates the time-variant regressor matrix, and $\varepsilon_{i,t,}$ is the error term; in order to validate the appropriateness of the fixed-effects model, the Hausman test was performed.

4 EMPIRICAL RESULTS

To avoid the implication of spurious results, we applied unit root tests and we verify the stationarity of data. We run Levin et al. (2002), Im et al. (2003), and Fisher-type tests for each variable and we test the unit root. The benchmark results listed in **Table 1** and **Table 2** reveal the results for unit root tests, which has been applied in level and the first difference with intercept, in intercept and trend or none of them incorporated in the test equation separately. Following the literature validation, when is run the ADF test, it is required to check both versions-with intercept only and intercept and trend (Al-Mulali, 2011).

The results of panel unit root tests reported in **Tables 1**, **2** clearly reveal that running Levin et al. (2002), Im et al. (2003), and Fisher-type tests we obtain mixed results at the level order. However, when we analyse the results of the panel unit root in first differences, the null hypothesis could be rejected, and the results indicate that all the panels are stationary. For GDP, the outcomes for unit root analysis exemplify that at the level, in most of case, the variable has unit root, but when we apply the first difference it becomes stationary. The Unit Root Test of Carbon Emission Variable (CO_2) reveals similar results, as Levin, Lin & Chu, Im, Pesaran and Shin, ADF—Fisher Chi-square and PP—Fisher Chi-square show non-stationarity in levels and stationarity in differences. The overview of the results is validated by literature background, studies such as those employed by Gün (2019), Mitić et al. (2017), Bastola and Sapkota (2014), Arouri et al. (2012), revealing similar results, the same variables not being stationary at the level but stationary at first difference. Once we established that both variables are stationary, we conduct panel cointegration tests and we focus on empirical analysis of the relationship between carbon dioxide (CO_2) emissions and economic growth. **Table 3** exhibits the estimation results for panel cointegration tests.

The overview of the results reveals that for the Pedroni test within-dimension when an intercept is included, the null hypothesis of no cointegration is rejected for two of the four tests for the panel statistics. For the Pedroni test within-dimension, when an intercept and a trend is included, it seems that for all four panels the null hypothesis is rejected, and it is cointegration between the variable. Overall, for most of the tests applied, the null hypothesis is rejected, and the results reveal that the variables are cointegrated and are moving together in the long run. Next, whereas the variables are cointegrated, we strengthen the quality of the research and we run the DOLS estimator. Estimation of cointegrating relationship between CO_2 emission and economic growth is reported in **Table 4**. Panel Dynamic Ordinary Least Squares (DOLS), represent a measurement tool for predicting a particular cointegrating vector in the panel, the rationale of the DOLS model requires that the variables be cointegrated.

Employing the DOLS estimator, we test the consistency of the results. The results from this estimation technique validate the existence of a long-run cointegration relationship between the emissions-economic growth. The positive relationship between the variables reveals that the higher is GDP, the higher will be CO_2 emissions in the EU countries. Estimation of cointegrating relationship through the DOLS method indicates a statistically significant effect of economic growth on CO_2 emissions in EU countries for both versions of estimators, revealing that on average, a 1% change in GDP leads to 0.072 change in CO_2 emissions on the profile of EU countries.

TABLE 1 | Unit root test of GDPCAP variable (GDPCAP).

	Level			First difference		
	Intercept	**Intercept and trend**	**None**	**Intercept**	**Intercept and trend**	**None**
Levin, Lin and Chu t	−8.10252 (0.0000)	−4.52672 (0.0000)	4.00107 (1.0000)	−9.85924 (0.0000)	−14.9930 (0.0000)	−12.9081 (0.0000)
Im, Pesaran and Shin	−3.321 (0.0004)	2.87412 (0.9980)	—	−7.87314 (0.0000)	−13.5794 0.0000	—
ADF—Fisher Chi-square	82.5761 (0.0074)	20.2582 (1.0000)	8.42745 (1.0000)	158.615 (0.0000	250.207 (0.0000)	218.488 (0.0000)
PP—Fisher Chi-square	98.3635 (0.0002)	8.03519 (1.0000)	5.81127 (1.0000)	195.789 (0.0000)	328.435 (0.0000)	274.610 (0.0000)

Note: Null hypothesis: Unit root (individual unit root process). Probabilities are given between parentheses.

TABLE 2 | Unit root test of carbon emission variable (CO_2).

	Level			First difference		
	Intercept	**Intercept and trend**	**None**	**Intercept**	**Intercept and trend**	**None**
Levin, Lin and Chu t	0.52688 (0.7009)	−1.6060 (0.0541)	−6.01321 (0.0000)	−4.30457 (0.0000)	−10.7501 (0.0000)	−10.82 (0.0000)
Im, Pesaran and Shin	3.39085 (0.9997)	0.07599 (0.5303)	—	−5.85093 (0.0000)	−2.32091 (0.0000)	—
ADF—Fisher Chi-square	22.6611 (0.9999)	47.5118 (0.7212)	100.518 (0.0001)	126.555 (0.0000)	80.6774 (0.0095)	203.116 (0.0000)
PP—Fisher Chi-square	30.5891 (0.9957)	90.0386 (0.0015)	90.7524 (0.0013)	369.295 (0.0000)	290.799 (0.0000)	429.249 (0.0000)

Note: Null hypothesis: Unit root (individual unit root process). Probabilities are given between parentheses.

TABLE 3 | Panel cointegration tests.

Dimension	**Test statistics**	**Intercept**		**Intercept and trend**	
		Statistic	**Prob.**	**Statistic**	**Prob.**
Within-dimension	Panel v-statistic	−2.2955	0.9891	1.7025	0.0443
	Panel rho-statistic	1.1202	0.8687	−14071	0.0797
	Panel PP-statistic	−2.2004	0.0139	−5.5743	0.0000
	Panel ADF-statistic	−4.0313	0.0000	−1.8520	0.0320
Between-dimension	Panel rho-statistic	3.1372	0.9991	0.9244	0.8224
	Panel PP-statistic	−0.5455	0.2927	−4.7699	0.0000
	Panel ADF-statistic	−2.5727	0.0050	−0.6319	0.0263
		Kao residual cointegration test			
ADF	t-statistic		Prob.		
	2.76692		0.0028		

Note: Null hypothesis: No cointegration. Trend assumption: no deterministic trend and Deterministic intercep and trend. Probabilities are given between parentheses.

TABLE 4 | Estimation of cointegrating relationship.

Estimation method	**DOLS**			
	Pooled		**Grouped**	
	Coefficient	**Prob.**	**Coefficient**	**Prob.**
Long-run coefficient	0.0730	0.0313	0.0726	0.0000
No. of observations	405			
R-squared adj.	0.9541			

Note: Dynamic OLS; OLS, ordinary least squares.

The results reveal that related to the status of convergence to global policy incentives, EU countries remain the group of countries with a significant contribution to worldwide greenhouse gas emissions and even if it has adopted an ambitious climate law framework, it is in search of new mechanisms and instruments for the purpose of reducing CO_2 emissions while attaining economic growth. The presence of a long-term relationship between environmental degradation and economic growth, reveals the necessity to develop a pivotal strategy for reducing CO_2 emissions and implement modern technologies for CO_2 capture and storage. From the perspective of strengthening the waste management strategy, we can exemplify: an increased analysis of the emissions trading system in all sectors, better forest management and increasing forested areas, facilitating the transition to electric and hybrid vehicles, as well as tightening emission standards for cars. The legislative instrument can also directly contribute to reducing CO_2 emissions and focusing on environmental regulations and taxes and emission reduction taxes could create support for managing the growing volume of CO_2 emissions.

Additionally, given that the nature of the long-run relationship between growth and carbon emission can be better understood if we examine the factors behind the observed relationship, we also

TABLE 5 | Panel data stationarity test estimates—Hadri and Larson.

Variables	Zt	*p*-value
Income growth	1.93391	0.0266
Saving rates (Gross savings)	6.24772	0.0000
Population growth	6.12319	0.0000
CO_2 emission	9.631448	0.0000
Gross fixed capital formation	6.24772	0.0000

Note: Null hypothesis: Unit root (individual unit root process). Probabilities are given between parentheses.

TABLE 6 | Cointegration test estimates for the Solow model.

Test type	Statistic	Probability
$Kao : D - F_\rho$	−6.625983	0.0000
$Kao : D - F_{t\rho}$	−5.846188	0.0000
$Pedroni_\rho$	2.733909	0.0053
$Pedroni_{t\rho}$	1.642403	0.0531

evaluate the Solow Growth Model and we included in the analysis other variables, such as income growth, gross savings, carbon emissions, gross fixed capital formation and population growth. Therefore, we follow the econometric literature, and we perform the panel data unit root tests for analysing the null hypothesises which refers to the non-stationarity of the time series and for this time, we follow Strauss and Yigit (2003) point of view and we carry out the potentially biased problems of Im, Pesaran, and Shin panel data unit root test. The results of Hadri tests are reported in **Table 5**. As can be seen, the results confirm that the null hypotheses of stationarity of all panels under individual heteroscedasticity and time series correlation can be rejected and reveal that EU countries have their growth variables guided by the unit root process.

Next, we follow Kao's (1999) and Pedroni's (1999, 2000) points of view and we perform the cointegration test with the null hypothesis regarding the estimated equation as not cointegrated. Therefore, we first perform the Dickey-Fuller t-based test ($Kao : D - F_\rho$), then we test the implication of the augmented Dickey-Fuller t-based test Kao: (D-F-tρ). Finally, we calculate the Pedroni tests. The results reported in **Table 6** highlight the hypothesis of cointegration between the variables and support the idea that the analysed variables have one common trend that combines them in the long run.

As a final step, following the rationale of Solow Growth theory and taking into account that general theory admits that high population growth leads to lower per capita output, in **Table 7** we report the results for testing this theory by regressing gross domestic product per capita relative to the EU countries on the rate of population growth. According to model 2, it is revealed that the effect of population growth is strong and statistically significant. It seems that the results for this simple regression, support the theory and reveal that population growth appears to have a very large negative effect on economic growth.

Furthermore, in model 1 we included other variables such as CO_2 emission, gross savings and gross fixed capital formation and we found that energy consumption together with gross fixed capital has a positive and statistically significant impact on economic growth in the long run, the results being similar to those obtained by Streimikiene and Kasperowicz (2016).

5 DISCUSSION

This paper seeks to fill a gap in the extant literature by exploring the causal relationship between economic growth and CO_2 emissions in EU countries. Cointegration analysis for EU economies was conducted using the DOLS approach developed by Pedroni (2004) and Kao (1999), respectively. First, we follow cointegration testing and Granger causality testing and based on the methodology promoted by Mikayilov et al. (2018), Zoundi (2017), we develop a clear modelling approach based on panel Dynamic Ordinary Least Squares (DOLS) estimation methods in the existence of cointegration (Zoundi, 2017; Mikayilov et al., 2018). The results perspicuously suggest the existence of a long run cointegrating relationship between growth and CO_2 emissions in EU countries and the DOLS method indicates a statistically significant effect of economic growth on CO_2 emissions for both versions of estimators. These results are consistent with the recent work of Fávero et al. (2022), Khan et al. (2022), which validate the existence of a global interrelationship between economic growth and carbon dioxide emissions. The main difference between previously mentioned studies and our research is that estimates static and dynamic contemporaneous relationships of GDP and CO_2, while our work provides long-run cointegration assessment. The multilevel approach conducted by Fávero et al. (2022), also includes interactions between fixed and random effects parameters regarding GDP and carbon dioxide emissions.

The literature survey on the empirical relationship between economic growth and CO_2 emission is vast and controversial, the main problem in terms of empirical validity was always related to the lack of diagnosis of the stationarity properties of the variables, and in a panel data context, the presence of cross-sectional dependence. Therefore, we take into consideration both criticisms, we use recent unit root tests and cointegration techniques that are robust to the presence of cross-sectional dependence. **Tables 1**, **2** reveal the results for Levin et al. (2002), Im et al. (2003), and Fisher-type tests for each variable, the unit root tests have been applied in level and the first difference with intercept, in intercept and trend or none of them incorporated in the test equation separately. If we analyse the results of the panel unit root in the first differences, the null hypothesis could be rejected, and the results indicate that all the panels are stationary. Our findings are consistent with the work of Bastola and Sapkota (2014), Mitić et al. (2017), Gün (2019), and Arouri et al. (2012), which reveal similar results, the same variables not being stationary at the level but stationary at first difference. From **Table 3**, we find that the economic growth and growth in emissions go hand in hand and the variables are cointegrated and are moving together in the long run. Moreover, applying the DOLS estimator we test the consistency of the results, and we validate the existence of a

TABLE 7 | The results of mixed-effect model.

Variables	**Model 1**		
	Pooled OLS	**Random effect**	**Fixed effect**
Population growth (POPGR)	−1.076 (5.12)**	−1.189 (4.67)**	−1.677 (4.44)**
CO_2 emisiion (CO_2)	−0.003 (0.05)	(0.003) (0.05)	0.079 (0.55)**
Saving rates (Gross savings) (GS)	−0.000 (2.27)*	−0.000 1.42	−0.000 (0.13)
Gross fixed capital formation (GFCF)	0.303 (7.62)**	0.334 (7.72)**	0.404 (7.49)**
Cons	−4.044 (4.19)**	−4.784 (4.42)**	−5.748 (4.14)**
Hausman		5.47***	
N	484	484	484
R2	0.43	0.48	0.51
Variables		Model 2	
	Pooled OLS	Random Effect	Fixed Effect
Population growth (POPGR)	−1.021 (3.97)**	−0.684 (1.81)	−1.021 (3.97)**
Cons	2.514 (9.67)**	2.442 (13.51)**	2.514 (9.67)**
Hausman		(14.9)**	
N	486	486	486
R2	0.36	0.38	0.40

*Source: Research results. Notes: the results include the coefficient of variable and *t statistic results in parentheses; ***p < 0.01, **p < 0.05, *p < 0.1.*

long run cointegration relationship between the carbon emissions and economic growth, meaning that on average, on the profile of EU countries, 1% change in GDP leads to 0.072 change in CO_2 emissions. Consequently, our results provide some important information on the directional predictability between economic growth and CO_2 emissions. First, the findings indicate that higher income levels lead to increased demand for environmental protection and underline the need for designing environmental policies, capable to reduce emissions during periods of economic growth. Of course, the status of economic growth does not automatically diminish climate vulnerability in EU countries, only the correct type of growth does. Second, given that emissions trading and economic incentive approaches are generally unpopular with some environmental analysts due to the impression of "polluter pays", we highlight the need to consolidate the efficiency of emissions trading systems. Third, the study reveals that even if several factors contribute to global warming, carbon dioxide (CO_2) emissions are particularly important, suggesting that EU economies need to follow global policy incentives, and try to implement new mechanisms and instruments for the purpose of reducing CO_2 emissions, such as taxes on environmentally harmful behavior, improved forest management and in general increasing areas of the Earth covered in forests, and facilitating the transition to electric and hybrid vehicles, as well as tightening emission standards for cars. Besides, the understanding of this relationship between environmental quality and economic growth is important for identifying appropriate policies for sustainable development. Therefore, it is necessary that EU policymakers be aware of the energy cost pressure and achieve economic growth in relationship with appropriate tools in terms of climate risk management.

It is of the utmost importance to emphasize that the nature of the long-run relationship between growth and carbon emission can be better understood if we observe the factors behind the observed relationship, meaning that it is important to have an overview of efficiency in terms of allocation of resources in European economies, analyse the costs for various technology, analyse investments in the modernization of production processes. There are two major limitations in this study that could be addressed in future research. First, considering that only a few studies focus on the profile of EU countries, losing sight of the largest contribution of the European Union to the global greenhouse gas emissions, it is required to solve the lack of previous research studies and to continue research on this topic. Second, in the context of future research, new variables can be introduced into the CO_2 emissions and economic growth nexus, such as energy consumption, renewables, environmental awareness, environmental sustainability index or technological development.

6 CONCLUSION

Global warming represents a concern for everyone, and governments are looking for effective ways to reduce the dangerous climate change. Several factors contribute to global warming, but carbon dioxide (CO_2) emissions are particularly important. This study is about identifying the potential nexus between the environment and economic growth, the subject is highly studied and of particular importance for policy makers, academia, and industry alike. Considering that the direct consequence of pollutant emissions is climate change and global warming, the principal aim of this study was to assess the causal relationships between economic growth and carbon emissions in European countries, from the period 2000 to 2017. The study has a broader coverage and represents an important contribution to the literature by the fact that it adds to the growing body of empirical investigations on the determinants of reducing CO_2 emissions while attaining economic growth, especially to the literature studying the impact of economic growth on environmental degradation. Moreover, we identify the literature gap, and we highlight that only a few studies focus on the profile of EU countries, losing sight of the largest contribution of the European Union to the global greenhouse gas emissions and we disentangle the implication of economic growth on CO_2 emissions on the profile of EU countries. Additionally, we provide more insights into the relationship between higher income levels and the demand for environmental protection and we underline the need for designing environmental policies, capable to reduce emissions during periods of economic growth. We used qualitative sequential methodology, involving empiric analysis that provides coherence and viability for our study, but also quantitative methods, including Dynamic Ordinary Least Squares (DOLS), unit root tests and cointegration techniques. The main source of data was the database of the World Bank, World Development Indicators.

Panel unit root tests have been applied in level and in the first difference with intercept, in intercept and trend or none of them incorporated in the test equation separately. The results reveal that running Levin et al. (2002), Im et al. (2003), and Fisher-type tests we obtained mixed results at the level order, but when we analyzed the results of the panel unit root in first differences, the null hypothesis was rejected, and the results indicate that all the panels are stationary. For both GDP and carbon emission it is validated the presence of stationarity differences. As a second step, after we established that both variables are stationary, we conduct panel cointegration tests and we focus on empirical analysis of the relationship between carbon dioxide (CO_2) emissions and economic growth. Cointegration analysis for EU economies was conducted using DOLS approach. We find that the status of economic growth does not automatically diminish climate vulnerability in EU countries, only the correct type of growth does, thus being necessary that EU policymakers be aware of the energy cost pressure and achieve economic growth in relationship with appropriate tools in terms of climate risk management.

The results confirm the existence of a statistically significant long run cointegration relationship between economic growth and CO_2 emissions, revealing that on average, a 1% change in GDP leads to a 0.072 change in CO_2 emissions. The fact that the variables are cointegrated and are moving together in the long run, reveals the necessity to strengthen the waste management strategy, and better analyze the pollutant emissions which directly influence climate change and global warming. The study also demonstrates that higher income levels lead to increased demand for environmental protection and underline the need for designing environmental policies, capable to reduce emissions during periods of economic growth. Additionally, increasing the efficiency in the allocation of resources and adopting instruments capable to direct consumers to the use of renewable energies must be the core of the European public agenda (Kao, 1999; Ozturk, 2010; Aye and Edoja, 2017; Lešá ková and Dobeš, 2020).

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://databank.worldbank.org/home.aspx.

AUTHOR CONTRIBUTIONS

MO, AV, and EC wrote and revised this paper, MO and EC provided suggestions for the revision and framework of this paper, and AV and MO gave some ideas of this paper.

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The impact of governance quality and educational level on environmental performance

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Environmental degradation and its impact on sustainable development have sparked the interest of national and international policymakers, specialists, and academia. This paper aims to demonstrate the empirical nexus between environmental performance, measured by carbon dioxide emissions, and education levels together with institutional quality in a society. To achieve this goal, the regression model includes the main variables that reflect the quality of governance (government effectiveness, regulatory quality, control of corruption, and rule of law), together with education dimension, gross domestic product, renewable energy consumption, fossil fuel energy consumption, and industry. The data were collected for the 1995–2020 period, for a set of 43 countries, consisting of all European Union (EU) members and The Group of Twenty (G20) states. The research uses three estimations methods, respectively Pooled ordinary least squares (Pooled OLS), Fixed effects model (FEM) and Random effects model (REM), together with a two-step dynamic GMM model, to address the endogeneity issue as well. The main results show that all the independent variables reflecting institutional quality from a technical point of view, included in the model when considering the PCSE estimation, have a direct and positive link to *CO2 emissions*' level, with control of corruption variable being the only one to influence in a positive manner *CO2 emissions* at a significant level. Education level, together with economic growth, fossil fuel energy consumption and industry, had a negative significant impact as well upon environmental performance, an increase of one unit in these variables contributing to increased carbon dioxide levels in the EU and G20 sample when considering both the panel corrected model as well as the GMM scenario. Renewable energy is the only independent variable to manifest a significant positive and direct link with environmental performance, drawing attention to the need of adapting the primary sources of energy, in line with international organizations' sustainable development policy recommendations. Also, there is a need to improve citizens' perceptions of public services and institutions by building confidence in government's ability to formulate and implement regulations.

KEYWORDS

environmental performance, education, governance quality, panel data regression, green future

1 Introduction

The subjects of ecological sustainability, green economy, circular economy, as well as environmental performance have been intensely analyzed by researchers in recent decades. This is no surprise, as the rapid growth of manufacturing economies poses a major threat upon environmental health and public health. The most notable example in this regard is China, the largest manufacturing economy, and at the same time, the most polluted country in the world in terms of CO2 emissions (Nguyen et al., 2021). Because of these threats, the regulatory institutions around the world have aligned their visions and acted to develop a concrete set of measures and instruments aiming at promoting a sustainable welfare economy, as stated by the EU Parliament's Environment Committee. Thus, governments and public institutions' quality play an important role in ensuring a green and sustainable development.

Besides the institutional perspective, one must not omit the role of education in enhancing environmental performance. It is considered that through increased educational levels, societies will become more aware of the necessity for a green future.

When seeking to reduce pollution levels, decision-makers should forward legislative proposals backed by long-term strategies in the educational sector, otherwise the expected results might fall short of the expected ones. To achieve sustainability goals, a mixture of environmental and educational policies should complement each other. Nevertheless, our current expectations will be tested in the remaining sections of this research.

As the topic of environmental performance has attracted a lot of interest from the general public in recent years, so did the scientific community become more active in tackling the topic. Whether for measuring pollution or highlighting the role and responsibilities of politics in obtaining the common objective of a green society, numerous studies of an undisputable quality have been conducted already.

The existing literature has not put enough emphasis on the link between education, governance quality, and environmental performance. Therefore, this research aims at developing a model to examine the relationships linking environmental performance and relevant macroeconomic variables such as the level of education, the quality of governance (government effectiveness, regulatory quality, control of corruption, and rule of law), together with the education dimension, gross domestic product, renewable energy consumption, fossil fuel energy consumption, and industry.

The paper aims to bridge this specific gap in the literature, generating the following research question: How significant are, amongst other variables, education and the quality of institutions in establishing our green, sustainable future? The underlying assumption of this research is that increased education and improved institutional quality will lead to higher levels of environmental performance. Addresing this issue underlines new key factors for intervention. The novelty and contributions made by this paper are to be found in an extensive database, including 43 countries and a multi-level research design. Furthermore, the current study contributes to enriching the current literature by developing the well-known model of Mavragani et al. (2016) by bringing into focus the importance of education level, technical quality of governance distributed over the four governance indicators, in connection with key macroeconomic variables such as economic growth, industry, and main sources of energy.

The results of this study should be relevant for policy makers as it will assist them prioritizing between the four pillars of governance which we have included. Also, if a significant connection is found between education and CO2 emissions, this will provide justification for a multi-layered approach.

The results can be taken as a reference point, promoting enhanced future research.

The current paper is organized as follows. The next section consists of a short literature review. The third section presents the data used in our model and the methodology. The fourth section reports the empirical results. The fifth section consists of a discussion based upon our findings. The final section presents the main conclusions of the research and policy recommendations.

2 Literature review

The purpose of current section is to develop a better understanding of the literature approaching the intertwined concepts of governance quality, educational attainment and environmental performance.

The environmental performance, measured through CO2 emissions, can be expressed as a function of income, population density, governance, political institutions, and government investment in education, as well as the level of education of the population, as portrayed by the years of schooling and other socio-economic factors (Dutt, 2009).

The constant economic growth observed worldwide throughout the past decades has led to an increased standard of living and a much more substantial energy consumption and demand. Nonetheless, the cost of this economic growth is transposed in growing CO2 emissions levels (Kasperowicz, 2015), which have become a reason for concern and a call for action.

In this regard, the Environmental Kuznets Curve (EKC) underlines that the cost of economic growth, in terms of environmental degradation, can be sustained by the benefits of economic growth, in terms of innovation and development of new technologies that shall reduce pollution in the long run. Furthermore, as income per capita increases, the intrinsic abilities of consumers develop, thus contributing to diminishing levels of degradation (De Bruyn et al., 1998).

The EKC theory has been tested in recent years by several researchers. All of the identified findings confirm the validity of the theory for less industrialized countries (Hamid et al., 2022a), countries heavily dependent on fossil fuels (Alam et al., 2022), and even for the G7 countries (Nathaniel et al., 2021). Also, according to Dutt (2009), higher-income countries are observed to yield lower CO2 emissions as a consequence of better institutions and higher levels of education. The EKC theory was recently tested for Turkey's case (Yunpeng et al., 2021) with two different proxies (carbon emissions and ecological footprint), the results confirming the EKC curve for tourism industry.

Education is an essential tool for promoting a sustainable set of values and for countering environmental degradation. A first channel through which education interferes is of political nature. Educated citizens have the ability to understand the necessity for green policies and will inevitably request them from policy makers. A second channel can be observed through consumption decisions. A household that is aware of environmental issues will seek to choose less harmful products. A third channel in which education indirectly contributes to the fight against environmental degradation is the accumulation of human capital in work places (Lan and Munro, 2013). These green-oriented work places are considered to deliver goods and services that are less harmful to the environment.

Therefore, one can consider that the primary institutions which lead to a substantial increase in environmental performance are educational institutions. The goal of these institutions should be to promote the objective of sustainable development with a clear vision and strategy, through modern teaching techniques such as blended learning (Aleixo et al., 2018; Alam and Agarwal, 2020). Gill et al. (2021) confirm the strategic position held by higher education institutions in the race towards improving environmental performance. Their findings suggest that green human resource management strategies for employees in higher education institutions will have a snowball effect towards their students, thus the entire population. Nevertheless, as we acknowledge educational institutions as responsible for modelling the future of our societies, we must not ignore the effect of external shocks towards attitudes and behaviors. For example, the COVID-19 pandemic has changed our working and transportation habits and indirectly reduced our environmental footprint (Khan et al., 2021).

In terms of available empirical evidence, we refer to Li et al. (2021), which find that a 1% increase in higher education enrolment leads to a 0.19% decrease in CO2 emission levels. In the long run, the effect of higher education is found to be even higher, respectively a decrease of 0.33% (Eyuboglu and Uzar, 2021). Nevertheless, the role of tertiary education should not be neglected as 1 year increase in tertiary education leads to a 50–60% decrease in CO2 emissions (Yao et al., 2020).

In today's societies institutions draw the rules and frameworks within which we live and conduct our activities. In regards to pollution, one can expect that a higher institutional quality will contribute towards a reduction in CO2 emissions (Bhattacharya et al., 2017). Similarly, increased democracy and social participation construct channels through which environmental performance is increased (Laegreid and Povitkina 2018). Furthermore, it is considered that countries which encourage the rule of law along with powerful political rights will, in fact, encourage their citizens to form interest groups, with the common goal of tackling environmental sustainability (Ali et al., 2019; Khan S. A. R. et al., 2020).

Nevertheless, institutional quality can be defined as a broad concept that embodies regulation, public services, control of corruption, political stability and does not benefit of a specific metric (Bruinshoofd 2016). If we were to further expand the concept of institutional quality to a wider "governance" approach, we should include the processes of exerting authority and implementing policies (World Bank, 1994). According to Smith (2007), good governance implies effective public policy and structures, as well as a network of economic cooperation.

The identified scientific literature that covers the impact of institutional quality on CO2 emissions presents similar results. Using GMM estimations, it was found that increased institutional quality leads to sustained environmental performance growth in the long run (Tamazian and Rao, 2010; Usman et al., 2020). In line with previously mentioned studies, using ARDL models, it was found that institutional quality reduces the levels of CO2 emissions (Ahmed et al., 2020; Zhan et al., 2021). Moreover, a meta-analysis of Ahmed et al. (2020) concluded that irrespective of the time frame or geographical area, the effect presented earlier persists and remains valid (Goel et al., 2013; Zakaria and Bibi 2019; Lau et al., 2014; Ibrahim and Law, 2016; Christoforidis and Katrakilidis 2021).

Currently, societies mostly rely upon fossil fuels to support their energy demands. Nevertheless, this dependency has proven itself to be a costly one in terms of CO2 emissions (Lotfalipour, Falahi and Ashena 2010; Ayompe, Davis and Egoh, 2021). In terms of the empiric dimensions of this relation, a study of Pachiyappan et al. (2021), shows that increases of 1% in fossil fuels, GDP and population each contribute to around 1% increase in CO2 emissions. Having acknowledged the constant pressure the current status quo exerts upon the environment, the scientific community has recently pointed out towards nuclear energy as a possible alternative. Even if the process of fully switching to nuclear energy dependency might be a slow one, there is proof of long-term benefits in terms of lowered CO2 emissions (Nathaniel et al., 2021; Rehman et al., 2021).

Besides nuclear energy, there is another possible long-term solution that needs to be accounted for, namely politics. Adding the political dimension to institutions which have assumed an environmental commitment (Lober, 1996; Jahn, 1998; Scruggs, 1999; Gallego-Alvarez et al., 2014), we find an increased presence of green parties (Müller-Rommel, 1989). This augmented political presence can be attributed to a more environmentally aware population that is constantly requesting more green-oriented legislation (Dolezal, 2010; Burchell, 2014; Shan et al., 2021). Finally, another identified tool in the race towards zero CO2 emissions is found in big data applications and improved data collection (Dragomir, 2018; Song et al., 2018).

The identified literature on the main determinants of CO2 emissions is noted to highlight similar effects. Firstly, more education, either through higher enrollment (Li et al., 2021) or additional years of education, leads to diminishing levels of CO2 in the long run (Eyuboglu and Uzar, 2021). Secondly, improved governance quality in conjunction with a green political agenda once more will determine increased environmental performance (Bhattacharya et al., 2017). Thirdly and finally, when the two aforementioned factors are deemed insufficient, returning to nuclear energy (Nathaniel et al., 2021).

Can offer important potential benefits, especially in the context of the Ukraine war.

Even if the available literature is significant in number and quality, a study accounting for institutional performance, educational attainment, fossil fuel and renewable energy altogether, in the case of the G20 countries and EU member states is yet to be found. In this regard, the following sections will contribute towards this identified gap.

3 Materials and methods

This paper aims to demonstrate the empirical nexus between environmental performance, measured by carbon dioxide emissions, and education levels together with institutional quality in a society. To achieve this goal, the regression model includes the main variables that reflect the quality of governance (government effectiveness, regulatory quality, control of corruption, and rule of law), together with the education dimension, gross domestic product, renewable energy consumption, fossil fuel energy consumption, and industry.

The panel data was built for the 1995–2020 period, for a set of 43 countries, consisting of all the European Union (EU) members and the Group of Twenty (G20) states (except for some isolated cases where no information was published by statistical institutions). The analysis includes Australia, Canada, Saudi Arabia, United States, India, Russian Federation, South Africa, Turkey, Argentina, Brazil, Mexico, France, Germany, Italy, United Kingdom, China, Indonesia, Japan, South Korea, Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, Greece, Hungary, Ireland, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain and Sweden.

The research design of this paper follows a model proposed by Mavragani et al. (2016) which identifies a positive relation between economic growth and environmental performance. The model was further developed by adding variables capturing the industrial development degree, the population's education level, and the main sources of energy used. Also, instead focusing on the impact of the open market on environmental performance, this model retained the four indicators of the technical quality of governance out of the six proposed in the original analysis. Furthermore, in comparison with the above-mentioned study, the current proposed model does not take into consideration the EPI index as the dependent variable, considering the data limitations for our analysis period. Instead, carbon dioxide emissions were considered as dependent variable to measure environmental performance, with an increase in this dependent variable reflecting the decrease in environmental performance.

The paper uses a regression that combines macroeconomic and institutional variables, presented in Table 1. The data used were collected from different sources, specified below.

The impact of education level on environmental performance of a society was investigated using the linear model shown below.

$$CO2\_EM_{it} = \alpha + \beta_1 EDU_{it} + \beta_2 GDP\_GR_{it} + \beta_3 RNEC_{it} + \beta_4 FFEC_{it} + \beta_5 IND_{it} + \beta_6 GOVEFF_{it} + \beta_7 REGQ_{it} + \beta_8 CCORR_{it} + \beta_9 RLAW_{it} + \mu_i + \varepsilon i_t$$

The regression equation presents CO2_EM it as a dependent variable, followed by the independent variables EDU_{it}, GDP_GR_{it}, $RNEC_{it}$, $FFEC_{it}$, IND_{it}, $GOVEFF_{it}$, $REGQ_{it}$, $CCORR_{it}$ and $RLAW_{it}$ *and* μ_i, which captures the constant effect and particularity of each G20 and EU member i = 1, 2...43, at the time t = 1,2, . . .,T, where T is the observed time in the model and εit is the error term that is correlated with the independent variables. The β_1, β_2, β_3, β_4, β_5, β_6, β_7, β_8 and β_9 are the parameter coefficients and α is the constant.

First of all, in this model, the main independent variable is represented by the *EDU* (the education index), which is an average of mean years of schooling (of adults) and expected years of schooling (of children), both expressed as an index obtained by scaling with the corresponding maxima. *EDU* measures the quality of life and economic development for every country included in our database. Numerous studies have documented the effect of education on environmental performance, according to which countries associated with higher levels of education tend to have lower levels of carbon dioxide emissions (Dutt, 2009). Also, countries with superior levels of education enjoy high-quality government institutions, which in turn positively affects economic growth. Tran et al. (2019) found that human development helps to improve environmental quality.

Secondly, *GDP_GR* (gross domestic product per capita growth) is calculated as the percentage change in the real GDP per capita between two consecutive years. An upper level of *GDP_GR* can be closely related to growth in the

TABLE 1 The variables.

Dependent variable	Abbreviation	Unit	Source
Carbon dioxide emissions	CO2_EM	Metric tons per capita	World Development Indicators (WDI)
Independent variables	Abbreviation	Unit	Source
Education index	*EDU*	Score (0–1)	United Nations Development Programme
Gross domestic product per capita growth	*GDP_GR*	Annual %	World Development Indicators (WDI)
Renewable energy consumption	*RNEC*	% of total final energy consumption	International Energy Agency (IEA)
Fossil fuel energy consumption	*FFEC*	% of total final energy consumption	International Energy Agency (IEA)
Industry (including construction)	*IND*	% of GDP	World Development Indicators (WDI)
Government effectiveness	*GOVEFF*	Score (-2,5;2,5)	World Bank Governance Indicators Database
Regulatory Quality	*REGQ*	Score (-2,5;2,5)	World Bank Governance Indicators Database
Control of corruption	*CCORR*	Score (-2,5;2,5)	World Bank Governance Indicators Database
Rule of law	*RLAW*	Score (-2,5;2,5)	World Bank Governance Indicators Database

modern sectors and industry, motorized transport, and urban areas. This growth is usually based on a higher level of fossil fuel energy consumption, which is the largest driver of global climate change because of the CO2 emissions resulted from burning fossil fuel.

Next, renewable energy consumption (*RNE*) represents the share of renewable energy in total final energy consumption, while *FFE* shows the used energy produced from burning fossil fuels like coal, oil, petroleum, and natural gas products.

IND is another independent variable used here (industry, including construction), which incorporates additional value generated in sectors such as mining, manufacturing, construction, electricity, water, and gas. Additional value is obtained as the net output of a sector, which includes all the outputs excepting the value of the intermediate inputs. The origin of value added is determined by the International Standard Industrial Classification (ISIC) (Metadata Glossary, World Bank).

The model takes into account four more indicators of governance quality, namely: *GOV_EFF* (government effectiveness), *REGQ* (regulatory quality), *CCORR* (control of corruption), and *RLAW* (rule of law).

Government effectiveness (*GOV_EFF*) variable sums up considerations about the quality of public services, the autonomy of civil service regardless of political constraints, and the way in which the government manages to formulate and implement its policies at a high-quality level.

The variable *REGQ* (regulatory quality) refers to laws that fall within the government's capacity to formulate and implement them so as to promote public sector development.

World Bank methodology defines control of corruption (*CCORR*) as perceptions of the extent to which politicians exercise power for their private interest and the public institutions are managed by financially potent people, guided by the increase of their personal gains.

TABLE 2 Descriptive Statistics for the set of 43 members of G20 and EU.

Variable	Obs	Mean	Std. Dev	Min	Max
CO2_EM	1,032	7.982938	4.448722	0.768838	25.6687
EDU	1,075	0.762647	0.116307	0.344	0.943
GDP_GR	1,110	2.207022	3.881688	−14.4643	23.99909
RNE	1,032	15.37741	12.91369	0	54.48412
FFE	886	77.88262	16.53382	13.05622	100
IND	1,109	26.70636	7.879628	9.984704	66.75666
GOVEFF	946	0.914968	0.733177	−0.72703	2.353998
REGQ	946	0.912205	0.696154	−1.07426	2.098008
CCORR	946	0.76552	0.923741	−1.17636	2.469991
RLAW	946	0.832173	0.826222	−1.09756	2.129668

The rule of law (*RLAW*) indicator shows the extent to which both citizens and social players comply with the law in terms of possession rights, courts, the quality of contract enforcement together with the possibility of crime and violence issues.

The institutional variables mentioned above range between -2.5 and 2.5 points. The value of -2.5 points expresses a weak governance, while the value of 2.5 shows a strong governance. Thus, the influences that these independent variables have on the dependent variable after model processing can be found in the section of empirical results.

4 Results

Table 2 summarizes the most important descriptive coefficients of the variables included in the research. Central tendency, dispersion and standard deviation are measured.

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Descriptive statistics show that fossil fuel energy consumption (*FFEC*), which holds 16.53382% of total energy consumption, is the variable with the most significant deviation from the average, This shows that the level of non-renewable energy consumption in the selected countries is the furthest away from their average value. Malta stands out in the top of the countries with significant levels of fossil fuel energy consumption, as no. 1 in 1995, 1996, 1997 and 1999, with 100% of total energy consumption among all the countries in the sample. Saudi Arabia (99.9% of total), Cyprus (97.8% of total) and Poland (96.3% of total energy consumption) follow Malta as countries where fossil fuels had and continue to have an important role in global energy systems. A high level of fossil fuel energy consumption generates a high level of CO2 emissions, that leads to global climate change. At the opposite pole, Sweden, Finland and France, presented the lowest levels of fossil fuel consumption, with Estonia being the country that in 2016 registered the minimum value of 13.05622% of total energy consumption.

The second variable which has a significant standard deviation value is renewable energy consumption (12.91369% of total). A high level of this variable indicates that future decarbonization of energy systems in the next decades will be beneficial. As we can see, the maximum value (of 54.48412%) was reached by India in 1995, yet in the next years, the level of its renewable energy decreased along with the growth of fossil fuel energy levels, which led to ensuing technological, social, economic, and development progress. The same path can be noticed in Indonesia. A better example can be observed in Sweden, which has one of the highest levels of renewable energy consumption (52.8577% of total) that has increased over the years, illustrating lower levels of pollution from 1995 to 2018. Finland is another good example of a country that followed the same path as Sweden. Countries with the lowest levels of renewable energy consumption include Malta (0.0000% of total), Saudi Arabia (0.0066% of total), and the United Kingdom (0.6083% of total), where fossil fuel is the primary source of energy.

Another relevant standard deviation is distinguished in the situation of industry variable (value is 7.879628% of GDP). A high weight of the industrial sector leads to high environmental degradation, according to the studies of Rai and Rawat (2022), Opoku and Aluko (2021), Patnaick (2018), Sunny et al. (2012). Countries like Saudi Arabia (with 66.76% of GDP in 2008), Indonesia (with 48.06% of GDP in 2006) and China (47.56% of GDP) have a significant industry compared with their gross domestic product. At the opposite pole, states with a low industrial weight, such as Cyprus (9.98% of GDP in 2014), Luxembourg (with 10.72% of GDP in 2020) and Malta (with 12.06% of GDP in 2017) are likely to generate lower environmental degradation levels.

The value of standard deviation of carbon dioxide emissions (4.448722 metric tons per capita), suggests a spread influenced by fossil fuel consumption to the detriment of renewable energy. India, Brazil, China and Indonesia recorded in the first years of this analysis low levels of CO2 emissions, yet they were increasingly affected in the last years by the development of industry based on fossil fuel consumption. Over time, this fact leads to environmental degradation. The United States and Luxembourg, known as developed economies, report the maximum values of CO2 emissions during the analyzed period of time.

The lowest levels of standard deviation are found in case of institutional variables and of education index, with the sampled countries showing more homogeneity. The highest levels of these variables were recorded in Finland, Australia, the Netherlands, and Sweden, illustrating strong governance. Saudi Arabia, Indonesia, China and the Russian Federation registered the lowest levels of governance, which might explain their high environmental degradation in the analyzed period.

Lastly, the education index displays the lowest value of standard deviation (0.116307). From 1995 to 2019, all countries followed an upward trend for this measure. In 1995, countries such as India, Indonesia, China, and Turkey displayed a reduced level of education, whereas, in 2019, Germany, United Kingdom, Finland, and Australia reached the maximum value of the education index variable. From year to year, people from these states increased their education level, which led to a superior quality of life that can negatively impact the environment. However, a higher level of education can lead to an improvement in institutional quality, which in turn contributes to a better protection of the environment.

The nature and level of correlation among the variables are presented in Table 3 below.

Table 3 illustrates that the education index, fossil fuel consumption and all institutional variables are positively correlated with the lack of environmental performance, as measured by the levels of CO2 emissions. Nevertheless, there is a negative relationship between GDP growth, renewable energy consumption, industry, and CO2 emissions, thus influencing in a favorable way environmental performance. Overall, we can confirm the absence of multicollinearity, as there is not a strong (larger than 0.7) correlation between variables, except for independent variables capturing governmental quality.

This paper considers the application of panel data regressions in the light of the advantages it has over classic cross-section or time-series data, especially its capacity to capture the complexity of a certain phenomenon, as presented by Hsiao (2006). Further, in view of our database, when applying the Breusch-Pagan Lagrange multiplier (LM) test, the presence of differences across entities was highlighted, therefore the data presents panel characteristics.

When testing the stationarity of the considered variables, both the first and the second generation of unit root tests have been used for analysis, in line with the study of Sini et al. (2022). The results of the panel unit root test are presented in Table 4. The variables rejecting the null hypothesis of non-stationarity at

TABLE 3 Correlation matrix with significance levels.

Variables	*CO2_EM*	*EDU*	*GDP_GR*	*RNE*	*FFE*	*IND*	*GOVEFF*	*REGO*	*CCORR*	*RLAW*
CO2_EM	1.000	—	—	—	—	—	—	—	—	—
EDU	0.456***	1.000	—	—	—	—	—	—	—	—
GDP GR	−0.104***	−0.157***	1.000	—	—	—	—	—	—	—
RNE	−0.483***	−0.237***	0.053*	1.000	—	—	—	—	—	—
FFE	0.229***	−0.102***	−0.056*	−0.665***	1.000	—	—	—	—	—
IND	−0.055*	−0.377***	0.223***	−0.009	0.092***	1.000	—	—	—	—
GOVEFF	0.499***	−0.652***	−0.152***	−0.120***	−0.114***	−0.430***	1.000	—	—	—
REGO	0.497***	−0.687***	−0.123***	−0.142***	−0.115	−0.453***	0.910***	1.000	—	—
CCORR	0.512***	−0.626***	−0.160***	−0.074**	−0.129***	−0.413***	0.956***	0.908***	1.000	—
RLAW	0.497***	−0.653***	−0.161***	−0.088***	−0.116***	−0.434***	0.951***	0.934***	0.957***	1.000

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

TABLE 4 The results of first and second generation unit root tests.

	Fisher ADF—First generation unit root test		**Pesaran CADF—Second generation unit root test**	
Variable	**Level**	**First difference**	**Level**	**First difference**
CO2_EM	4.4558	−25.2445***	4.771	−17.117***
EDU	−3.7543***	−17.5205***	−0.941	−14.339***
GDP_GR	−10.6047***	−28.9599***	−9.336***	−22.860***
RNEC	7.2640	−23.3200***	0.350	−19.673***
FFEC	5.5805	-19.9008***	3.841	−15.119***
IND	0.8711	−24.0145***	0.092	−17.876***
GOVEFF	−1.4098*	−23.7128***	−0.670	−16.494***
REGQ	−3.1760***	−23.9484***	−2.502***	−16.388***
CCORR	0.5558	−21.4037***	−1.265	−13.734***
RLAW	−1.5564*	−23.9497***	−0.130	−16.813***

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

1% significance levels are the variables that capture education level, economic growth, and regulatory quality when considering the Fisher type unit root test for panel data with augmented Dickey-Fuller unit root tests on each panel with zero lags. Governance efficiency together with rule of law variable reject the null hypothesis of non-stationarity at the significance threshold of 10%. Using the second generation Pesaran test for unit roots accounting for heterogenous panels with cross-section dependence, only economic growth and regulatory quality variables are stationary at first level.

When the first difference of the considered variables is taken into account, they all become stationary at a 1% significance level, also confirmed by the second generation Pesaran stationarity test.

Furthermore, the Kao panel cointegration test is used to examine the long-run equilibrium between variables. The Kao test proved a long-run relationship between variables, considering the Kao ADF (Augmented Dickey Fuller) statistic of 6.5521, significant at 1% level, with a p-value of 0.0000.

This research uses for the estimations the following three methods with this panel data regression model: Pooled ordinary least squares (Pooled OLS), Fixed effects model (FEM) and Random effects model (REM), together with a two-step dynamic GMM model to address the endogeneity issue as well. Those techniques mentioned before are the most frequently used techniques, also found in the other similar relevant research papers. Each of them has advantages as well as limitations.

Pooled OLS, which considers all the countries homogeneous, has also one important shortcoming. Individual characteristics of the countries are represented by the constant and the error term that are

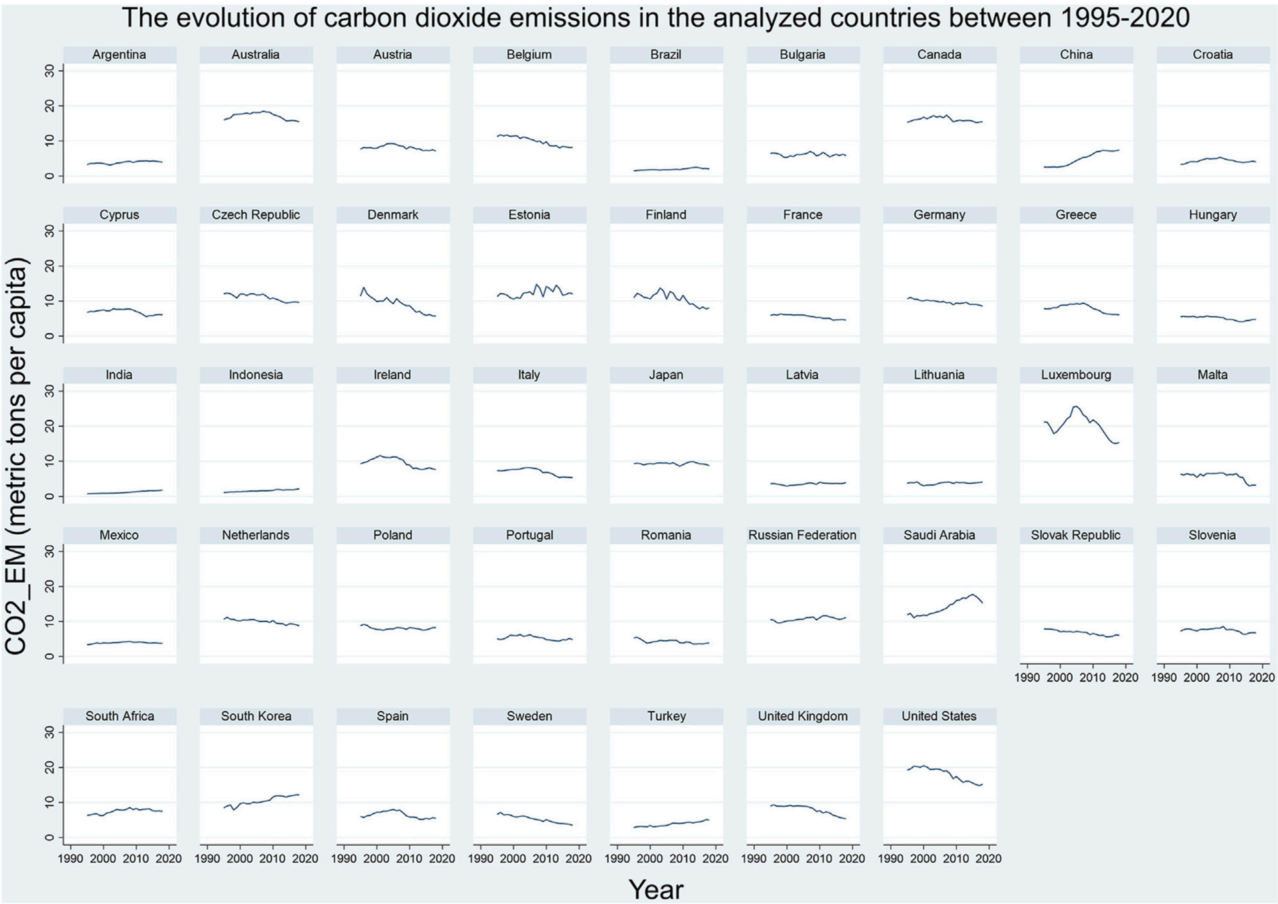

FIGURE 1
Representation of panel data- CO2 emissions by countries for the period 1995-2020.

not correlated with the others. It is already known that this particular method can lead to erroneous estimates when correlations between individual elements and independent variables are not controlled.

The fixed effects model differs from the random effects model in that the former investigates the explanatory variables as non-random. FEM is often used to illustrate the type of impact variables which changes from year to year, and it is considered necessary to check if individual characteristics can affect the variables. The net effect of the independent variables may be evaluated using FEM, whose primary function is to eliminate the influence of these time-independent factors from the independent variables.

According to Greene (2008), the fundamental difference between FEM and REM is the link between individual effects and the regressors in the model. When these effects are random with the independent variable, REM is more appropriate to be used, but if there is a correlation between them, FEM is best suited.

There are some tests that can be used when it is time to choose between these three methods. F test (based on Lagrange Multiplier) is used for the decision to select pooled OLS or FEM and Hausman test is used to choose between REM or FEM. Next, to illustrate how the variance of the FEM model is not homogeneous, the Breusch- Pagan test was applied.

Figure 1 below summarizes these considerations for the sampled countries.

As we can see in Figure 1 There is a sign of heterogeneity between countries because the confidence interval for each country has different widths and the graph has significant oscillations.

Table 5 below presents the regression results.

Evaluation of the pooled OLS regression model

From the Pooled OLS regression in Table 5 it results that education has a negative impact on environmental performance during the analyzed period, impacting in a positive manner *CO2 emissions*. Moreover, looking at the probabilities, variables such as education index, renewable energy consumption, industry, and control of corruption are significant for this model. The value of R-squared shows the amount of variance of environmental

TABLE 5 Regression results.

Dependent variable	(1)	(2)	(3)	(4)	(5)	(6)
CO2_EM	OLS	REM	FEM	LSDV	PCSE	TWO-STEP GMM
EDU	4.754**	4.140***	4.141***	4.141***	5.951***	12.53**
	(1.605)	(0.683)	(0.684)	(0.684)	(1.431)	(4.211)
GDP_GR	−0.0135	−0.0126	−0.0131	−0.0131	0.0218*	0.0394**
	(0.0333)	(0.00860)	(0.00856)	(0.00856)	(0.00846)	(0.0121)
RNEC	−0.130***	−0.115***	−0.110***	−0.110***	−0.104***	−0.353***
	(0.0149)	(0.0117)	(0.0119)	(0.0119)	(0.0140)	(0.0970)
FFEC	0.0105	0.0702***	0.0776***	0.0776***	0.0283	0.155*
	(0.0109)	(0.0113)	(0.0116)	(0.0116)	(0.0150)	(0.0683)
IND	0.112***	0.107***	0.111***	0.111***	0.0575***	-0.0739
	(0.0176)	(0.0143)	(0.0145)	(0.0145)	(0.0165)	(0.0639)
GOVEFF	−1.253	0.720***	0.692**	0.692**	0.237	−3.839
	(0.641)	(0.212)	(0.211)	(0.211)	(0.259)	(2.215)
REGQ	0.610	0.495*	0.500*	0.500*	0.257	1.416
	(0.527)	(0.202)	(0.202)	(0.202)	(0.281)	(1.466)
CCORR	2.690***	0.0142	−0.121	−0.121	1.155***	2.275
	(0.540)	(0.221)	(0.222)	(0.222)	(0.286)	(1.893)
RLAW	0.363	−0.224	−0.351	−0.351	0.401	−0.586
	(0.602)	(0.278)	(0.280)	(0.280)	(0.328)	(0.672)
L.CO2_EM	—	—	—	—	—	−0.148
	—	—	—	—	—	(0.101)
_cons	0.832	−2.585	−3.078*	3.340*	−0.349	−4.789
	(1.907)	(1.381)	(1.294)	(1.473)	(2.031)	(9.705)
N (Obs.)	713	713	713	713	713	713
R^2	0.497		0.507	0.976	0.748	—

Standard errors in parentheses.
* $p < 0.05$,
** $p < 0.01$,
*** $p < 0.001$

performance explained by the independent variables, and as such exogenous variables explain 49.70% of carbon dioxide emissions' variance. Furthermore, an increase of a unit of education index will lead to an increase of *CO2 emissions* by 4.754 metric tons per capita and also, a change of one unit of industry variable or control of corruption will determine an increase of carbon dioxide emissions by 0.112 metric tons per capita and 2.690 metric tons per capita respectively. The negative impact on the *CO2 emissions* is led by renewable energy consumption whose growth with a unit will decrease *CO2 emissions* by 0.130 metric tons per capita.

Evaluation of the random effects model (REM)

Table 5 (column 2) presents the results of the evaluation random effects method and also illustrates the positive impact of education on *CO2 emissions*, and the variables *EDU, RNEC, FFEC, IND, GOVEFF* and *REGQ* as statistically significant in the model (*p-value<0.001*). Withal, the table illustrates how variables significantly affect the environmental performance. The value of *Wald chi2* reveals the model explains 50.54% of the dependent variable, respectively the variance of CO2 emissions.

Evaluation of the fixed effects model (FEM)

In light of using the Fixed Effects method for the 43 set of countries, (all European Union members and Group of Twenty - G20 states), it is easily noted that education has a positive impact on CO2 emissions and that all the variables (except *GDP_GR, CCORR* and *RLAW*) have some significant impact on environmental performance. The value of *R-squared* reveals that the estimated model explains 50.70% of the variance of the *CO2 emissions*. Because the *p-value* of the education index is 0.0000, education is statistically significant, thus a change of one unit of the education

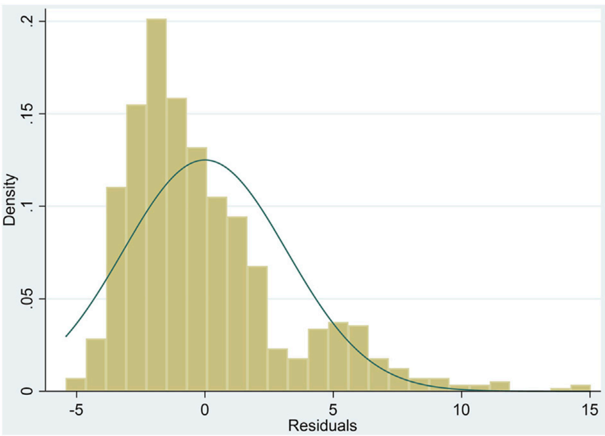

FIGURE 2
Residual control for the FEM

index will increase carbon dioxide emissions by 4.141 metric tons per capita. A growth of fossil fuel energy consumption, industry, government effectiveness or regulatory quality with a unit increases CO2 emissions by 0.077 metric tons per capita, 0.111 metric tons per capita, 0.692 metric tons per capita and 0.5 metric tons per capita. Meanwhile, one unit modification of renewable energy consumption contributes to a decrease in carbon dioxide emissions by 0.11 metric tons per capita.

All three evaluations present alpha test *F value* equal to zero (<0.05) allowing us to reject the hypothesis that the estimated model is significantly invalid, and accept the validity of the model.

Evaluation of residuals

Skewness Kurtosis is a normality test that helps determine the probability that a random variable underlying the data set is normally distributed. The probability of skewness is 0.0000 implying that skewness is not asymptotically normally distributed (*p-value of skewness < 0.05*). Similarly, Pr (Kurtosis) points out that kurtosis is not also asymptotically distributed (*p-value of kurtosis 0.0000 < 0.05*). Finally, *chi* (2) is 0.0000 which is lower than 0.05 implying its significance at a 5% level. Consequently, the null hypothesis can be rejected. Therefore, according to the Skewness test for normality, residuals are not normally-distributed as it is illustrated by Figure 2.

Evaluation of the best model

The results of the statistical tests show that the use of FEM together with a panel corrected standard error regression would be the most appropriate methods of analysis for selected data.

To choose the most appropriate estimation technique, the analysis begins by testing the OLS model, applying the Breusch-Pagan/Cook-Weisberg test for heteroskedasticity (*p = 0.0000 < 0.05*) and the White test for heteroskedasticity (*p = 0.0000 < 0.05*), as well as the testparm command (*p = 0.0000 < 0.05*). The obtained results reject the null hypothesis of homoscedasticity, further indicating that OLS would not be the most significant estimation technique for this sample.

Moreover, performing the Breusch and Pagan Lagrangian multiplier test for random effects to choose between panel data regressions and the classical OLS, it results that the probability (0.0000) is less than 5% also highlighting the fact that heteroskedasticity is present in the data set, rejecting the null hypothesis (residuals are homoscedastic) and proving that there is a panel effect in the considered dataset.

Both the Hausman and Sargan Hansen tests allow selecting between FEM or REM, and the null hypothesis (H0) reveals the random effects model is more efficient as compared to the alternative fixed effects (see Greene, 2008, chapter 9). In light of the *Chi-square* statistics of the Hausman test (17.27) and of the probability value (*p value =0.0447 < 0.05*) the null hypothesis is rejected and thereby the fixed effects model is more efficient than the random effects model for this analysis.

The fixed effects model with dummy variables (LSDV) was also performed, which included a dummy variable that absorbed the specific influence of each country. This allowed for estimating the pure impacts of each independent variable on the *CO2_emmissions* variable, while simultaneously correcting for unobserved variation between nations. When applying the LSDV model, the significant independent variables affecting environmental performance are education, industry, fossil fuel energy, and renewable energy at a significance threshold of 0.1%, while regulatory quality is significant for the upper threshold of 5%, and governmental efficiency for the 1% threshold.

However, to correct the limitations of the FEM model (groupwise heteroskedasticity, autocorrelation in panel data and cross-sectional independence) emphasized by the modified Wald test, Wooldridge test, as well as Pesaran's test, with all three *p values < 0.05* threshold, a panel-corrected standard errors regression (PCSE) was applied.

In the PCSE scenario, the estimates indicate that education, industry, control of corruption and economic growth, have a positive impact on carbon emissions (at a significance level of 0.1 and 5% respectively), deterring the environmental performance of the considered sample, while a change of one unit in renewable energy, impacts negatively *CO2 emissions* with a significance threshold of 0.1%, increasing environmental performance (Supplementary Appendix S1).

Furthermore, to control for endogeneity in the considered panel, the generalized method of moments technique (GMM) is applied. The two-step difference GMM is utilized, considering that it is more efficient and robust to the issues of heteroscedasticity and autocorrelation in the panel (Roodman, 2009). The results emphasize that education, together with economic growth positively impacts CO2 emissions, at a 1% significance level, while the use of fossil fuels increases air pollution at a 5% significance level. However, one unit increase in the consumption of renewable energy decreases CO2 emissions by 0.353 metric tons per capita in the 43 considered states, at a 0.1%. Significance level The Arellano and Bond autocorrelation test AR (2) indicates the absence of second-order serial correlation in the residuals of the model. Moreover, the Sargan-Hansen tests for over identifying restrictions emphasize the validity of the model and used instruments.

5 Discussions

The results obtained emphasize that education, economic growth, and industry, together with the control of corruption variable, manifest a positive significant impact upon the *CO2 emissions*, thus affecting environmental sustainability in the PCSE scenario of the analysis. Other institutional quality variables such as governmental efficiency, regulatory quality, and the rule of law also exert a positive impact upon *CO2 emissions*, although not significant in statistical terms. In the PCSE hypothesis, renewable energy consumption is the only independent variable sustaining environmental performance at a significant level, considering the selected sample. In light of FEM methodology, besides renewable energy consumption, variables such as economic growth, control of corruption, and rule of law are the determinants of environmental performance. When accounting for endogeneity, education, economic growth and fossil fuel energy consumptions are the main significant determinants of CO2 emissions, whereas renewable energy consumption has a significant positive impact on environmental performance.

In all three scenarios (LSDV, PCSE, and GMM), considered the most relevant from a statistical point of view, as argued in the results section, higher education seems to be one of the causes of increasing *CO2 emissions*. The results are in line with those of Eyuboglu and Uzar (2021), who, through a vector error correction model (VECM) applied to Turkey, proved that education is positively associated with *CO2 emissions* and stress that education policies can be employed to address environmental issues, considering that their study confirmed the long-term effect of higher education on *CO2 emissions*. The authors argue that *CO2 emissions* and environmental damage may grow throughout the development of educational capacity, particularly with increasing energy consumption, highlighting the need for an integrated education policy leading to an improved human capital quality, which can prevent environmental degradation by enhancing environmental innovations and boosting environmental awareness.

Furthermore, the aforementioned authors point out the long-term and short-term positive influences on *CO2 emissions* of both economic expansion and energy consumption for Turkey, as also demonstrated in the current study for the 43 countries of the G20 group.

Moreover, Gangadharan and Valenzuela (2001) and Hill and Magnani (2002), found that higher levels of education drive to an increasement of using polluting technologies, which utilize non-renewable resources and, in the end, can lead to a degradation of the environment. Improving the level of education can influence the increase of the population's income, which in turn facilitates the use of polluting technologies and negatively impacts the environment.

The positive impact of economic performance on environmental degradation was also confirmed by numerous studies in the literature (Azomahou et al., 2006; Aye and Edoja, 2017; Paramati et al., 2017; Dauda et al., 2019; Anwar et al., 2020). This study reinforced this assumption by centering around a more recent database and a wide range of countries. The results of these studies have had real implications for economic and environmental policymaking among the world's countries. The paradigm shift in what was first referred to as sustainable economic growth, which put at the center of the concept the efficient use of economic resources to ensure performance in key economic sectors, is now transformed into a post growth, green growth, or degrowth policy, focusing on economic growth through the use of renewables and the implementation of more efficient and sustainable manufacturing methods, abandoning the use of only the GDP indicator as a metric of economic performance. On the other hand, Lee and Thiel (2017) demonstrate in their study that an increase in GDP does not have any significant impact on the Environmental Performance Index when applying the latent growth curve model.

Renewable energy consumption significantly improves environmental performance in the considered G20 sample, in accordance with the findings of York and McGee (2017), proving that countries that use a higher share of renewable energy resources have lower *CO2 emissions*, in comparison with the countries that still rely on classic energy sources. The study of Silva et al. (2012) through a structural autoregressive methodology proved that, even though it imposes significant costs on GDP, renewable energy significantly increases environmental performance. Moreover, Khan Z. et al. (2020) argue the use of renewable energy in logistics improves environmental sustainability and also provides greater export chances in environmentally friendly nations, promoting long-term green economic growth.

Furthermore, the study of Dauda et al. (2019) proves that energy consumption is one of the major causes of *CO2 emissions*. The paper of Gani (2021) concludes the urgent need for the "world's fossil fuel energy-dependent countries" to adapt to the development and use of renewable energy sources to prevent environmental damage. Our study is in line with the aforementioned papers, pointing out the significant negative influence of the fossil fuel energy consumption on environmental performance. The study of Zhang and Lin (2012) indicates the direct link between urbanization and increased energy consumption in the case of China, manifesting a positive impact on *CO2 emissions*. In the current context of a continuously growing and developing society, policymakers should prioritize urban planning and the use of renewable energy consumption to make significant contributions to both the use of classic energy sources while also fighting against climate change, as stated by Shafiei, and Salim (2014), which also conclude that the use of green energy decreases carbon footprint, while classic, non-renewable energy consumption increases air pollution and environmental performance.

The results of the panel regression methodology indicate that a one-unit growth in industrialization determines the increase in *CO2 emissions* at a significant level when considering the PCSE approach. The results are in line with the estimation presented in the paper of Li and Lin (2015), who proved through a Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) framework that industrialization reduces energy consumption, but increases *CO2 emissions*, in comparison with urbanization, which raises energy consumption as well as the carbon footprint drastically, when analyzing the middle low-income and high-income groups of countries. The same hypothesis is sustained by Shabaz et al. (2014), who studied the link between industrialization and emissions in Bangladesh, Raheem and Ogebe (2017) who studied the effects of industry and urbanization on CO2 emissions for a sample of twenty African countries in the last decades, and the paper of Liu and Bae (2018), who studied the implications of industrialization in China through a autoregressive distributed lag approach. However, the study of Lin et al. (2015), in which the authors analyzed the impact of industrialization on air pollution in the case of Nigeria, emphasized that industry has an inverse relationship with *CO2 emissions* for the considered sample. Moreover, analyzing the issue from the perspective of the ICT industry, Zhang and Liu (2015), conclude that this particular industry significantly reduces China's carbon footprints.

The independent variables capturing institutional quality manifest a positive, however not significant impact on *CO2 emissions* in the PCSE model of our analysis, except for the control of corruption variable, which is significantly correlated with *CO2 emissions* at a 0.1% level of significance. In the FEM, control of corruption manifests a negative impact on the G20's carbon footprint, increasing environmental performance even though not statistically significant, but even in this scenario, the results are inconclusive regarding the link between institutional quality and environmental performance, in line with the findings of Ahmed et al. (2020). However, the positive coefficients of these variables are in contrast with the results obtained by Mavragani et al. (2016), who concluded that good and effective governance increases a country's environmental performance. Moreover, the findings of Musa et al. (2021) emphasize that to mitigate the possible detrimental effects of economic expansion and also tourism on environmental performance, institutional quality might be investigated and strengthened. Furthermore, an important point to consider when addressing this issue was highlighted by Tamazian and Rao (2010), who demonstrated that if it were not for a solid institutional and governmental structure and governance, financial liberalization may be detrimental to environmental quality.

6 Conclusions and policy recommendations

The present research has started from the following question: How significant are, amongst other variables, education together with the quality of institutions in establishing our sustainable green future?

After applying the research methodology, the main results show that all the independent variables that capture institutional quality from a technical point of view, included in the model, have a direct and positive link to the level of *CO2 emissions*, with control of corruption variable being the only one influencing in a positive manner *CO2 emissions* at a significant level, in the PCSE scenario. In the FEM scenario, government effectiveness, together with regulatory quality are the institutional quality variables that impact carbon emissions at a significant level. Education level, together with economic growth, fossil fuel energy consumption and industry, also resulted in having a negative significant impact upon environmental performance, an increase of one unit in these variables contributing to increased carbon dioxide levels in the EU and G20 sample when considering both the panel corrected model as well as the GMM scenario. Renewable energy is the only independent variable manifesting a significant positive and direct link with environmental performance, drawing attention to the need of adapting the primary sources of energy, in line with the sustainable development policy recommendations of international organizations. The current study's primary limitation might be referred to as its methodology approach, considering that it does not account for a quantile approach, which might be suitable for analyzing the impact of the independent variables on environmental performance at different levels of registered *CO2 emissions*. A future study that accounts for these particular aspects is being taken into consideration. Moreover, there is a need to deepen the empirical link between education level, institutional quality, and their impact on environmental performance, however, we hope that our analysis can be taken as a reference point in the elaboration of the following studies and will promote enhanced future research.

Another limitation that can be viewed as a good starting point for an additional analysis refers to the period of time used, which can be considered slightly short. This fact may be a barrier to the generalization of obtained results.

The main results of this study, namely that economic growth, education, energy consumption, and industry impact in a negative manner environmental performance, and that renewable energy consumption have a positive impact on this performance, are important points to consider for policymakers. Therefore, a sustainable solution to the environmental problems would be to raise the level of renewable energy consumption in all countries by promoting it.

The idea of using as many natural renewable resources as possible would contribute to improving eco-friendly transportation facilities and even the use of fuel-efficient production technologies without ruining forests or contaminating water and air. This approach to green growth and development is the solution to reduce the poverty level in analyzed countries without affecting the environment.

Through a well-defined legislative framework, economic policies should aim at achieving high levels of economic performance, without referring only to long-term economic growth and financial gain, strictly observing already imposed environmental policy measures and further highlighting the need to transition to a renewable energy society, which can only be achieved through coherent and well-defined government and education policies.

Furthermore, a growth built on a higher quality of institutions and of human capital is worth exploring by countries to preserve the environment, because only improvements to these factors can promise less volatile and more sustainable growth.

This can lead to higher per capita incomes, better quality of life based on a balanced natural ecosphere. With the aim of achieving both green environment and economic growth, to the levels of governments there is a need of devoting enough resources to sustain regulatory quality and corruption control, enforce the rule of law, and assist governance effectiveness.

Changes and policies to adapt the economy to an eco-friendlier and greener economic environment are being felt among countries, however, the pace of environmental degradation is rapid and needs direct and concrete action, which cannot be delayed.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, GD, MB, CN; methodology, GD, MB and CN; software, MB and CN; validation, GD and DD; formal analysis, GD, MB, CN and DD; investigation, MB, CN, DD, and LM; resources, GD, MB, CN, DD, and LM; data curation, MB, CN, and DD; writing—original draft preparation, GD, MB, CN, DD, and LM; writing—review and editing, GD, DD, CN, and MB; visualization, CN and MB; supervision, GD, MB, and CN; project administration, GD and MB All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.950683/full#supplementary-material

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Can the technologically advanced policy achieve green innovation of small and medium-sized enterprises?—The case of China

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The purpose of this study is to apply a multidimensional fixed-effects difference-in-differences (DID) model to empirically examine the impact, policy mechanism, and heterogeneity of Technologically Advanced Policy (TAP) on green innovation in small and medium-sized enterprises (SMEs) based on the data of China's A-share listed companies from 2004 to 2021. The results show that TAP significantly improves the green innovation level of listed companies on the small and medium-sized board, and has a more significant role in promoting technologically advanced enterprises (TAEs). The results of the policy effect are still robust after the placebo test, changing the dependent variable, and controlling for the influence of the environmental inspection system, the emissions trading system (ETS), and the carbon emissions trading system (CETS). Furthermore, we find that the policy effect of TAP is better in state-owned SMEs and SMEs in the eastern, central, and western regions. In addition, further research shows that the green innovation effect of TAP is mainly realized through mechanisms such as government subsidies, tax reduction, credit financing, and market competition. Moreover, state-owned SMEs have obvious advantages in the three mechanisms of government subsidy, tax reduction, and market competition, while private SMEs only have significant advantages in credit financing mechanisms. Overall, our findings show that TAP has achieved policy effects in promoting green innovation for SMEs in China, but state-owned SMEs still receive significant policy preference. It is recommended that future policy reforms favor private SMEs.

KEYWORDS

technologically advanced policy (TAP), small and medium-sized enterprises (SMEs), green innovation, difference-in-differences (DID), government subsidy, tax reduction, credit financing, market competition

1 Introduction

To cope with environmental pollution, climate change, and the increasingly complex international political, economic, and trade situation, the Chinese government has put forward high-quality development requirements for its economy (An et al., 2021; Zhao et al., 2021; Ge et al., 2021), that is, to transform from extensive development with high pollution and high emissions to green and sustainable quality development (Su et al., 2022; Yuan et al., 2022). As the largest economic entity in economic and social development, small and medium-sized enterprises (SMEs) are the key to expanding employment, improving people's livelihoods, promoting green innovation and development, and then realizing economic transformation in China (Yu and Fu, 2021; Dai et al., 2021). According to Sixlens data, by the end of 2020, the number of SMEs in business in China exceeded 42 million, accounting for more than 98% of the total number of Chinese enterprises (Zhang et al., 2021). However, there is still a big gap between the innovation and development of SMEs and the leading large enterprises (Zhu et al., 2012). By the end of 2020, only 1.011 million Chinese SMEs had patents, accounting for only 2.4%. In Guangdong Province, which has the largest number of SMEs (5.865 million), SMEs with patents only account for 3.4%, which shows that the innovation and development situation of SMEs is not optimistic (Jia et al., 2020; Zheng et al., 2021). Therefore, the Chinese government has issued a series of economic policies to help SMEs quickly promote green innovation and development (Sizhen et al., 2005; Min et al., 2021; Wang and Kesan, 2022). In July 2013, China's Ministry of Industry and Information Technology issued the "Guiding Opinions on Promoting the Development of Technologically Advanced Small and Medium-sized Enterprises", which aims to guide SMEs to carry out technological innovation, management innovation, and business model innovation, and cultivate new growth points, to form new competitive advantages and improve the overall quality of SMEs. And from 2019 to 2021, three batches of technologically advanced "little giant" companies have been announced, and it is planned to form 1 million innovative SMEs and 100,000 ″technologically advanced" SMEs during the "14th Five-Year Plan" period (Zhang et al., 2022; Dong and Li, 2021; Li, 2021). Therefore, an in-depth understanding of the processing effect of Technologically Advanced Policy (TAP) will help the Chinese government more effectively use policy tools to promote green innovation in SMEs to meet the challenges of green and sustainable development under complex climate conditions.

According to the existing researches, few scholars have conducted an empirical analysis on whether the Chinese government's TAP can play a role in promoting the SMEs' green innovation (Zhang et al., 2022). On the one hand, China's TAP has a long time span and involves a wide range of areas making it difficult to simply judge the policy effect. In theory, such policies may not only promote the high-quality development of SMEs, but also have a dampening effect due to the green requirements of the policy. On the other hand, China's TAP is rich in content, diverse in policy intervention methods, and the channels through which policy effects are exerted and the heterogeneity of policy effects are relatively complex (Yu et al., 2016).

To better solve the above problems, we manually collected the green patent data of SMEs, and matched it with the CSMAR listed company Database to obtain the green patent data set of listed companies including SMEs, and constructed the TAP variable, using a variety of estimation methods including the difference-in-differences (DID) method with multi-dimensional fixed effects to examine the influence, mechanism and heterogeneity of policy effects of China's TAP on green innovation of SMEs.

Our contributions are mainly reflected in the following three aspects: Firstly, we enriched the research on the influencing factors of SMEs' green innovation. There is abundant theoretical and empirical literature on enterprise green innovation (Zhou et al., 2021; Du et al., 2022), but there are few works of literature on the evaluation of relevant policy effects of SMEs' green innovation (Iqbal et al., 2021), especially the research on the impact of TAP on SMEs' green innovation. We use the small and medium-sized board of Chinese A-share listed companies and other listed companies to form a treatment group and a control group, combined with the TAP implementation time treatment variable, and confirm the positive effect of the Chinese government's introduction of TAP through empirical testing. Secondly, we try to use a variety of causal identification methods, such as the DID method with multi-dimensional fixed effects, the difference-in-difference-in-differences (DDD) method, etc. to estimate Chinese TAP effects, mechanisms, and heterogeneity. Thirdly, we further examine the effect of Chinese TAP on the cultivation of technologically advanced SMEs and technologically advanced "little giants". The above research provides ideas for subsequent scholars to evaluate the effects of similar SMEs' stimulus policies introduced by other countries or regions.

The rest of this paper is organized as follows: Section 2 discusses the policy background and theoretical analysis. Section 3 presents the methodology and data. Section 4 presents the empirical results of the benchmark model and robustness tests. Section 5 is an in-depth analysis of the mechanism. Section 6 is the investigation of policy heterogeneity. The last part is the discussion and conclusions.

2 Policy background and hypothesis

With global climate change, the intensification of Sino-US trade friction, and the global abuse of COVID-19, China's green innovation development is facing severe challenges. The Chinese government urgently needs to speed up the solution of green innovation problems, and gives full play to the supporting role of macroeconomic policies in the high-quality development of "technologically advanced" SMEs (Dong and Li, 2021; Zhang et al., 2022). In July 2013, China's Ministry of Industry and Information Technology issued the "Guiding Opinions on Promoting the Development of Technologically Advanced Small and Medium-sized Enterprises", and it put forward opinions on promoting the development of "technologically advanced" SMEs from the perspectives of overall thinking, key tasks, and promotion measures, and called for strengthening the cultivation and support of "technologically advanced" SMEs. In July 2021, the Politburo meeting of the CPC Central Committee emphasized the need to strengthen technological innovation and the resilience of industrial and supply chains, and to develop "technologically advanced" SMEs. China's central and local governments have introduced a series of "technologically advanced" policies on fiscal and taxation, direct financing, credit, government procurement, and technological innovation. By the end of 2021, China has cultivated 4,762 national-level technologically advanced "little giant" enterprises, driving more than 40,000 provincial-level "technologically advanced" SMEs, and 117,000 warehousing enterprises, involving more than 30 sub-sectors. At the beginning of 2022, the government work report of China's Two Sessions once again proposed to "focus on cultivating 'technologically advanced' enterprises, and provide strong support in terms of funds, talents, incubation platform construction, etc." (Dong and Li, 2021; Li, 2021).

TAP pointed out the key tasks (targets): to enhance the technological innovation capabilities of enterprises; to give play to the role of SMEs as the main body of innovation; to encourage SMEs to continuously increase investment in R&D and technological transformation; to improve the ability of independent innovation, integrated innovation and introduction, digestion, absorption, and re-innovation; and to enhance the driving force of innovation-driven development. Based on the above policy content and literature (Zhang et al., 2022), we propose the core hypothesis of this study:

H_1: TAP will increase the level of green innovation of SMEs.

In addition, according to the content of the policy document, we summarize the main measures of TAP:

①Fiscal and taxation support. Give full play to the guiding and supporting role of special funds and funds at all levels to support the development of SMEs, increase support for technological progress and technological transformation of SMEs, focus on supporting "technologically advanced" technologies and products, and cultivate "technologically advanced" SMEs. Implement incentive policies to support the innovation and development of SMEs, such as pre-tax deduction of corporate R&D expenses and accelerated depreciation of eligible fixed assets. Accordingly, based on the above policy content and literature (Li and Wang, 2022; Wang and Kesan, 2022), we propose the first hypothesis about the policy effect mechanism:

H_2: Fiscal and taxation policy support is an important mechanism for TAP to enhance the green innovation level of SMEs.

② Financial support. Broaden the financing channels to support the technological innovation of SMEs, build a financing service platform, and facilitate the connection of projects between banks and "technologically advanced" enterprises. Encourage banking financial institutions to innovate in financial products and services, and support "technologically advanced" SMEs to take credit loans and other means of financing. Accordingly, we propose a second hypothesis about the policy effect mechanism (Zhang et al., 2022):

H_3: Credit financing support is an important mechanism for TAP to enhance the green innovation level of SMEs.

③Enhance competitiveness. Establish and improve the service system, organize market development activities, strengthen the cultivation and promotion work, actively carry out the work of promoting the "technologically advanced" development of SMEs, cultivate and identify a batch of "technologically advanced" SMEs, and enhance industrial competitiveness. Accordingly, we propose a third hypothesis about the policy effect mechanism (Han, 2022):

H_4: Enhancing market competitiveness is an important mechanism for TAP to enhance the green innovation level of SMEs.

3 Methodology and data

3.1 Methodology

For credible identification of policy effects, we mainly use the DID method (Card and Krueger, 1994; Goodman-Bacon, 2021) with multi-dimensional fixed effects and the DDD method (Huang and Chen, 2022; Wang et al., 2021) to investigate the impact of TAP on the green innovation of SMEs, especially technologically advanced enterprises. Specifically, this study uses the TAP year as the first difference to compare the impact before and after the policy implementation; SMEs are used as the second difference to examine the impact of policy implementation on SMEs, while non-SMEs have no significant or no impact; taking technologically advanced enterprises as the third difference, compare whether the impact of technologically advanced enterprises is different from that of non-technologically advanced enterprises. Accordingly, we constructed the following DID model to test the impact of TAP on the green innovation of SMEs:

$$Gap_{ijt} = \beta \underbrace{Post_t \times Treat_i}_{DID_{it}} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + Year_t + \varepsilon_{ijt} \quad (1)$$

Further, we construct the following DDD model to examine the impact of TAP on technologically advanced firms in SMEs:

$$Gap_{ijt} = \delta \underbrace{Post_t \times Treat_i \times TSE_m}_{DDD_{imt}} + \sum_k \eta_k X_{jk(t-1)} + Firm_i + Province_j + Year_t + \varepsilon_{ijt} \quad (2)$$

In the above two models, $\{i,m\}$represents the listed company, j represents the province, and t represents the year. Gap_{ijt} is the dependent variable, and represents the green innovation level of the listed company. $Post_t$ is the policy time dummy variable. $Treat_i$ is the dummy variable of the treatment group (whether the company is listed on the SME board). TSE_m is a dummy variable of whether it is a technologically advanced enterprise. $X_{jk(t-1)}$ is the control variable with a lag of one period. $Firm_i, Province_j, Year_t$ represents the individual, province, and time fixed effect items, respectively. ε_{ijt} is the error term.

3.2 Variables

1) *Dependent Variable*. Referring to the studies of Li and Zheng (2016), Wang and Wang (2021), etc., we use the number of green patent applications of listed companies to measure the level of corporate green innovation. Liu and Xiao (2022) believe that, firstly, compared with green patent data, it is difficult for researchers to obtain green innovation R&D data from enterprise-level R&D data, while green patent data can be accurately obtained through matching multiple databases. Secondly, because green patent application data is more reliable and timelier than patent grant data and other metrics, patent granting often requires a relatively long processing and certification cycle, with serious lag, but patent application data does not have this problem. Specifically, the number of green patent applications of listed companies is obtained by adding up the number of green invention patents and green utility model patents of listed companies. In addition, in the follow-up research, we will conduct a robustness test with the number of green invention patents and green utility model patents of listed companies as proxy variables of the dependent variable. To eliminate the obvious right-skewed distribution problem of green patent data of listed companies, we take the natural logarithm of the number of patents plus 1 to obtain the dependent variable Gap_{ijt} of this study and $Indgap_{ijt}$, $Giap_{ijt}$ in the robustness test.
2) *Key Explanatory Variable*. The key explanatory variable in the benchmark model (1) is the multiplication term of the dummy variable of TAP time and the dummy variable of the treatment group of whether the company is listed on the small and medium board. $Post_t$ is the TAP time dummy variable, which takes the value of 0 before the implementation of the policy, that is, before 2013, and 1 after the implementation of the policy. $Treat_i$ is a dummy variable of the treatment group, and it is 1 if the company i belongs to a listed company on the small and medium board; otherwise, it is 0. The key explanatory variables in model (2) are the policy multiplication term DID and the DDD term of the technically advanced enterprise dummy variable. TSE_m is a dummy variable of a technologically advanced enterprise or not. When enterprise m belongs to a technologically advanced enterprise announced by the government, the value is 1; otherwise, it is 0. A company listed on the SME board is a listed company whose stock code starts with 002 in A-shares listed on the Shenzhen Stock Exchange. Technologically advanced enterprises are obtained by matching the lists of three batches of technologically advanced small giant enterprises announced by the Chinese government from 2019 to 2021 with small and medium-sized enterprises. What we care about is the coefficient β of $Post_t \times Treat_i$ and the coefficient δ of $Post_t \times Treat_i \times TSE_m$. If $\{\beta, \delta\}$ is greater than 0, it indicates that TAP significantly promotes the green innovation of SMEs, and less than 0 indicates that it significantly inhibits the green innovation of SMEs.
3) *Control Variables*. To control the potential confounding factors that may affect the green innovation of enterprises and obtain a more reliable policy effect estimation result, we refer to Qi et al. (2018) to control the following firm-level variables: ① Enterprise size (*Size*); ② asset-liability ratio (*Lev*); ③ Return on assets (*ROA*); ④ Enterprise TobinQ (*TobinQ*); ⑤ Enterprise age (*FirmAge*). In addition, we also control for province fixed effects, firm individual fixed effects, and year fixed effects, which remove unobservable confounding factors at the regional and firm levels that do not change with time, and time factors that do not change with individuals, respectively, improving the credibility of policy effect estimates.

3.3 Data sources

This paper takes the establishment of the SME board in 2004 as the starting year of the research, and manually collects the green patent data of A-share listed companies from 2004 to 2021. Financial insurance and abnormal trading listed companies (ST and PT listed companies) are excluded, and samples of companies with serious missing variables are also removed. The data sources for this study mainly include two parts: The first is the characteristic data of listed companies. This part of the listed company's financial situation, equity attributes, and other data comes from the CSMRA database, and the data of enterprise R&D investment comes from the Wind and Flush databases. The second is the patent data of listed companies. This part obtains the patent data (including green patents) of listed companies by matching the patent identification of listed companies in the China Research Data Service Platform (CNRDS) with the "Green List of International Patent Classification" issued by the World Intellectual Property Organization (WIPO) (Wang and Wang, 2021). By matching firm feature data with patent

TABLE 1 Descriptive statistics.

Variables	Obs	Mean	Sd	Min	Median	Max
Gap	37,804	0.74	1.114	0.00	0.00	5.34
Indgap	37,804	0.67	1.054	0.00	0.00	5.02
Giap	37,805	0.52	0.942	0.00	0.00	7.23
DID	42,161	0.17	0.379	0.00	0.00	1.00
Size	42,161	22.02	1.287	19.24	21.83	26.43
Lev	42,161	0.43	0.207	0.03	0.43	0.99
ROA	42,159	0.04	0.067	−0.40	0.04	0.25
TobinQ	41,513	1.99	1.361	0.80	1.56	17.73
FirmAge	42,161	2.79	0.398	0.69	2.83	3.61

data, we end up with 42,161 observations. To eliminate the influence of extreme values, this paper performs a 1% winsorize treatment on the main variables.

3.4 Descriptive statistics

Table 1 shows the descriptive statistics of the main variables. The mean value of Gap is 0.74, the standard deviation is 1.114, and the maximum value is 5.34, which indicates that the number of green patent applications varies greatly among the sample listed companies. Similarly, the statistics of $Indgap$ and $Giap$ also show that the level of green innovation among listed companies is quite different.

4 Empirical results

4.1 Parallel trend test

The important premise of using the DID model to identify policy effects is that the policy treatment group and the control group have a significant parallel trend before policy implementation (Huang and Chen, 2022; Wang et al., 2021). That is, before 2013, the green innovation levels of listed companies on the SME board and non-SME board companies should have had a parallel time series trend. Based on the literature (Deschenes et al., 2017; Liu and Xiao, 2022), we use the event study method to carry out the parallel trend test. The model is as follows:

$$Gap_{ijt} = \sum_{m=-7}^{5} \lambda_m Treat_i \times Time_m + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + \varepsilon_{ijt} \quad (3)$$

In model (3), $Time_m$ is the corresponding year dummy variable relative to 2013 For example, m = 3 is 2016, and m = −4 is 2009. λ_m is the coefficient of the difference between the treatment group and the control group affected by the policy effect in the corresponding year.

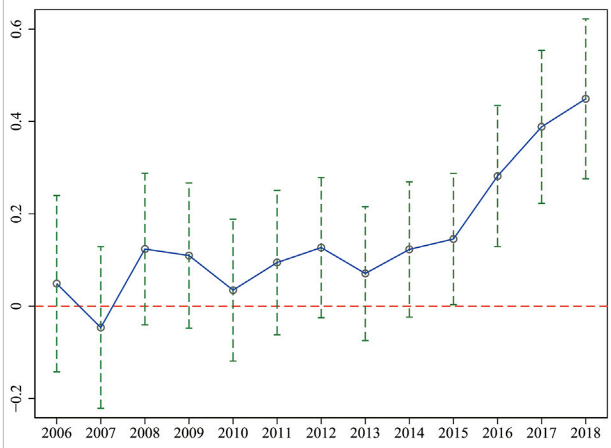

FIGURE 1
Parallel trend test.

TABLE 2 Baseline regression results.

Variables	(1)	(2)	(3)	(4)	(5)
DID	0.243***	0.226**	0.245***	0.204***	
	(0.016)	(0.086)	(0.016)	(0.053)	
DDD					0.326***
					(0.075)
Obs	37,804	37,804	33,719	33,719	33,719
R-squared	0.007	0.029	0.179	0.198	0.193
Controls	N	N	Y	Y	Y
Province FE	N	Y	N	Y	Y
Year FE	N	Y	N	Y	Y
Firm FE	N	Y	N	Y	Y

Ps: Robust standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$.

According to the model estimation results, draw a parallel trend test result graph, as shown in Figure 1. There was no significant difference between the treatment group and the control group before 2013, and the policy effect of the treatment group increased year by year after 2013. This means that TAP has a significant positive effect on the green innovation of SMEs, which preliminarily verifies the theoretical hypothesis of this paper. However, it should be noted that the significant policy effects only began to appear in 2016, 3 years after the implementation of the policy, that is, there is a 3-year lag period of TAP.

4.2 Benchmark results

As shown in Table 2, columns (1)–(3) are estimated by the DID model without control variables without fixed effects, without control variables with fixed effects, with control variables without fixed

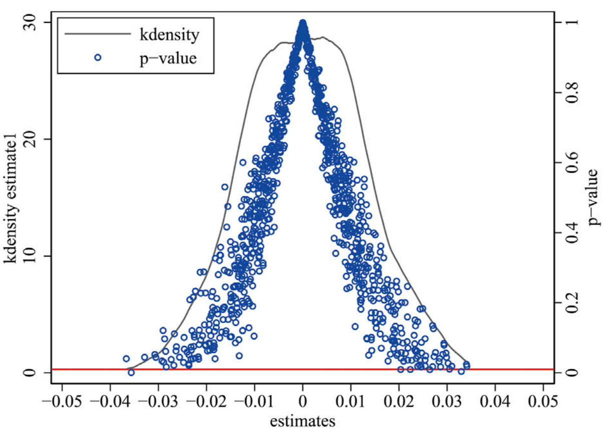

FIGURE 2
Placebo test.

TABLE 3 Baseline regression with different dependent variables.

Model	(1)	(2)	(3)	(4)
Variables	*Gap*	*Indgap*	*Giap*	*Gapratio*
DID	0.204***	0.198***	0.113**	0.011*
	(0.053)	(0.051)	(0.040)	(0.006)
Obs	33,719	33,719	33,720	33,719
R-squared	0.198	0.174	0.195	0.029
Controls	Y	Y	Y	Y
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y

Ps: Robust standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

effects, and DID models including control variables and multidimensional fixed effects. Average treatment effect results, where column (4) is the estimated result from the baseline model (1). By comparison, we can examine the difference in estimated results with or without control variables and with or without fixed effects. The results show that after controlling for enterprise-level control variables and fixed effects of the province, individual, and time, TAP shows a significant promoting effect on the number of green patents of listed companies on the small and medium-sized boards, and the estimated coefficient is significant at the 1% confidence level. The above benchmark regression results confirm for the first time that China's TAP has significantly improved the green innovation of SMEs, which is consistent with the theoretical hypothesis H_1, that is, the implementation of China's TAP will help SMEs achieve green transformation and promote green innovation of SMEs.

In addition, column (5) in Table 2 is the estimation result of the DDD model (2). It is not difficult to see that the green innovation of the three batches of technologically advanced enterprises announced by the Chinese government has been significantly promoted compared with non-technologically advanced enterprises. The coefficients of the DDD estimates are higher than those of the DID estimates, and the estimated results are significant at the 5% confidence level.

4.3 Robustness tests

4.3.1 Placebo test

To further exclude the influence of other unknown confounding factors on the estimation of policy effects, this study selected a virtual experimental group through 1,000 random samples, and also used a multidimensional fixed effect DID model to estimate the results of the placebo test. Figure 2 shows the distribution of DID term coefficients in the random sampling estimation results. It can be found that most of the sampling estimation coefficients still have a low pass rate at the 10% confidence level, that is, the significance of the placebo sampling results fails. It shows that the TAP effect does not exist significantly in the random sampling simulation, that is, the benchmark estimation results pass the placebo test.

4.3.2 Change the dependent variable

Based on Xu and Cui (2020), in addition to using the number of green patent applications in the current year as the dependent variable, this study also added three variables as dependent variables: the number of green patents applied for independently in the year (*Indgap*), the number of green inventions applied for in the year (*Giap*), and the proportion of green patents applied for in the year to the total number of patent applications (Gapratio), carried out a robustness test, and re-identified and estimated the benchmark model (1). This way of processing can exclude the influence of unobservable confounding factors that may be ignored by the use of the total number of green patents and the use of quantitative data alone.

The estimation results are shown in Table 3. Columns (2)–(4) are the analysis results of using the benchmark model (1) to estimate policy effects when *Indgap, Giap*, and *Gapratio* are used as dependent variables. Column (1) is the benchmark result as a control. It is not difficult to find that the estimated results of the three groups of dependent variables are significantly positive at the 1%, 5%, and 10% confidence levels, respectively. This shows that under a variety of dependent variables that measure the level of green innovation, the promotion effect of TAP on green innovation of SMEs is still significant, and the benchmark estimation results are robust, which verifies hypothesis H_1 again.

4.3.3 The difference-in difference-in-differences method

To further eliminate the confounding effects of other competing policies, such as the environmental inspection

TABLE 4 DDD estmation result.

Model	(1)	(2)	(3)	(4)
DID	0.124***	0.197***	0.171***	0.101**
	(0.042)	(0.053)	(0.049)	(0.039)
EnIns	0.405***			0.368***
	(0.082)			(0.078)
CETS		0.430***		0.240***
		(0.061)		(0.044)
ETS			0.282***	0.306***
			(0.063)	(0.054)
Obs	33,719	33,719	33,719	33,719
R-squared	0.219	0.206	0.199	0.225
Controls	Y	Y	Y	Y
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y

Ps: Robust standard errors in parentheses, $^{***}p < 0.01$, $^{**}p < 0.05$.

mechanism implemented in 2015, the carbon emissions trading system (CETS) implemented in 2011, and the emissions trading system (ETS) implemented in 2007, based on the research of Liu and Xiao (2022), we constructed the environmental supervision mechanism, policy dummy variables of CETS and ETS respectively. Incorporated into the benchmark model (1) to control for the confounding effects of the three policies, DID estimation of multi-dimensional fixed effects was performed, and the estimation results are shown in Table 4.

Columns (1)–(3) are the estimation results of adding the environmental supervision mechanism, CETS, and ETS policy dummy variables, respectively. The DID estimation results are all significantly positive at the 1% level, indicating that after controlling the above three possible confounding factors alone, TAP still has a positive effect on the green innovation of SMEs. Then, we incorporate the three policy interference factors into the control variables for benchmark estimation and get column (4). The results show that the green innovation effect of TAP's SMEs is still significantly positive after controlling the three kinds of policy disturbances simultaneously, which verifies hypothesis H_1 again and verifies the robustness of the benchmark estimation results.

5 Mechanism analysis

Since the specific measures of TAP are similar to those of China's industrial policies, they are supportive economic policies. Therefore, we refer to the practice of Yu et al. (2016) which examines the mechanism of TAP's role in promoting green innovation of SMEs from four aspects: government subsidy, tax reduction, credit financing, and market competition.

TABLE 5 Government subsidy mechanism estimation results.

Model	*Gap*			*Giap*	*Indgap*
	Total	*SOE*	*NSOE*		
	(1)	(2)	(3)	(4)	(5)
*DID*SUB*	0.049***	0.099***	0.051***	0.044***	0.057***
	(0.011)	(0.025)	(0.013)	(0.010)	(0.011)
Obs	30,629	11,539	19,089	30,629	30,629
R-squared	0.244	0.320	0.198	0.245	0.216
Controls	Y	Y	Y	Y	Y
Province FE	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y

Ps: Robust standard errors in parentheses, $^{***}p < 0.01$.

5.1 Government subsidy mechanism

Previous studies have shown that government subsidies in the Chinese government's supportive economic policies are an important mechanism to promote the green innovation of enterprises (Li and Zheng, 2016; Yu et al., 2016). To test whether government subsidies in TAP achieve their policy goals, we constructed the following model to test hypothesis H_2:

$$Gap_{ijt} = \sigma_1 DID_{it} \times SUB_{it} + \sigma_2 DID_{it} + \sigma_3 SUB_{it} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + year_t + \varepsilon_{ijt} \quad (4)$$

In the formula, the government subsidy variable for listed companies is calculated by $SUB_{it} = \ln(\text{Amount of government subsidies received by listed companies in the current year})$.

The estimated results are shown in Table 5. Columns (1)–(3) are the estimated results of the overall sample, the state-owned listed company sample, and the private listed company sample. The results show that the three $DID_{it} \times SUB_{it}$ coefficients are all significantly positive at the 1% level, which proves that government subsidies are an important mechanism for TAP to promote green innovation in enterprises, that is, hypothesis H_2 is proved; On the other hand, it also shows that TAP can better promote the green innovation of state-owned SMEs through the government subsidy mechanism.

This is consistent with the research of Li and Zheng (2016), that is, compared with private enterprises, state-owned enterprises are more likely to obtain government policy inclination and financial support. In addition, we also test the robustness of the government subsidy mechanism by changing the dependent variable. Columns (4) and (5) take the number of green invention patents applied for in the current year and the number of independent green patent applications in the current

TABLE 6 Tax reduction mechanism estimation results.

Model	*Gap*			*Giap*	*Indgap*
	Total	*SOE*	*NSOE*		
	(1)	(2)	(3)	(4)	(5)
*DID*TRate*	−0.057**	−0.100**	−0.055***	−0.035**	−0.054**
	(0.021)	(0.035)	(0.018)	(0.016)	(0.020)
Obs	36,666	14,720	21,945	36,667	36,666
R-squared	0.030	0.049	0.030	0.030	0.029
Controls	Y	Y	Y	Y	Y
Province FE	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y

Ps: Robust standard errors in parentheses, $^{***}p < 0.01$, $^{**}p < 0.05$.

TABLE 7 Credit financing mechanism estimation results.

Model	*Gap*			*Giap*	*Indgap*
	Total	*SOE*	*NSOE*		
	(1)	(2)	(3)	(4)	(5)
*DID*LLoan*	0.093***	0.059	0.106***	0.071***	0.095***
	(0.026)	(0.071)	(0.029)	(0.023)	(0.025)
Obs	20,732	10,223	10,507	20,732	20,732
R-squared	0.252	0.339	0.193	0.249	0.225
Controls	Y	Y	Y	Y	Y
Province FE	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y

Ps: Robust standard errors in parentheses, $^{***}p < 0.01$.

year as the dependent variables, and the estimated results of the robustness test according to the above model. In both test results, the $DID_{it} \times SUB_{it}$ coefficients are significantly positive at the 1% level, which indicates that the government subsidy mechanism is still significant under a variety of dependent variables that measure the level of green innovation, and the validation estimates are robust.

5.2 Tax reduction mechanism

Previous studies have shown that tax incentives are an important means for the Chinese government to effectively stimulate the innovation of economic entities (Chen and Yang, 2019). Based on the research of Yu et al. (2016), we use the effective tax rate $TRate_{it}$ to examine whether there is a tax incentive mechanism in TAP. We construct the following model to test the hypothesis H_2:

$$Gap_{ijt} = \sigma_1 DID_{it} \times TRate_{it} + \sigma_2 DID_{it} + \sigma_3 TRate_{it} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + year_t + \varepsilon_{ijt} \tag{5}$$

In theory, the reduction of the effective tax rate of listed companies will reduce the operating costs of enterprises, which in turn will indirectly promote the green innovation process of enterprises. Therefore, the $DID_{it} \times TRate_{it}$ coefficient of the transportation term should be negative. The estimated results are shown in Table 6. Columns (1)–(3) are the estimated results of the overall sample, the state-owned listed company sample, and the private listed company sample. The results show that the three coefficients are significantly negative at the 5%, 5%, and 1% levels, respectively. On the one hand, it is demonstrated that tax incentives are an important mechanism for TAP to promote the green innovation of enterprises, assuming that H_2 is certified; On the other hand, it is also demonstrated that TAP can better promote the green innovation of state-owned SMEs through the tax incentive mechanism.

It is different from Yu et al. (2016) results on the tax mechanism test in industrial policy and enterprise innovation, that is, compared with private enterprises, state-owned enterprises are more likely to obtain preferential tax policies from the government. In addition, we also test the robustness of the tax incentive mechanism by changing the dependent variable. Columns (4) and (5) take the number of green invention patents applied for in the current year and the number of independent green patent applications in the current year as the dependent variables, and the estimated results of the robustness test according to the above model. In both test results, the $DID_{it} \times TRate_{it}$ coefficient is significantly negative at the 5% level, which indicates that the tax incentive mechanism is still significant under a variety of dependent variables that measure the level of green innovation, and the validation estimation results are robust.

5.3 Credit financing mechanism

In China, the credit financing policy, together with government subsidies and tax incentives, is an important measure for the government to stimulate the innovation of various economic entities (Hu et al., 2021). We use long-term loans $LLoan_{it}$ in the financial data of listed companies to examine whether there is a credit financing mechanism in TAP. To test whether the credit financing mechanism exists, that is, hypothesis H3, we construct the following model:

$$Gap_{ijt} = \sigma_1 DID_{it} \times LLoan_{it} + \sigma_2 DID_{it} + \sigma_3 LLoan_{it} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + year_t + \varepsilon_{ijt} \tag{6}$$

Theoretically, the Chinese government's support for listed companies' credit financing will ease corporate financing constraints, reduce corporate financing costs, and indirectly promote the green innovation process of companies. The estimated results are shown in Table 7. Columns (1)–(3) are the estimated results of the overall sample, the state-owned listed company sample, and the private listed company sample. The results show that the coefficients of columns (1) and (3) are both significantly positive at the 1% level, while the coefficient of the state-owned sample is positive but not significant. On the one hand, it is demonstrated that credit financing is an important mechanism for TAP to promote green innovation of enterprises, assuming that H_3 is certified; On the other hand, it also shows that TAP can better promote green innovation of private SMEs through the credit financing mechanism.

It is consistent with the research results of Yu et al. (2016), and Xu and Cui (2020), that is, compared with state-owned enterprises, private enterprises will face greater credit financing constraints in their daily production and operation, and their financing costs are generally higher than state-owned enterprises. Therefore, when faced with credit financing support in TAP, private SMEs are more sensitive and play a more significant stimulating role. Although we still doubt that in this mechanism, state-owned listed companies still receive government credit policies, due to the long-standing "financial discrimination" problem, private listed companies are more flexible with this policy support.

In addition, we also test the robustness of the credit financing mechanism by changing the dependent variable. Columns (4) and (5) use the number of green invention patents applied for in the current year and the number of independent green patent applications in the current year as the dependent variables, and the estimated results of robustness testing according to the above model. In both test results, the coefficients are significantly positive at the 1% level, which indicates that under a variety of dependent variables that measure the level of green innovation, the credit financing mechanism is still significant, and the validation estimates are robust.

5.4 Market competition mechanism

TAP not only includes policy support such as government subsidies, tax incentives, and credit financing but also includes many policies to improve the environment and enhance market competitiveness, which provides us with the option of the last mechanism test, that is, the market competitiveness mechanism. We use the Herfindahl-Hirschman Index (*HHI*) of listed companies to measure the level of market competitiveness of enterprises (the higher the *HHI* value, the lower the market concentration and the worse the market competitiveness). Then, investigate whether the market competitiveness mechanism also plays a role in the process of TAP promoting green innovation of SMEs. To test the above mechanism, namely hypothesis H_4, we constructed the following model:

$$Gap_{ijt} = \sigma_1 DID_{it} \times HHI_{it} + \sigma_2 DID_{it} + \sigma_3 HHI_{it} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + year_t + \varepsilon_{ijt} \quad (7)$$

Theoretically, the lower the *HHI* value of the listed company, the better the market concentration measurement index, the higher the actual competitiveness level, the greater the operating income of the enterprise, and then indirectly promotes the green innovation process of the enterprise, so the multiplier coefficient should be negative. The estimated results are shown in Table 8. Columns (1)–(3) are the estimated results of the overall sample, the state-owned listed company sample, and the private listed company sample. The results show that the three $DID_{it} \times HHI_{it}$ coefficients are all significantly negative at the 5% level. On the one hand, it demonstrates that market competitiveness is an important mechanism for TAP to promote the green innovation of enterprises, assuming that H_4 is certified. On the other hand, it also shows that TAP can promote the green innovation of state-owned SMEs by improving the market competitiveness of enterprises.

It is different from the results of Yu et al. (2016) on the test of market competitiveness mechanisms in industrial policy and enterprise innovation, that is, compared with private enterprises, state-owned enterprises are more likely to gain more market competitiveness, which is more in line with China's actual national conditions. In addition, we also test the robustness of the market competitiveness mechanism by changing the dependent variables. Columns (4) and (5) take the number of green invention patents applied for in the current year and the number of independent green patent applications in the current year as the dependent variables, and the

TABLE 8 Market competition mechanism estimation results.

Model	*Gap*			*Giap*	*Indgap*
	Total	*SOE*	*NSOE*		
	(1)	(2)	(3)	(4)	(5)
*DID*HHI*	−0.103**	−0.187**	−0.086**	−0.097**	−0.086**
	(0.037)	(0.076)	(0.039)	(0.033)	(0.036)
Obs	22,692	10,625	12,067	22,692	22,692
R-squared	0.164	0.232	0.129	0.162	0.141
Controls	Y	Y	Y	Y	Y
Province FE	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y

Ps: Robust standard errors in parentheses, $^{**}p < 0.05$.

TABLE 9 Patent type heterogeneity estimation results.

Model	(1)	(2)	(3)	(4)	(5)	(6)
Variables	*Giap*	*Unigiap*	*Indgiap*	*Guap*	*Uniguap*	*Indguap*
DID	0.113**	−0.008	0.110**	0.137***	−0.011	0.136***
	(0.040)	(0.015)	(0.038)	(0.040)	(0.011)	(0.038)
Obs	33,720	33,720	33,720	33,719	33,720	33,719
R-squared	0.195	0.136	0.168	0.168	0.128	0.146
Controls	Y	Y	Y	Y	Y	Y
Province FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y	Y

Ps: Robust standard errors in parentheses, $***p < 0.01$, $**p < 0.05$.

estimated results of the robustness test according to the above model. In both test results, the $DID_{it} \times HHI_{it}$ coefficients are significantly negative at the 5% level, which indicates that the market competitiveness mechanism is still significantly negative under a variety of dependent variables that measure the level of green innovation, and the validation estimates are robust.

6 Heterogeneity analysis

6.1 Patent type heterogeneity

The green patents of listed companies are mainly divided into two categories: green invention patents and green utility model patents. Based on the benchmark model, we conduct a heterogeneity analysis of policy effects according to patent types and investigate the heterogeneity of the green innovation effect of TAP in terms of green patent types, and the estimated results are shown in Table 9.

In Table 9, columns (1)–(3) are the estimated results of the number of green invention patents applied for in the year, the number of green invention patents applied for jointly in the year, and the number of green invention patents applied for independently in the year as dependent variables. The estimation results show that the estimated coefficients of *Giap* and *Indgiap* are significantly positive at the 5% confidence level, which means that the specialization feature policy significantly promotes the number of green invention patents applied by small and medium-sized board listed companies and the green invention patents applied for independently, but the level of green invention patents applied for jointly is not significantly affected.

Columns (4)–(6) are the estimated results of the number of green utility model patents applied for in the year, the number of green utility model patents applied for jointly in the year, and the number of green utility model patents applied for independently in the year as the dependent variable. The estimation results show that the estimated coefficients of *Guap* and *Indguap* are significantly positive at the 1% confidence level. It means that the specialization feature policy significantly promotes the number of green utility model patents applied for by listed companies on the small and medium-sized boards and the green utility model patents applied for independently, but the level of green utility model patents applied for jointly has not been significantly affected.

This result shows that the green invention patents and green utility model patents independently applied for by SMEs listed companies are the keys for TAP to promote the green innovation of SMEs, while the two types of green patents jointly applied for do not show significant policy influence.

6.2 Ownership heterogeneity

China is a typical economy where the government intervenes in the economy, and the owner's attribute is an important factor affecting the business development of enterprises. In addition, TAP is an important tool for the Chinese government to stimulate the transformation of SMEs into technologically advanced high-quality development. State-owned enterprises and private enterprises may enjoy different "treatments" in the face of specific stimulus tools introduced by the government. Therefore, we performed estimation analyses of all fabrications as significant sources of heterogeneity. Referring to the research of Jiang (2022), we construct a DDD estimation model to investigate whether TAP will have a heterogeneous green innovation effect on different types of listed companies. This model can not only directly show the difference in the policy effect coefficient between the state-owned and private groups, but can also be realized by testing H_{SOE}: $\gamma_1 = \gamma_2$. The test model is as follows:

TABLE 10 Ownership heterogeneity estimation results.

Model	(1)	(2)	(3)
Variables	*Gap*	*Indgap*	*Giap*
*DID*SOE*	0.339***	0.237***	0.351***
	(0.094)	(0.076)	(0.092)
DID(1-SOE)*	0.115**	0.046	0.105**
	(0.048)	(0.038)	(0.047)
Obs	33,719	33,719	33,719
R-squared	0.204	0.199	0.181
Controls	Y	Y	Y
Province FE	Y	Y	Y
Year FE	Y	Y	Y
Firm FE	Y	Y	Y
F(H_{SOE})	6.240	6.540	7.800
p-value (H_{SOE})	0.024	0.021	0.013

Ps: Robust standard errors in parentheses, $^{***}p < 0.01$, $^{**}p < 0.05$.

$$Gap_{ijt} = \gamma_1 DID_{it} \times SOE_{it} + \gamma_2 DID_{it} \times (1 - SOE_{it}) + \theta SOE_{it} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + year_t + \varepsilon_{ijt} \quad (8)$$

The estimated results are shown in Table 10. Columns (1)–(3) take the total number of green patents applied for in the year, the number of green patents applied for independently in the year, and the number of green invention patents applied for in the year as dependent variables, respectively, and the estimated results of the policy effects of different ownership attributes. The results show that the policy effect coefficients of state-owned listed companies are larger than those of private listed companies under the three dependent variables, and all three H_{SOE}: $\gamma_1 = \gamma_2$ tests reject the null hypothesis. It shows that state-owned entities get more green innovation effects under TAP, and the difference is significant.

For this difference in policy effects, the general explanation is that private enterprises are subject to "policy discrimination" in similar policies. Policy implementation and management units are more inclined to allocate policy resources to state-owned economic entities, and it is difficult for private economic entities to enjoy the same "policy treatment" as state-owned entities, which is closer to China's actual national conditions.

6.3 Regional heterogeneity

Previous studies have shown that the policy effects of the Chinese government often have significant spatial heterogeneity. On the one hand, there are significant differences in humanistic, economic, and social development between regions in China, and on the other hand, there are also significant differences (financial and administrative levels) between local governments at all levels. Therefore, we divided China into four parts, namely the northeastern region, the eastern region, the central region, and the western region, to investigate whether there is significant spatial heterogeneity in the TAP effect. The estimated results are shown in Table 11:

TABLE 11 Regional heterogeneity estimation results.

Model	(1)	(2)	(3)	(4)
Variables	*East*	*Northeast*	*Central*	*West*
DID	0.199***	0.013	0.171*	0.319***
	(0.060)	(0.146)	(0.097)	(0.095)
Obs	22,014	1,718	5,023	4,808
R-squared	0.185	0.193	0.193	0.249
Controls	Y	Y	Y	Y
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y

Ps: Robust standard errors in parentheses, $^{***}p < 0.01$, $^{*}p < 0.1$.

Columns (1)–(4) are the estimation results for the eastern, northeastern, central, and western regions, respectively. The DID term coefficients in the eastern, central, and western regions are significantly positive at the levels of 1%, 10%, and 1% respectively, which indicates that the TAP in these three regions has played a policy effect in promoting green innovation of SMEs. However, the coefficient of DID term in Northeast China is not significant, indicating that TAP in this region does not play a significant role in green innovation. In addition, in the three regions where the policy effect is significantly positive, the DID term coefficient presents the ordering feature of "Western > Eastern > Central".

We believe that the possible reason is that the eastern and central regions are relatively developed regions of China's market economy and have the vast majority of SMEs in China. Before the central government issued stimulus policies, local governments had built a relatively free and open market environment. However, the western region and the northeastern region are "heavy" state-owned economic regions, and the thought of a state-owned economy is deeply rooted in the hearts of the people. The development of SMEs lags far behind that of the eastern and central regions. When the central government introduced policies to stimulate the green innovation of SMEs, for the northeast and western regions where the development of SMEs was seriously lagging, the policy stimulus is more flexible, but due to the unspoken financial rule of "Investment does not go beyond Shanhaiguan", it is difficult for SMEs in Northeast China to obtain financial support from capital within the customs. Therefore, the policy effects are more significant in the western region, however, not significant in the northeast region.

7 Conclusion and recommendation

Green innovation is the core concern of green development in the new development concept of the Chinese government, and an important starting point for the Chinese government to deal with climate change and environmental pollution. TAP is an important policy of the Chinese government trying to achieve "technologically advanced" development of SMEs and achieve high-quality development under the background of the new development concept. By taking "Guiding Opinions on Promoting the Development of Technologically Advanced Small and Medium-sized Enterprises" as the policy entry point, manually collecting and matching to get the green patent data of listed companies from 2004 to 2021, and applying the multi-dimensional fixed-effects DID model, we empirically investigate the effects, mechanisms, and heterogeneity of TAP on green innovation in SMEs for the first time. The estimation results found that TAP can significantly improve green innovation in SMEs. It enriches the literature on the influencing factors of SMEs' green innovation and is consistent with other research conclusions on the promotion of green innovation by other policies (Bai et al., 2019; Xia et al., 2022; Zhu and Tan, 2022). Furthermore, based on Yu et al. (2016), we examined the mechanism of TAP's role in promoting green innovation of SMEs from four aspects: government subsidy, tax reduction, credit financing, and market competition. The results demonstrated that state-owned SMEs have significant advantages in the government subsidy mechanism, and private SMEs have prominent advantages in the credit financing mechanism. This result is consistent with existing relevant research conclusions, that is, compared with private enterprises, state-owned enterprises are more likely to obtain government policy inclination and financial support (Li and Zheng, 2016). Private SMEs are more constrained by credit financing, so when faced with credit financing support in TAP, private SMEs are more sensitive and play a more significant role in stimulating (Yu et al., 2016; Xu and Cui, 2020). At the same time, different from the conclusion of Yu et al. (2016), our research results found that state-owned SMEs also have significant advantages in the two mechanisms of tax incentives and market competitiveness, that is, compared with private enterprises, state-owned enterprises are more likely to obtain preferential government tax policies and more market competitiveness blessings, which is also more in line with China's actual national conditions. In addition, policy effects show significant heterogeneity in policy types, enterprise ownership attributes, and regional levels.

Although this research provided some valuable findings and enlightenment for the research in the field of TAP on SMEs' green innovation, it inevitably has certain limitations. First of all, our research only considers the policy effects of China's TAP on SMEs' green innovation and does not analyze the policy effects of similar TAPs in other countries or regions, which makes the research conclusions limited in scope. Secondly, although we pointed out that state-owned enterprises received more policy support in the TAP, we did not conduct a more in-depth analysis of the possible reasons behind it. For example, whether there is corruption leading to this policy outcome. In this regard, future research can try to improve on the following aspects: Firstly, follow-up research can try to include the relevant policies of other emerging market economies and developed countries or regions, and to analyze and compare the effects of TAP policies in China, then can comprehensively examine the regional differences in the effects of major TAP policies. Secondly, the heterogeneity analysis can be carried out from the perspectives of the regional marketization index, government-business relationship, and the corruption of regional officials to deeply analyze the deep-seated reasons for the phenomenon of "state-owned enterprise inclination" and "private discrimination".

In conclusion, the TAP of the Chinese government has achieved the goal of promoting green innovation and the development of SMEs from the perspective of policy objectives. However, there are still some problems with the existing policy measures in practice. From the empirical results of this study, it can be seen that the existing TAP effect has a significant policy preference for state-owned SMEs, and the "policy discrimination" suffered by private SMEs cannot be ignored. Accordingly, we propose the following policy recommendations: ①The government should continue and increase policy efforts in areas related to financial subsidies, tax incentives, credit financing, and the construction of a competitive market environment, pay attention to the evaluation of policy implementation effects and find a balance between policy practice and policy evaluation, which can better promote the development of SMEs. ②Pay attention to the development of private SMEs, analyze the root causes of the "policy discrimination" ("financial discrimination") that private SMEs generally suffer in policy support, try to increase the policy preference for private SMEs in the future TAP reform, and improve the green innovation and development capabilities of private SMEs from the perspective of marketization. ③Pay attention to the influence of regional heterogeneity on the TAP effect, and effectively improve the spatial allocation efficiency of China's central and local TAP resources through "city-specific policies".

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

Conceptualization, GC, DH; methodology, GC; software, GC; validation, GC, DH; formal analysis, GC, DH; data curation, GC, DH; writing—original draft preparation, GC; writing—review and editing, GC; visualization, GC, DH; supervision, GC; project administration, GC, DH; funding acquisition, GC, DH. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Can the modified ESG-KMV logit model explain the default risk of internet finance companies?

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With the rapid development of internet finance in China, the risk management of internet finance has become an urgent issue. This study analyzes the factors that affect the default risk of Chinese internet finance companies based on measuring the distance to default of companies. This study incorporates ESG rating into the evaluation model to comprehensively reflect the default risk factors. The traditional KMV model is modified with ESG rating, and results are used to construct the panel logit model. Based on internet finance firms listed on China A-Shares data from 2016 to 2020, our results show the following: first, the modified ESG-KMV logit model can effectively analyze the influencing factors of the internet finance default risk. Second, ROE, accounts receivable turnover ratio, asset-liability ratio and z-value are important factors that affect the default risk of internet finance companies. Third, it is also found that COVID-19 has significantly impacted the default risk of internet finance companies. As a policy implication, the regulator can incorporate ESG into the measurement of the default risk to create more awareness among internet finance companies on the importance of the environment and sustainability to human societies.

KEYWORDS

default risk, ESG, KMV, internet finance, early warning system

1 Introduction

After 2013, China ushered in a great development in internet finance (Ping and Chuanwei, 2013). With the rise of new internet finance models such as Yu'ebao, P2P, and crowdfunding, 2013 was known as "the first year of the internet finance in China" (Guan and Gao, 2022). Internet finance is a brand new financial model that makes payment more convenient and cost-effective. The most important thing is that the division of labor and specialization in the financial industry has been greatly diluted under the internet finance model. Market participants are more popular, and the huge benefits of internet finance market exchanges are more inclusive to ordinary people. However, internet finance also faces more complex risks than traditional financial models as a new financial model (Xu et al., 2020). With the development of the internet financial market, credit risk is gradually showing more complex and diversified characteristics, which also seriously impacts the internet financial market (Xiao-li and Long, 2013; Ma and Lv, 2019; Wang and Yang, 2020).

Although internet finance makes it easier and faster for investors to obtain information related to financial products, it also gives fund-raisers more chances to hide their real situation, such as misreporting information or concealing information (Zhongkai and Hassan, 2019). Investors find it very difficult to discovery a practical way to solve the real situation of the fund-raiser like the participants in the traditional financial market, thus leading to the emergence of the misbalance phenomenon between investors and fund-raisers. The information risk caused by information asymmetry factors will not be lost due to the convenience of the internet financial market (Xie et al., 2016). Still, it will become more complex due to network trading for its trading participants. Subsequently, the internet financial market has branched into various sectors, from crowdfunding to payments, insurance, and other financial industries (Xie et al., 2015). In addition, due to the convenient and fast characteristics of internet financial facilities, once a large-scale default event occurs in the internet financial market, its credit risk will quickly spread to the entire financial industry by borrowing network channels. Therefore, compared with the credit risk of the traditional financial market, the credit risk of the internet financial market is higher (Ping and Chuanwei, 2013; Xie et al., 2016; Xu et al., 2020).

Credit risk has been studied for a long time, and many models have been applied to the evaluation process of the credit risk (Altman and Saunders, 1997; Caouette et al., 1998; Dong and Wang, 2014; Li and Wang, 2011). Traditional credit risk assessment methods focus on qualitative indicators and rely on experts' professional skills and subjective judgment. Among them, the more famous method is the 5C analysis method, which is based on the analysis of character, the evaluated enterprise's capacity and capital, collateral, and conditions (Wu et al., 2021). In addition, the traditional credit risk assessment methods also include similar characteristic analysis and financial ratio analysis. The credit scoring model is a statistical model that reflects the evaluated object's credit status with systematic data. The model can predict the likelihood that a borrower will default and become insolvent (Chen et al., 2016; Guo et al., 2016).

Altman (1968) first proposed the famous Z-Score model and applied it to analyze enterprises' financial crisis and default risk. In addition, there are logistic and neural network models proposed by scholars (Angelini et al., 2008; Sanford and Moosa, 2012). With globalization, financial market openness has also increased over the years. However, it has also created more frequent incidents of financial crises, where measuring credit risk is increasingly valued by major banks and regulators (Sachs et al., 1996). Since the 1990s, more modern foreign companies and scholars have begun to pay attention to and successfully developed a series of credit risk measurement models. For example, in 1993, KMV Company launched the KMV model, which could estimate the default probability of borrowing enterprises (Rehm and Rudolf, 2000; Gou and Gui, 2009; Zhang et al., 2010). In 1997, Morgan (1997)and other cooperative financial institutions put forward the CreditMetrics model based on value-at-risk. In 1997, Credit Suisse issued a Credit Risk + model similar to the default mode (Wilde, 2010).

In recent years, a large number of scholars in China have used the KMV model to study the credit risk in the financial field and prove the effectiveness of the KMV model (Valášková et al., 2014; Zhao et al., 2016; Liu and Chen, 2020; Yu, 2021). Internet finance is an emerging field, and some scholars have applied this model to this field. Xiao-li and Long (2013) used the traditional KMV model to calculate the volatility of the asset value (σA), distance to default (DD), and expected default frequency (EDF) of 18 listed companies in China. Aware of the rise of internet finance in China, Xu (2022) chose internet finance companies as objects to study the feasibility of KMV to measure their credit risks. The research results prove the feasibility and effectiveness of KMV in the current credit risk calculation of internet finance in China.

However, in the process of studying the credit risk in the field of internet finance, there is a lack of research on the impact of ESG. ESG is the abbreviation of environmental, social, and governance factors, reflecting the enterprise's environmental, social responsibility, and corporate governance factors on the three dimensions. ESG is an important concept and standard for the international community to measure enterprises' ability to achieve sustainable development (Gillan et al., 2021).

Scholars have proved the relative influence of ESG on financial risk. Scholtens and van't Klooster (2019) analyzed the significant relationship between bank performance and sustainability from the perspective of the risk and proved that this sustainability may affect the entire financial system. Moreover, ESG is considered a key factor influencing investor decisions. The importance of ESG is reflected in financial performance in many studies. Friede et al. (2015) proposed that ESG positively impacts CFP based on more than 2000 empirical studies. Scholars in different countries have verified the positive relationship between ESG and financial performance based on local conditions, such as the United States, China, and Germany (Velte, 2017; Zhao et al., 2018; Dalal and Thaker, 2019; Okafor et al., 2021).

Some scholars have analyzed the relationship between ESG and firm value from different perspectives, such as the influence of company size or CEO power. Overall, ESG has positively impacted the enterprise value and its role in valuation (Aouadi and Marsat, 2018; Fatemi et al., 2018; Li et al., 2018; Wong et al., 2021). In recent years, COVID-19 has become an important factor affecting global development. During this period, the impact of ESG became even more pronounced. Umar and Gubareva (2021) used wavelet analyses to point out that ESG indices can maintain positive effects despite catastrophizing like COVID-19. Broadstock et al. (2021) have studied how ESG can perform better in times of crisis and mitigate financial risk to some extent. There are still many studies on the relationship between ESG and risk in the context of COVID-19. Most scholars have proposed the importance of ESG in the face of disasters (Ferriani and Natoli, 2021; Umar et al., 2021; Lööf et al., 2022). Therefore, the special background of COVID-19 should also be taken into account in the research.

Scholars have proved the relative influence of ESG on the financial system risk. Scholtens and van't Klooster (2019) analyzed the significant relationship between bank performance and sustainability from the risk perspective and proved that this sustainability may affect the entire financial system. Regarding credit risk, scholars have studied the relationship between ESG and credit risk from different perspectives. Bannier et al. (2022) studied the relationship between companies' social responsibility and credit risk of US and European companies from 2003 to 2018. Höck et al. (2020) studied the relationship between the ESG level and credit risk premium from the perspective of a bond investment. Barth et al. (2022) analyzed the relationship between the credit risk of American and European companies and ESG from the perspective of credit spreads. Ahmed et al. (2018) analyzed the relationship between ESG and credit risk from banks' perspectives. No matter from which angle of analysis, most of the final conclusions given by scholars are that there is a significant relationship between them. In addition to the credit risk analysis, some scholars analyzed the impact of ESG from the credit rating perspective. They believed that ESG should be considered in the process of credit rating (Devalle et al., 2017; Kiesel and Lücke, 2019; Höck et al., 2020; Michalski and Low, 2021). Chodnicka-Jaworska (2021)used a group event model to verify the importance of ESG factors in credit ratings, especially in the context of COVID-19. Brogi et al. (2022) showed that higher ESG awareness is closely associated with a better reputation measured by the Altman Z-Score. The research results support the rationality of introducing ESG awareness parameters into the credit evaluation of borrowers. Therefore, ESG factors should be considered in analyzing the credit default risk.

Consequently, 49 listed internet finance companies in China are selected as samples to establish a revised KMV model using ESG ratings. Based on this, it uses a panel logit regression to further find the influence factors of the internet finance credit risk in China. This study's contribution to the credit risk field incorporates ESG rating into the evaluation model to comprehensively reflect the default risk factors in internet finance. It also considers the relationship between COVID-19 and internet finance credit risk. As a policy implication, the regulator can incorporate ESG into the measurement of default risk to create more awareness among internet finance companies on the importance of the environment and sustainability to human societies.

2 Modified KMV-logistic with the ESG rating model

This study adopts a mixed model to verify the importance of ESG in credit risk management in internet finance. Based on the aforementioned analysis, we believe ESG should be considered in credit risk research. First, the logic of the traditional KMV model is stated. Then, ESG rating data are used to correct the default point of the KMV model. After obtaining the default to distance corrected by ESG, it uses the idea of quantile to determine the internet finance industry's critical point of DD. The results of DD are used as the explained variable to establish the panel regression model. Finally, the mixed ESG model is used to find the factors affecting the default risk of internet finance. The factor found is the default risk analysis after considering ESG, which is more comprehensive than the original simple default risk analysis.

2.1 KMV model

In the 1990s, KMV Company proposed the KMV model to measure the probability of default, predicting the possibility of default of financial institutions such as companies or banks publicly listed in the security market. The calculation steps are as follows:

Step 1: Calculate the asset value and asset volatility.

$$E = V_A N(d_1) - De^{-rT} N(d_2), \quad (1)$$

$$d_1 = \frac{\ln\left(\frac{V_A}{D}\right) + \left(r + \frac{\sigma_A^2}{2}\right)T}{\sigma_A \sqrt{T}}, \quad (2)$$

$$d_2 = d_1 - \sigma_A \sqrt{T}, \quad (3)$$

$$\sigma_E = \frac{V_E}{E} N(d_1)\sigma_A, \quad (4)$$

where σ_A is the volatility of V_A, T is the debt maturity, E is the equity value of the company, D is the debt of the company, r is the risk-free rate, and σ_E is the volatility of the equity value.

Step 2: Calculate the default point and default to distance.

$$DPT = STL + 0.5LTL, \quad (5)$$

$$DD = \frac{E(V_A) - DP}{E(V_A)\sigma_A}, \quad (6)$$

where DP is the default point, DD is the default to distance, STL means short total liability, and LTL means long total liability.

Step 3: Estimate the expected default rate.

$$EDF = N(-DD), \quad (7)$$

where $N()$ is the standard normal distribution function.

2.2 Modification of the KMV model with ESG rating

This study incorporates ESG ratings into the KMV model and modifies the traditional KMV model. The ESG rating adopted is Sino-Securities Index ESG Evaluation (also known as the Huazheng ESG rating in China). According to the ESG rating description of Sino-Securities, a rating above BBB indicates that the company has a relatively good ESG situation. Therefore, this study divides the rating into two parts to modify the KMV model. If the rating is above BBB, it will reduce default point weights. If the rating is below the BBB rating, it will be increased by a down-weighted default point. The weight determination is standardized according to the rating level. Table 1 shows the results of ESG rating correction.

The new distance to default and expected default probability of sample companies can be calculated using the modified KMV model. In this study, the distance to default is taken as the representative of the default of sample companies. According to the calculation results of distance to default, an early-warning line for default of internet finance companies can be set, and the sample companies can be further divided into default and non-default groups.

2.3 Panel logit model

The panel logit model is chosen according to the research object of whether the company defaults or not. The expression for the model is shown as follows :

$$L_{it} = \ln\left(\frac{p(Y=1)}{p(Y=0)}\right) = \alpha + \sum_{i=1}^{n} \beta_i \chi_{it} + \varepsilon_{it}, \tag{8}$$

where χ_{it} are explanatory variables, α is a constant term, and β_i is the parameter to be estimated.

If the company defaults, $Y = 1$. Suppose the company does not default, $Y = 0$. The default situation of internet finance companies is estimated according to the distance to default result calculated by the modified KMV model with ESG rating. The default data set is sorted according to the theoretical default rate based on the modified KMV model and takes 10% quantile as the critical default value. The smaller the distance to default, the higher is the default risk. The 10% quantile is set as the default criterion because 90% of the companies have a higher distance to default than the quantile. If the company's distance to default is lower than the distance to default at the quantile, the distance to default will be too low, and the default risk will be high. The sample companies with distance to default ranking in the top 10% were set as 1, and the rest were set as 0.

3 Data and variable selection

3.1 Data selection

This work aims to study the factors influencing the credit risk of listed internet finance companies based on considering ESG rating. This study takes 49 listed internet finance companies in China as the research sample, and the period is from 2016 to 2020. Data were obtained from the Wind database.

3.2 Variable selection

In selecting variables, this study selects independent 12 variables based on the summary of the previous literature. The COVID-19 outbreak occurred in December 2019, so the year 2020 affected by the outbreak was used as the annual dummy variable in this study. Then, the stepwise regression method is performed to select appropriate independent variables. The 12 alternative variables are shown in Table 2. The observation frequency of this study is the year. Correlation analysis was used before the model estimation to check whether the key explanatory variables are highly correlated. The results are shown in Table 3, and there is no high correlation between alternative independent variables.

After establishing the regression equation, all variables are considered by the stepwise regression method. According to the value of McFadden R-Squared of the logit regression model, the statistical significance of variables and whether they conform to the actual economic significance are evaluated. According to the regression results of the model, five indicators are screened out: ROE, RT, ALR, z, and Year 2020.

At the same time, according to literature research and economic common sense, this study puts forward the following hypotheses:

- H1: The possibility of internet finance companies defaulting decreases as the return on equity increases.
- H2: The possibility of internet finance companies defaulting decreases as the accounts receivable turnover rate rises.
- H3: The possibility of internet finance companies defaulting increases as the asset liability ratio rises.
- H4: The probability of internet finance companies defaulting increases as the z-value increases.
- H5: The probability of internet finance companies defaulting increases with COVID-19.

TABLE 1 Results of ESG rating correction.

Sino-Securities ESG rating	Code	Weight	Revised plan	Revised default point result
AAA	4	0.4	Decrease	$DPT \times (1-0.40)$
AA	3	0.3		$DPT \times (1-0.30)$
A	2	0.2		$DPT \times (1-0.20)$
BBB	1	0.1		$DPT \times (1-0.10)$
BB	1	0.07	Increase	$DPT \times (1+0.07)$
B	2	0.13		$DPT \times (1+0.13)$
CCC	3	0.2		$DPT \times (1+0.20)$
CC	4	0.27		$DPT \times (1+0.27)$
C	5	0.33		$DPT \times (1+0.33)$

TABLE 2 List of independent variables to be selected.

Variable name	Variable symbol	Variable definition
Return on equity	ROE	Net income/Shareholder's equity
Net profit margin on sales	NPM	Net profit/Sales revenue
Receivable turnover	RT	Net credit sales/Average accounts receivable turnover
Inventory turnover	IT	Net sales/Average inventory at selling price
Total assets turnover	TAT	Net sales/Average total assets
Liquidity ratio	LR	Current assets/Current liabilities
Total profit growth rate	TPG	Annual profit growth/Total profit of last year
Total asset growth rate	TAG	Total asset growth/Total assets of last year
Asset liability ratio	ALR	Total liabilities/Total assets
Equity multiplier	EM	Total assets/Total shareholders' equity
Z-value	z	Z-score calculated according to Altman's Z-score model
Year of 2020	Year 2020	Year of COVID-19

TABLE 3 Correlation matrix.

	Y	ROE	NPM	RT	IT	TAT	LR	TPG	TAG	ALR	EM
Y	1										
ROE	−0.19 (0.00)	1									
NPM	−0.21 (0.00)	0.29 (0.00)	1								
RT	−0.08 (0.23)	0.03 (0.61)	0.05 (0.44)	1							
IT	0.05 (0.41)	−0.07 (0.29)	−0.03 (0.69)	−0.02 (0.77)	1						
TAT	−0.08 (0.22)	0.03 (0.69)	0.06 (0.37)	−0.01 (0.85)	−0.02 (0.80)	1					
LR	0.09 (0.18)	0.16 (0.02)	0.15 (0.02)	0.16 (0.01)	0.05 (0.40)	−0.11 (0.08)	1				
TPG	−0.13 (0.04)	0.48 (0.00)	0.40 (0.00)	0.03 (0.65)	0.03 (0.69)	0.05 (0.47)	0.09 (0.15)	1			
TAG	−0.06 (0.34)	0.30 (0.00)	0.23 (0.00)	−0.02 (0.81)	−0.06 (0.32)	0.13 (0.04)	0.27 (0.00)	0.24 (0.00)	1		
ALR	0.09 (0.15)	−0.21 (0.00)	−0.31 (0.00)	−0.06 (0.34)	−0.06 (0.31)	0.09 (0.17)	−0.37 (0.00)	−0.14 (0.03)	−0.21 (0.00)	1	
EM	0.14 (0.03)	−0.40 (0.00)	−0.14 (0.03)	−0.02 (0.78)	−0.03 (0.67)	−0.00 (1.00)	−0.10 (0.12)	−0.06 (0.38)	−0.10 (0.11)	0.12 (0.07)	1

Note: sample period: January 2016 to December 2020. Values in parenthesis are p-value.

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TABLE 4 Descriptive statistics of independence variables.

Items	N	Minimum	Maximum	Mean	Std. deviation
ROE	245	−428.53	56.29	−4.75	42.97
RT	245	0.09	8,819.73	71.29	598.75
ALR	245	4.24	472.36	56.63	58.09
z	245	−16.32	95.38	6.25	10.94
Year 2020	245	0.00	1.00	0.20	0.40

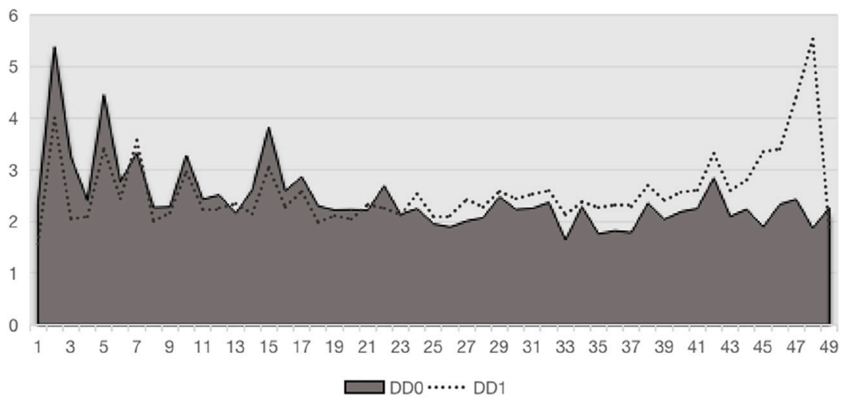

FIGURE 1
Distance to default comparison chart.

The credit default risk of internet finance companies results from a combination of factors. It mainly includes repayment ability and repayment willingness. For a company, the factors that affect the repayment ability and willingness include the company's profitability, operating capacity, capital structure, bankruptcy probability, and macro-environment. If its profitability is strong, it has more revenue to pay off its debts. High operating capacity means that the company's assets are used efficiently, and the company will have a lower probability of default. A company with a low debt ratio means that the lower the company's debt load, the less likely the company will default. The Z-value is an indicator that comprehensively reflects the probability of a company going bankrupt. The lower the probability of bankruptcy, the less likely the company will default. China's economic environment is affected by various factors, such as COVID-19. Hence, the closer we reach 2020, the higher the likelihood companies will default. Based on this, this study proposes the aforementioned hypotheses.

4 Results and discussion

4.1 Descriptive statistics of independence variables

Descriptive statistics of influencing factor variables of sample companies are shown in Table 4 as follows.

4.2 Descriptive statistics of the dependence variable

Distance to default and expected default probability are two corresponding values. This study chooses distance to default as an index to measure the company's credit default status. The distance to the default of sample companies is the dependent variable of this study.

The distance to the default of sample companies was calculated using the modified KMV with the ESG model. Then, the average value of distance to default from 2016 to

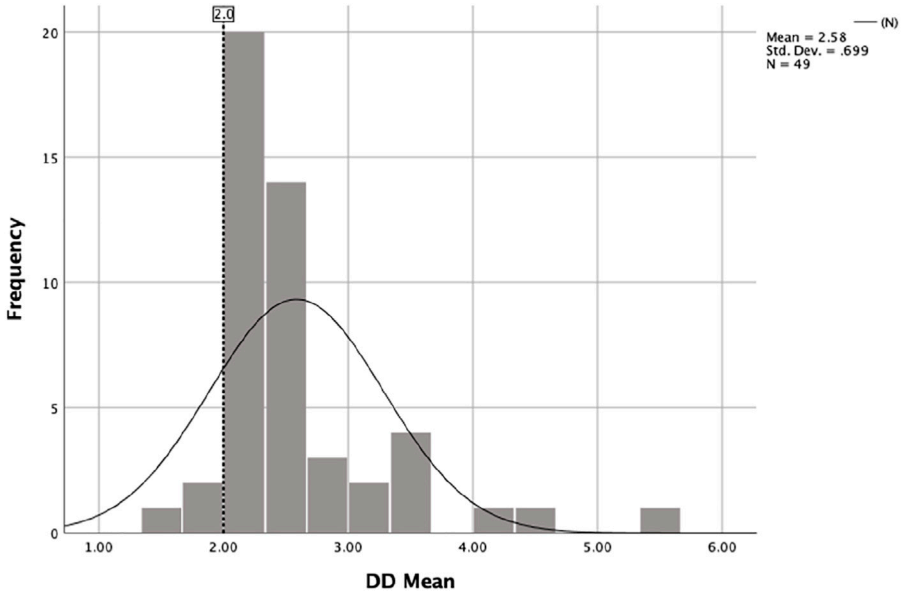

FIGURE 2
Average distance to the default of sample companies.

TABLE 5 Descriptive statistics of the dependent variable.

		Frequency	Percentage	Valid percentage	Cumulative percentage
Valid	0	158	64.5	64.5	64.5
	1	87	35.5	35.5	100.0
	Total	245	100.0	100.0	

Note: dependent variable is the distance to the default.

TABLE 6 Hausman test results.

Item	Result
Chi2 (5)	0.26
Prob > chi2	0.9983

TABLE 7 Wald test results.

Item	Result
Wald chi2 (5)	27.16
Prob > chi2	0.0001

2020 was calculated. Figure 1 shows the original distance to default means and corrected distance to default mean with the ESG rating of 49 sample companies. DD_0 refers to the original distance to the default mean result, and DD_1 refers to the modified results with an ESG rating.

The distance to default means is arranged in an ascending order. Then, the distance to default means of 10% quantile is taken as the critical default value. The frequency histogram of the average distance to default is shown in Figure 2. Distance to default = 2 is the default threshold.

According to the critical value of distance to default, all data can be divided into default and non-default groups. If the distance to default is lower than the critical value 2, the dependent variable is set as 1. If the distance to default is higher than 2, the dependent variable is 0. Descriptive statistics for the dependent variable data is shown in Table 5.

4.2 Panel logit regression results

The distance to the default of sample companies is classified as the independent variable. The five selected variables, ROE, RT, ALR, z, and Year 2020, are independent variables to establish a

TABLE 8 Logit regression results.

Item	Coefficient	Std. error	z	P> |z|	[95% Confidence interval]	
Constant	−1.97***	0.43	−4.56	0.00	−2.82	−1.12
ROE	−0.01**	0.05	−2.43	0.02	−0.2	−0.00
RT	−0.02**	0.01	−2.05	0.04	−0.04	−0.00
ALR	0.01**	0.04	2.47	0.01	0.00	0.02
z	0.12***	0.04	3.39	0.00	0.05	0.19
Year 2020	1.30***	0.39	3.35	0.00	0.54	2.07

Notes: the asterisk*** and **denote statistical significance at 1% and 5%, respectively. Sample period: January 2016 to December 2020.

TABLE 9 Odds ratio results.

Item	Odds ratio	Std. error	z	P> |z|	[95% Confidence interval]	
Constant	0.14***	0.06	−4.56	0.00	0.06	0.32
ROE	0.99**	0.00	−2.43	0.02	0.98	1.00
RT	0.98**	0.01	−2.05	0.04	0.96	1.00
ALR	1.01**	0.00	2.47	0.01	1.00	1.02
z	1.13***	0.04	3.39	0.00	1.05	1.21
Year 2020	3.69***	1.43	3.35	0.00	1.72	7.90

Notes: the asterisk*** and **denote statistical significance at 1% and 5%, respectively. Sample period: January 2016 to December 2020.

panel logit model. Before panel data analysis, the Hausman test is performed on the data to determine whether the fixed-effect logit model or random-effect logit model is used in this study. According to Table 6, the *p*-value is greater than 0.05. The test statistic does not reject the hypothesis. This result shows that the random-effect model is better than the fixed-effect model. Therefore, this study adopts the random-effect logit model for regression.

Table 7 shows the model fitting effect. The *p*-value is 0.0001, which means that the model's overall fit is significant at 1%.

The panel logit results of the model and odds ratio results are shown in Table 8 and Table 9. The influence of the index variable on the credit default risk of listed internet finance companies is judged according to the regression coefficient of the variable. Suppose the regression coefficient of the index variable is positive, in that case, it indicates that the index positively correlates with the default risk of listed internet finance companies. The variation of indicator variables will lead to an increase in the default risk of networked financial companies. Suppose the regression coefficient of the index variable is negative, in that case, it indicates that the index is negatively correlated with the default risk of internet finance companies. The variation of index variables will reduce the default risk for internet finance companies.

According to the regression results in Table 8, the regression coefficients of return on equity are negative, and it is significant at 5%. This shows that the higher the profitability of the Internet financial company, the lower is the default risk. The profitability of an enterprise represents its ability to resist risks. The more profit an enterprise has, the more funds it will invest in ESG, thus reducing its default intention. Therefore, assumption H1 is supported. The inventory turnover coefficient was negative and significant at 5%. With accounts receivable turnover speed and high management efficiency, enterprise ESG performance will improve. Companies are less likely to default. The fast turnover of enterprise assets will bring high liquidity, and the speed of profit will be faster. Enterprises will invest their excess capital in ESG, thus reducing their default risk. This result supports hypothesis H2. The regression coefficient of the asset liability ratio is positive, indicating that it is positively correlated with the credit risk of internet finance companies. A high debt-to-asset ratio means that a higher percentage of a company's total assets are financed by borrowing. Hence the company will default more. This conclusion supports hypothesis H3.

The regression coefficient of the Z-value is positive and significant under 1%, indicating that it is positively correlated with the credit risk of Internet finance companies. The Z-value itself is a measure of the risk of failure. Companies with a higher risk of bankruptcy are more likely to default. Therefore, H4 has been proved. The regression coefficients for Year 2020 are positive and significant at 1%. The significance of the time

TABLE 10 Further logit regression results.

Variable	Model (9)	Model (10)
Constant	−2.83***	−1.74***
	(0.00)	(0.00)
L_{it-1}		0.79**
		(0.03)
ROE	0.00	0.01***
	(0.74)	(0.01)
RT	−0.20	−0.20
	(0.13)	(0.06)
ALR	0.01***	0.01
	(0.01)	(0.07)
z	0.17***	0.07*
	(0.00)	(0.05)
Year 2020	1.81***	1.03***
	(0.00)	(0.01)
Wald test	22.86***	29.01***
	(0.00)	(0.00)
Obs	196	196

Notes: The asterisk***, **, and *denote statistical significance at 1%, 5%, and 10%, respectively.

dummy variable Year 2020 indicates that COVID-19 impacts the default of internet finance companies. COVID-19 is a catastrophic global health event that has affected the economic growth of the internet finance industry and increased the risk of default. The conclusion supports hypothesis H5. Therefore, all hypotheses are supported.

According to Table 9, when the ROE of an internet finance company increases by 1 unit, the probability of the default risk of the internet finance company decreases by 0.01 (1-odds ratio) units. Similarly, when the accounts receivable turnover of an internet finance company increases by 1 unit, the probability of default risk of the internet finance company decreases by 0.02 units. Likewise, when the asset liability ratio, Z-value, and Year 2020 increase by 1 unit, the probability of the default risk of internet finance companies will increase by 1.01, 1.13, and 3.69 units, respectively. Consequently, COVID-19 has a greater impact on the credit risk of internet finance among all the influencing factors.

For further discussion, two extended models were established for comparison. In real economic life, many economic variables are affected not only by the same period factor but also by the early-stage factor of the variable. Therefore, the first-order lag variable of the dependent variable was added for analysis in this study. First, the dependent variable is regressed with first-order lag, and a new regression model (9) is established to analyze the explanatory power of the impact indicators. Second, the first-order lag variable of the dependent variable was added to model (8) as an independent variable, and model (10) was established to analyze the influence of its early value.

$$L_{it-1} = \ln\left(\frac{p(Y=1)}{p(Y=0)}\right) = \alpha + \sum\nolimits_{i=1}^{n}\beta_i\chi_{it} + \varepsilon_{it}, \tag{9}$$

$$L_{it} = \ln\left(\frac{p(Y=1)}{p(Y=0)}\right) = \alpha + L_{it-1} + \sum\nolimits_{i=1}^{n}\beta_i\chi_{it} + \varepsilon_{it}. \tag{10}$$

Table 10 shows the model regression results after adding lag variables, and the results of the Wald test show that the two models are still valid. In the regression results of model (9), the three variables ALR, Z and Year 2020 are still significant, indicating that these three variables are more robust than the other two variables. The regression result of the model (10) shows a significant relationship between the explained variables lagging one period and the original explained variables, which proves that the credit risk of Internet finance integrated with ESG is indeed affected by its early stage.

5 Conclusion

Based on the classic credit risk assessment model, this study constructs a KMV-logit mixed model to study the credit risk of Chinese listed internet finance companies. The traditional KMV model only considers financial factors but ignores non-financial factors. In this study, the ESG index is introduced into the KMV model. The revised KMV-logit mixed model effectively analyzes the influence factors of the default risk for internet finance companies.

Second, return on equity, receivable turnover, asset liability ratio, Z-value, and Year 2020 all affect the default risk of internet finance companies to a certain extent. Among the independent variables, Z-value and the year 2020 have the strongest relationship with default risk. The significant results of the year 2020 indicate that China's internet finance environment has increased risks because of COVID-19. The Z-value is calculated according to Altman's Z-value model and represents its bankruptcy probability. This finding further indicates that the default result obtained by the model is valid.

Moreover, this study introduced the hysteresis variable of the explained variable to conduct an extended analysis. The results proved that the credit risk of internet finance after incorporating ESG correction would be affected by its preliminary results. Meanwhile, among all explanatory variables, asset-liability ratio, Z-value and Year 2020 are more rubust. The conclusion is calculated based on the data on internet finance companies in China, so it applies to the reality of China's internet finance industry. However, the research essence of this study is based on the impact of ESG on credit risk, which is similar to the global financial system. Therefore, this study has reason to believe that the conclusion can also be applied to other countries and industries. However, the specific situation needs further analysis using data from different countries.

The policy implications of this study are as follows:

From the enterprise level, internet finance firms should value ESG in the process of credit risk management and reshape the cognitive concept of sustainable development of the enterprise. ESG is not only in the single dimension of the sustainable idea of corporate social responsibility. It covers enterprise for a sustainable social environment and the internal governance of multi-dimensional concepts, especially during the current economic downturn with the impact of COVID-19. Enterprises are facing long-term transformation and upgrading and performance decline pressure. In this context, enterprises are prone to credit risks and may go bankrupt once they are poorly managed. Therefore, enterprises should strengthen ESG management and integrate it into the credit risk management process by improving their ESG performance to predict and manage credit risks. Based on the conclusion of influence factors, internet finance companies should pay attention to managing their own profitability, operating capacity, and debt capacity to enhance their ability to resist risks.

From an investor's perspective, ESG performance should be incorporated into investment choices. Under the background of sustainable development, investors are important external supervisors and administrators to promote listed companies to fulfill their social responsibilities and improve corporate governance. When choosing investment objects, corporate investors should pay attention to their financial performance and non-financial performance, such as environmental performance, social performance, and corporate governance performance. This can help enterprises better manage risks, achieve sustainable long-term returns, and enhance the sustainable competitiveness of enterprises.

From the perspective of the government, the company's ESG performance evaluation system and information disclosure system should be improved. Meanwhile, the government should combine the ESG performance of internet financial companies in credit risk supervision. For those companies with better ESG performance, the government can give appropriate policy support. The government can impose appropriate penalties for companies with poor ESG performance. The government should gradually guide companies to improve their ESG performance and consciously disclose ESG information to provide effective information for credit risk supervision.

Data availability statement

Publicly available datasets were analyzed in this study. These data can be found at: https://www.wind.com.cn/en/edb.html.

Author contributions

The first author has sourced and analyzed the data, and drafted some parts of the manuscript. The second author has been involved in the modeling and discussion of research ideas and drafted some parts of the manuscript. The third author has involved in the discussion of ideas and drafted some parts of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Regional integration policy, industrial chain and corporate total factor productivity: An econometric empirical analysis from China

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This paper aims to investigate the impact, mechanism, and heterogeneity of regional integration policy (RIP) on firms' total factor productivity (TFP). We take the integration of the Shenzhen-Dongguan-Huizhou policy (ISDHP) as the research object and conduct a multi-dimensional fixed-effect DID analysis based on China's listed A-share firms' data. The results show that RIP can significantly improve corporate TFP within the region, while it is more pronounced in the SOE group. After a series of robustness tests, the policy effects are summarized as robust. In addition, we use a set of industry chain indicators to identify the mechanism between RIP and corporate TFP from the industry chain perspective. We conclude that the ISDHP can improve corporate TFP by significantly improving the upstream degree of firms' industrial chain. Further research shows that the impact of ISDHP policies can also improve corporate TFP by green innovating, innovating, and improving market competitiveness. Moreover, the state-owned listed firms have significant advantages in these mechanisms. In general, China's ISDHP has achieved the expected effect in improving enterprises' TFP. However, in the future, attention should be paid to the issues of "state tilt" and "private discrimination".

KEYWORDS
regional integration policy (RIP), integration of shenzhen-dongguan-huizhou policy (ISDHP), total factor productivity (TFP), industrial chain, difference-in-differences (DID), green innovation, market competition, listed firms

1 Introduction

Since China implemented the reform and opening-up policy in the late 1970s, the national economy has achieved a miracle of economic growth driven by capital and resource factors. However, the extensive growth mode that intensively relies on resources and factors is difficult to maintain. Resource and environmental issues have become important constraints restricting China's economic growth, and the issue of high-quality development is imminent (Yu et al., 2020). The 19th National Congress of the Communist

Party of China proposed: "China's economy has shifted from a stage of high-speed growth to a stage of high-quality development, and is in a critical period of transforming its development mode, optimizing its economic structure, and transforming its growth drivers." High-quality economic development no longer only emphasizes the speed of economic growth, but also pays more attention to the quality and efficiency of economic growth. In this context, the improvement of total factor productivity (TFP) has become the key content of high-quality economic development. How to improve corporate TFP to achieve high-quality development at the enterprise level has become an important topic of concern for scholars in recent years.

In order to solve similar problems related to the quality of economic development, China and other emerging economies have taken many measures (Ma & Zhu, 2022). Among these attempts, the regional integration policy (RIP), which is represented by targeted integration of regions, is the policy attempt that the Chinese government attaches great importance to. Previous studies have shown that the degree of integration of the economic circle determines the spatial arrangement and strategic position of a region. It directly determines the development quality and efficiency of a country or region (Chen A. Z et al., 2021; Zhang et al., 2021). On this basis, scholars have studied the relationship between RIP and high-quality economic development. They mainly focus on the impact of regional integration on high-quality development at the macro level, for example, by studying the impact of regional integration on urban TFP (Li et al., 2017; Huang and Zhang, 2019; Zhang et al., 2021). Surprisingly, however, few studies have examined the impact of RIP on firm-level TFP at the microenterprise level. To address this gap, we use data from Chinese listed companies to examine the impact of RIP on firm TFP, taking the integration of the Shenzhen-Dongguan-Huizhou Policy (ISDHP) as an example.

In theory, the main content of the RIP is to ease the constraints on the cross-regional circulation of resource elements. It reduces the cost of transportation and trade while promoting the spatial diffusion and spillover of knowledge and technology. It realizes the efficient allocation of resource factors and reduces the cost of technological innovation for enterprises (Li et al., 2017; Gries et al., 2018; Zhang et al., 2021). Therefore, logically, RIP may have a positive impact on corporate TFP. Many scholars have carried out theoretical and empirical analyses and provided empirical supporting evidence (Jensen & Miller, 2018; Bau and Matray, 2020; Blankespoor et al., 2022). For example, Li et al. (2022) apply the PSM-DID method to examine the impact of RIP on firm productivity and its heterogeneity based on the city data of the Yangtze River Economic Belt. Their findings support this view. However, RIP does not always have a positive impact on corporate TFP as expected. Many scholars have come to the exact opposite conclusion. They believe that the process of regional integration will boost the cross-regional location choices of heterogeneous companies. It will exacerbate regional imbalances, increase the productivity gap between regions, and inhibit the productivity of enterprises in backward regions (Liang et al., 2012; Lv et al., 2019). For example, Lv et al. (2019), based on the theoretical model of the new economic geography, examines the relationship between the integration process and corporate productivity. They found that in the process of integration, low-productivity firms in developed regions migrated out first. Then the economic gap between regions is narrowing, but the productivity gap is widening. Although the above studies have drawn completely contradictory conclusions, they also confirm that RIP does have an impact on corporate TFP. To this end, it is necessary to introduce new empirical evidence to assess the causal relationship, providing new empirical extensions to the existing literature.

In addition, COVID-19 swept the world at the end of 2019, and the global outbreak of the epidemic and extreme weather conditions had a great impact on international economic trade. It has brought a series of severe challenges to the development of the industrial chain in China's southeast coastal economic circle. The high-quality development of each economic circle has been negatively affected to varying degrees (Dou et al., 2021). This raises another question, will the level of industrial chain linkages in the economic circle be an important mechanism that affects the effect of RIP on corporate TFP? However, to the best of our knowledge, this leaves a gap in existing research on the impact of RIP on corporate TFP. In the field of international trade, many scholars have conducted many investigations on the link between the industrial chain and corporate TFP (Yan et al., 2018; Hu et al., 2021; Opazo-Basáez et al., 2021; Hu et al., 2022). For example, Ge et al. (2018) used Chinese firm-level data from 2000 to 2007 to study the impact of industrial chain participation on firm productivity. The results show that Chinese manufacturing firms experience significant productivity enhancement effects in industrial chain embedding. Cainelli et al. (2018) also provide empirical support for this conclusion. Therefore, the link between the industrial chain level and corporate TFP has been confirmed. While the relationship between RIP and the industrial chain has been generally ignored in the existing literature. Therefore, we conducted this empirical analysis to examine the impact of the ISDHP on the industrial chain to complement research in this area.

As discussed above, the relationship between RIP and corporate TFP remains uncertain in the literature. However, clarifying this relationship will help us better understand the micro-mechanisms of the high-quality development of the economic circle. It provides new insights for formulating scientific and accurate policies for the high-quality development of enterprises and RIP. To better solve the above problems, we choose the Shenzhen-Dongguan-Huizhou economic circle (SDHEC) as the research object among the many economic circles in China. We use 2007–2021 China

A-share listed company data from CSMAR database and apply the DID method to investigate the impact of RIP on corporate TFP. To get a more detailed grasp, we also use the number of patents filed by listed companies and the HHI index to further investigate the other mechanisms. It found that the implementation of RIP can significantly increase the number of patents, reduce the HHI index of enterprises, and then achieve a positive impact on corporate TFP. In addition, starting from the ownership of listed companies, we use the DDD method to further investigate the heterogeneity of the policy effects of economic circle integration. We find that the policy effect of ISDHP shows a more significant TFP improvement effect in state-owned listed companies.

The marginal contributions of our research are mainly reflected in the following aspects: Firstly, this study is one of the few studies that enrich the impact of RIP on corporate TFP at the micro level. Our findings link economic circle integration policies at the macro level with high-quality enterprise development at the micro level. It provides new insights for relevant policymakers and business managers. Secondly, to our knowledge, this study is the first paper that attempts to examine the mechanism of RIP on corporate TFP from the perspective of industrial chain linkages. It provides new ideas for the RIP and industrial chain builders of emerging economies including China. It also helps to realize the high-quality development of enterprises in the region in the post-epidemic era. Thirdly, we introduce a variety of causal identification methods such as the multi-dimensional fixed-effect DID method and DDD method. These econometric methods help to scientifically estimate the policy effects, mechanisms, and heterogeneous characteristics of ISDHP in China. It also improves the scientific nature of policy treatment effect evaluation and provides ideas for such policy evaluation work.

In the following text, Section 2 discusses the policy background and literature. Section 3 explains the methodology and data. Section 4 illustrates the empirical results of the benchmark model, robustness tests, and policy heterogeneity. Section 5 is an in-depth analysis of the mechanism. The last Section brings out the conclusions and recommendations for future research.

2 Background and literature

2.1 Policy background

The Pearl River Delta is an important urban agglomeration along the southeast coast of China and an important engine of China's economic growth. Its economic and social development is deeply affected by the combined effects of globalization and localization (Liu et al., 2022). The integration process of the Pearl River Delta is as follows: firstly, the key construction of the core cities of Guangzhou, Shenzhen, and Zhuhai, forming a core-edge structure; secondly, to form secondary urban agglomerations or economic circles around these three core cities, namely Guang-Fo-Zhao (Guangzhou, Foshan, Zhaoqing), Shen-Guan-Hui (Shenzhen, Dongguan, Huizhou), and Zhu-Zhong-Jiang (Zhuhai, Zhongshan, Jiangmen), forming a multi-center ring-layer structure. On 24 September 2009, the third joint meeting on the integration of Shenzhen-Dongguan-Huizhou was held in Huizhou. Following the requirements of the "Outline of the Reform and Development Plan for the Pearl River Delta Region" on "optimizing the functional layout of the east bank of the Pearl River estuary" and the Guangdong Provincial Government's "Guiding Opinions on Accelerating the Promotion of the Regional Economic Integration of the Pearl River Delta", Shenzhen, Dongguan, and Huizhou held three joint meetings of the main leaders of the party and government in the three cities in 2009. They signed a series of cooperation agreements, such as "Implementing the Outline of the Reform and Development Plan for the Pearl River Delta Region and Promoting Close Cooperation in the East Bank of the Pearl River Estuary", and "Shenzhen-Dongguan-Huizhou Planning Integration Cooperation Agreement". In 2014, Guangdong Province's revitalization and development strategy for the east, west, and north regions of Guangdong was carried out. Heyuan and Shanwei were officially included in the SDHEC.

The SDHEC has successively established a multi-level and multi-channel cooperation structure. Under this cooperation framework, SDHEC has adopted a series of integrated reform policy measures. It mainly includes the following five aspects: industrial integration, environmental protection integration, transportation infrastructure integration, technological innovation integration, and market integration (as shown in Table 1).

At present, under the integrated reform policy measures, SDHEC has made significant progress in industrial development, environmental governance, infrastructure construction, and collaborative innovation. However, it is difficult for us to directly judge whether ISDHP has brought improvement to corporate TFP. If so, by what mechanism does ISDHP achieve its influence on corporate TFP? Is there heterogeneity in the policy effects of ISDHP? These issues need to be further identified and analyzed.

2.2 Literature and hypothesis

2.2.1 The RIP and corporate TFP

Although, as a macro-regional planning policy, RIP focuses on the macro-level multi-regional and cross-administrative boundary economic coordination policy, the micro-effects of policies have been a hot research direction of scholars in recent years. As mentioned in the introduction, the key job of RIP is to break through the barriers, which can significantly reduce the cost of acquiring advanced knowledge and technologies for some

TABLE 1 Main integration policy elements of the ISDHP.

Policy elements	Policy content	Mechanisms Involved
Industrial integration	Implement a "double transfer"; With the help of the industrial advantages of Shenzhen and Dongguan, reconstruct the industrial spatial layout, and focus on "points", "lines" and "surfaces" according to the industrial chain; Promote industrial transfer and structural upgrading, and form an industrial division of labor system	Industrial Chain Mechanism
Environmental protection integration	Signed the "Three Cities Boundary River and Cross-Boundary River Comprehensive Management Agreement", "Boundary River and Cross-Boundary River Comprehensive Management Task Force Charter" and other documents; Set up a cross-city environmental problem governance special group; Adopt strong systems such as the heavily polluting enterprise contracting system, reward system for reporting, and accountability system, etc; Promote the implementation of corporate pollution control and emission reduction work, and promote the governance of environmental problems across administrative regions	Green Innovation Mechanism
Transportation infrastructure integration	Sign the "Shenzhen-Dongguan-Huizhou Infrastructure Integration Plan", "Three Cities Boundary Road Construction and Connection Agreement", "Three Cities Cross-Border Passenger Line Bus Operation Cooperation Agreement", "Planning Integration Cooperation Agreement", and "Supplementary Agreement on Accelerating the Promotion of Transportation Integration"; Build a "five horizontal and three vertical" expressway network, formulate intercity rail planning, promote the reconstruction and resumption of flights at Pingtan Airport; Build the integrated transportation network	Industrial Chain, Green Innovation, Innovative, Market Competition Mechanisms
Technological innovation integration	The docking of the technology management system, the regular seminars of the leaders of the Science and Technology Bureau, and the docking of technology business and policies; Establish a database and a unified data information platform; Build cross-regional scientific and technological innovation carriers, such as innovation incubators and accelerators, high-tech industrial parks, industrial technology alliances, etc.; Regional cooperation in major scientific research projects to promote regional collaborative innovation	Green Innovation, Innovative Mechanisms
Market integration	Gradually clear up unreasonable administrative approval items; Gradually unify the scope of approval, approval standards, and approval procedures; Strengthen collaboration in the management of social and public affairs; Increase cooperation in regional education, health, medical care, social security, employment, and other social and public services; Eliminate the cross-city flow of people, finance and resources and market access restrictions, and establish a unified market.	Market Competition Mechanism

enterprises in the economic circle, thereby improving the TFP of these enterprises. Much literature supports this view. For example, Blankespoor et al. (2022) examine the integration effect such as the Jamuna Bridge construction in Bangladesh. They found that integration by the bridge construction led to economic revival in the Jamuna hinterland and increased productivity. In addition, under RIP, human capital represented by advanced managers will be efficiently circulated between regions. It can bring advanced management levels and allocation efficiency to some enterprises and improve the TFP of enterprises (Chang et al., 2016; Hou & Song, 2021). For China, Li et al. (2022) report similar conclusions. Therefore, RIP may have a positive impact on their TFP. Accordingly, we propose the first hypothesis:

H_{1a}: The ISDHP will have a positive impact on corporate TFP within the territory.

However, RIP does not always lead to high-quality development as expected while being introduced to more and more countries and regions. Scholars have even found the exact opposite conclusion. They believe that the RIP will interfere with the spatial location choice of enterprises and hinder the free choice and productivity ranking in market competition. It interferes with the resource allocation process, resulting in rising transaction costs and restricting the improvement of corporate TFP (Chuah et al., 2018; Chen & Lin, 2021). In addition, although the RIP can reduce transaction costs, however, this positive effect is mainly reflected in the core areas. For the non-central areas, excellent enterprises, resources, and factors are attracted and absorbed by central cities and regions. At the same time, relatively inefficient enterprises are squeezed into non-central areas. This will further deteriorate the productivity improvement of the non-central areas. This argument is supported by Lv et al. (2019). Based on the theoretical model of the new economic geography, they found that in the process of integration, low-productivity firms in developed regions migrated out first. Then the economic gap between regions is narrowing, but the productivity gap is widening. On this basis, we propose the following hypothesis:

H_{1b}: The ISDHP will have a negative impact on corporate TFP within the territory.

2.2.2 RIP's industrial integration measures and industrial chain mechanism

As mentioned in the introduction, scholars have confirmed the link between the industrial chain level and corporate TFP (Amiti et al., 2014; Baldwin & Yan, 2014; Chen H et al., 2021). As for China, due to its latecomer advantages, it can easily learn and absorb advanced production processes, management systems, and advanced technologies from importing countries in international trade (Liu et al., 2017; Chen W et al., 2021). However, the relationship between RIP and the industrial chain has been generally ignored in the existing literature.

As shown in Table 1, we can reasonably believe that RIP's industrial integration measures can reshape the industrial structure and layout of the economic circle. This makes the original homogeneous industrial competition evolve into a rational division of labor. On the one hand, industrial redistribution can stimulate the extension and expansion of the local industrial chain. This directly enhances the domestic connection of the industrial chain. The regional integration of the industrial chain will also enhance the international competitive advantage and connection of the industrial chain. On the other hand, enterprises in the economic circle can enjoy the amplification effect of the integrated local market in industrial redistribution. This will lead to an increase in competitiveness, allowing companies to climb further upstream in the global industrial chain and global value chain. Therefore, we propose the hypothesis as follows:

H_{2a}: Industrial chain linkage is an important mechanism for ISDHP to improve corporate TFP. ISDHP can significantly improve the upstream of the industrial chain of local enterprises and drive the growth of corporate TFP.

However, some scholars have found that the international linkage of the industrial chain may not always improve corporate productivity. For example, Daveri & Jona-Lasinio (2008) did not find the productivity improvement effect brought by international production segmentation in their research. Lin & Ma (2012) suggested that during their sample period Korea's experiment with service outsourcing did not lead to an increase in its productivity. This mismatch in the global industrial chain will somehow affect its positive impact on corporate TFP. On this basis, we propose the opposite hypothesis:

H_{2b}: The industrial chain connection has no significant mechanism role in the influence of the ISDHP on corporate TFP.

2.2.3 RIP's environmental protection integration measures and green innovation mechanism

Previous studies have shown that environmental policy has a significant impact on corporate green innovation (Hazarika & Zhang, 2019; Takalo & Tooranloo, 2021). As shown in Table 1, ISDHP has taken many environmental protection integration measures. These measures are indeed the environmental policy. Therefore, logically, RIP can convey green management signals to company management by exerting environmental pressure on enterprises. It will prompt company management to take green behavioral decisions in response to policy pressures from the integrated system of environmental protection (Wang et al., 2020; Liu et al. al., 2021). Thus, RIP can promote corporate green innovation. The improvement of corporate green innovation will inevitably lead to the improvement of corporate TFP. Therefore, we propose the green innovation mechanism hypothesis:

H_3: Green innovation plays a significant mechanism role in the influence of the ISDHP on corporate TFP.

2.2.4 RIP's infrastructure integration measures and innovative mechanisms

Theoretically, innovation integration can significantly improve the allocation efficiency of knowledge, technology, and human resources in the spatial dimension. It can significantly reduce the cost of acquiring advanced resources for enterprises. This helps to improve the probability of enterprises achieving technological innovation and independent innovation, thereby improving TFP (Davids & Frenken, 2018; Kijek & Matras-Bolibok, 2019). Based on that, we propose the innovation mechanism hypothesis:

H_4: ISDHP has significantly improved the local corporate TFP by enhancing the innovation capabilities and the green innovation level of the companies in the circle.

2.2.5 RIP's market integration measures and market competition mechanism

As shown in Table 1, the market integration policy measures in RIP aim to form a unified market within the economic circle. That is, to build a relatively unified and perfect market environment and form a market atmosphere with complete competitiveness. Therefore, we believe that the advancement of the market integration process in the integration of economic circles will help improve the degree of market competition, improve market efficiency, accelerates the replacement and elimination of outdated production capacity and technology, and improves the TFP of enterprises in the circle (Abdoh, 2019; Liu and Li, 2021). In conclusion, we propose the market competition mechanism hypothesis:

H_5: ISDHP significantly improves corporate TFP by raising the level of market competition in the economic circle.

3 Methodology and data

3.1 Methodology

The DID method is widely used in the existing literature when assessing the impact of a government's economic and social policy (Card and Krueger, 1994; Goodman-Bacon,2021).

Accordingly, we mainly use the multi-dimensional fixed-effects DID model to examine the impact of ISDHP on micro corporate TFP as follows:

$$tfp\_lp_{ijt} = \beta \underbrace{Post_t \times Treat_i}_{DID_{it}} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + Year_t + \varepsilon_{ijt} \quad (1)$$

In the above model, i represents the listed company, j represents the province, and t represents the year. tfp_lp_{ijt} is the dependent variable, and represents the TFP level of listed companies. $Post_t$ is the policy time dummy variable. $Treat_i$ is the dummy variable of the treatment group (whether the enterprise is within the spatial scope of the SDHEC). $X_{jk(t-1)}$ is the control variable with a lag of one period. $Firm_i$, $Province_j$, $Year_t$ represents the individual, province, and time fixed effect items, respectively. ε_{ijt} is the error term.

3.2 Variables

1) *Dependent Variable*. The existing methods for measuring the TFP of listed companies mainly include the parametric method, non-parametric method, and semi-parametric method. Among them, semi-parametric estimation has become the main method for estimating micro corporate TFP because it can avoid simultaneous bias and selection bias (Liu et al., 2017). Commonly used semiparametric methods are the OP method (Olley & Pakes, 1996) and the LP method (Levinsohn & Petrin, 2003). However, due to the high requirements of OP for raw data, scholars gradually turned to the LP method, which takes into account the problem of endogeneity and missing data, to estimate the TFP of listed companies (Lu & Lian, 2012). Therefore, this paper mainly refers to the practice of Zhang & Shen (2020), Giannetti, et al. (2015), Yang (2015), and other scholars. We first use the LP method to calculate the TFP of Chinese listed companies for benchmark model estimation. Secondly, we adopt the OP method and other methods to measure the TFP of various listed companies (*tfp_op, tfp_xie, tfp_liao*) for robustness testing. The input-output variables required for the calculation are as follows: Operating income (total output), net fixed assets (capital input), number of employees (labor input), intermediate inputs (operating cost plus selling expenses plus administrative expenses plus financial expenses minus depreciation and amortization minus paid to and for employees cash).

2) *Key Explanatory Variable*. The key explanatory variable in the benchmark model 1) is the multiplication term of the time dummy variable and the treatment group dummy variable $Post_t \times Treat_i$. $Post_t$ is the ISDHP time dummy variable, which is 0 before the policy is implemented and 1 after the policy is implemented. $Treat_i$ is a dummy variable of the treatment group, and enterprise i is within the spatial range of the SDHEC and takes one; otherwise, it takes 0. What we care about is the coefficient β of $Post_t \times Treat_i$, if it is significantly greater than 0, it means that deep ISDHP significantly improves corporate TFP, and if it is less than 0, it means it significantly inhibits corporate TFP.

3) *Key Mechanism Variables*. ①Industry chain mechanism variables. We choose the number of production stages in the industrial chain and the industrial chain position index to measure the level of the regional industrial chain. Accordingly, we examine how ISDHP affects the regional industrial chain and then act on corporate TFP. Based on the research of Wang (2017a, 2017b), we use the production chain forward link production length *Plv* to measure the number of production stages in the industrial chain. The larger the value *Plv*, the farther the sector is from the final consumer end, and the more upstream the sector is in the value chain of the industrial chain. Then we use the production chain backward link production length *Ply* to examine the upstream and downstream levels of the industry. The larger the value *Ply*, the closer the sector is to the final consumer, and the more downstream the sector is in the value chain of the industrial chain. Besides, we use the ratio of forward link production length to backward link production length *POS* and the APL-based production position index *POS_ APL* to measure the industrial chain position index (Wang, 2017a; Zhao). When the Position value is high, it means that this sector is relatively further from the final consumption end.

② Green Innovation mechanism variables. Based on the research of Li and Zheng (2016), Wang et al. (2021), etc., we use the number of green patent applications of listed companies to measure the level of corporate green innovation *GAP*. In addition, we use the ratio of the number of green patent applications filed by listed companies in the current year to the number of patents filed in the current year, *GAPR*, as another robustness test dependent variable.

③ Innovation mechanism variables. Based on the research of Im & Shon (2019), and Chen (2021), we use the number of patent applications filed by listed companies to measure the level of corporate innovation. Specifically, the number of patent applications of listed companies is obtained by adding up the number of invention patents and utility model patents of listed companies. In addition, we take the number of invention patents authorized by listed companies as a robust test in the follow-up study. To eliminate the obvious right-skewed distribution problem of the patent data of listed companies, we take the natural logarithm of the number of patents plus one to obtain APT_{ijt} and GPT_{ijt}.

④ Market competition mechanism. Based on the research of Yu et al. (2016) and other scholars, we use HHI (Wang & Zhou, 2017) and Lener Index (Zhang & Zhao, 2022) to measure the level of competitiveness of listed companies in the market. The values of HHI and LI reflect the level of monopoly power in the market in which the company is located. Therefore, the larger the value, the stronger the market monopoly power of the industry and the lower the degree of market competition.

4)*Control Variables*. To control the potential confounding factors that may affect the total factor productivity of enterprises and obtain more reliable estimation results of policy effects, based on the research of Chen W et al. (2021), Zhang and Liu (2022), and other scholars, the following enterprise-level variables are controlled: ① Enterprise size (Size); ② Asset-liability ratio (Lev); ③ Return on assets (ROA); ④ Enterprise TobinQ (TobinQ); ⑤ Enterprise age (Age). In addition, we also control for the fixed effect of the province, the individual company, and the year. It removes unobservable confounding factors at the regional and enterprise levels that do not change with time and time factors that do not change with individuals, to improve the credibility of policy effect estimates.

3.3 Data sources

The data used in this paper mainly come from three sources: listed company data, industry chain data, and patent data. In this study, the LP method is used to measure the explained variable corporate TFP, which requires input and output variables. These IO variables and the main control variables are all from the CSMRA listed company finance and characteristics database. We manually collect data on variables related to A-share listed companies. Financial insurance and abnormal trading listed companies (ST and PT listed companies) are excluded, and samples of companies with serious missing variables are also removed. The data for calculating the industrial chain comes from the ADB-MRIO in the UIBE GVC Indicators database RIGVC UIBE 2016. The ADB-MRIO (2021) database contains data from 63 countries and regions and 35 industrial sectors in 15 years from 2000 to 2007–2020. Based on the data of ADB-MRIO (2021) and the method of Wang (2017a, 2017b), this paper calculates the industrial chain length and industrial chain position data of various industries. To make full use of ADB-MRIO (2021), this paper selects the samples from 2007 to 2020 to match and merge with the data of listed companies to obtain the industrial chain data of listed companies.

In addition, to verify the innovation mechanism of ISDHP, the patent data of listed companies is also required. The patent data of listed companies including patent application data and patent authorization data comes from the China Research Data Service Platform (CNRDS). Then, we obtain the green patent data by matching the patent identification in the CNRDS with the "Green List of International Patent Classification" issued by the World Intellectual Property Organization (WIPO). Then, the characteristic data, the industrial chain data, and the patent data are matched and merged to obtain the final dataset. To eliminate the influence of extreme values, this paper performs a 1% Winsorize treatment on the main variables.

TABLE 2 Descriptive statistics.

Var	Obs	Mean	SD	Min	Median	Max
tfp_lp	30269	9.04	1.107	6.33	8.94	12.27
DID	30269	0.08	0.271	0.00	0.00	1.00
Plv	30269	3.05	0.795	1.04	3.00	4.99
Ply	30269	3.10	0.686	1.30	3.41	3.86
APT	30269	2.39	1.782	0.00	2.48	9.70
Size	30269	22.08	1.294	19.41	21.89	26.43
Lev	30269	0.42	0.208	0.03	0.42	0.92
ROA	30269	0.04	0.067	-0.40	0.04	0.25
TobinQ	30269	2.06	1.398	0.80	1.62	17.73
Age	30269	2.83	0.375	0.69	2.89	3.61

3.4 Descriptive statistics

Table 2 shows the descriptive statistics of the main variables. *tfp_lp* has a mean of 9.04, a standard deviation of 1.107, a minimum value of 6.33, and a maximum value of 12.27, and it shows that the TFP measured by the LP method is quite different among the sample listed companies. Similarly, the statistics of *Plv, Ply* and *APT* also show that the length of the regional industrial chain and the level of innovation among listed companies are quite different.

4 Empirical results

4.1 Parallel trend test

The important premise of using the DID model is that the policy treatment group and the control group have a significant parallel trend before the policy (Huang and Chen, 2022a; Wang et al., 2021). That is, before the implementation of the integration policy, the TFP levels of listed companies in Shenzhen-Dongguan-Huizhou and non-Shenzhen-Dongguan-Huizhou should have a significantly parallel time series trend. Based on the literature (Deschenes et al., 2017; Liu & Xiao, 2022), we use the event study method for reference to carry out the parallel trend test, and the model is as follows:

$$tfp\_lp_{ijt} = \sum_m \lambda_m Treat_i \times Time_m + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + \varepsilon_{ijt} \quad (2)$$

In model (2), $Time_m$ is the year dummy variable. λ_m is the coefficient of the difference between the treatment group and the control group affected by the policy effect in the corresponding year. According to the model estimation results, draw a parallel trend test result graph, as shown in Figure 1. There is no significant difference between the treatment group and the control group before the implementation of the integrated policy, which satisfies the parallel trend assumption.

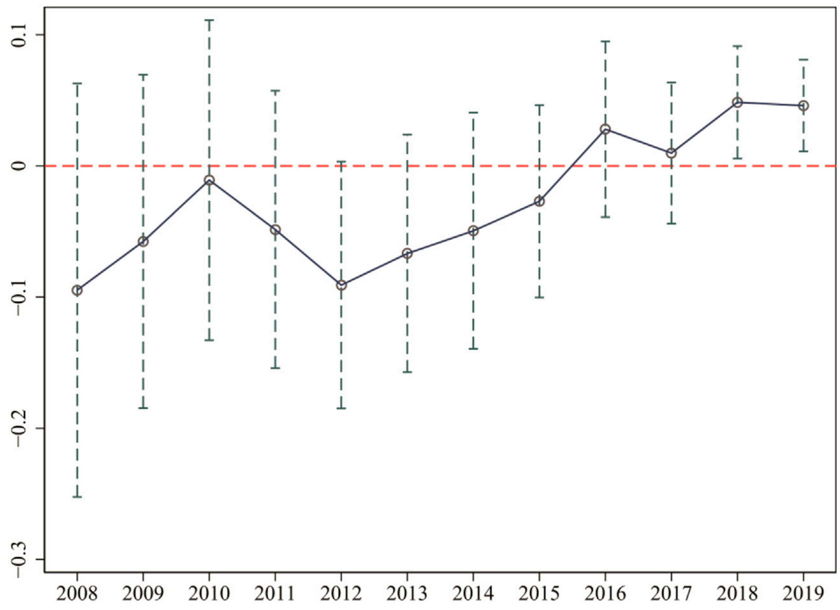

FIGURE 1
Parallel trend test (PS: The figure is drawn according to the value and the confidence interval of the coefficient $\lambda_m$estimated by the event study model).

TABLE 3 Baseline regression results.

Model	(1)	(2)	(3)	(4)	(5)
DID	0.045*	0.098***	0.113**	0.174***	0.162***
	(0.025)	(0.016)	(0.048)	(0.014)	(0.015)
Obs	30,269	28,181	30,072	27,982	4,155
R-squared	0.0001	0.677	0.868	0.918	0.917
Controls	N	Y	N	Y	Y
Province FE	N	N	Y	Y	N
Year FE	N	N	Y	Y	Y
Firm FE	N	N	Y	Y	Y

Ps: Robust standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

4.2 Benchmark results

As shown in Table 3, columns (1)–4) are the results of the average treatment effect estimated by the DID model with or without the control variable and fixed effect. Column 4) is the estimation result of the benchmark model (1). By comparison, we can examine the difference in estimated results with or without control variables and with or without fixed effects. The results show that after controlling for firm-level control variables and fixed effects, ISDHP has a significant promoting effect on the TFP of listed companies. The estimated coefficient is significant at the 1% confidence level. The above benchmark regression results for the first time confirm the significant improvement effect of Chinese ISDHP on corporate TFP, which is consistent with the theoretical hypothesis H_{1a}.

In addition, column 5) in Table 3 is the estimation result of selecting the listed companies in Guangdong Province to identify the benchmark model. When the sample is limited to Guangdong Province, the baseline estimation results are still significant at the 1% confidence level, again supporting the theoretical hypothesis H_{1a}.

To understand the time series characteristics of policy effects more clearly, we added dynamic policy effect analysis to the benchmark regression.

As shown in Table 4, column 1) is the dynamic policy effect analysis results of the full sample. After the policy is implemented, RIP has a positive impact on corporate TFP and the policy effect varies over time. However, from 2011 to 2013, the policy effect is not significant, and after that turns to positive and significant. In addition, we add the dynamic policy effect analysis of the Guangdong Province sample for the robust test as shown in column (2). It found that the policy effect still varies over time and the policy effect disappears in 2011–2013 and 2018–2019.

4.3 Robustness tests

4.3.1 Dynamic sliding window test

The previous article has analyzed the average policy effect of ISDHP on corporate TFP and lacks a sufficient comparison

TABLE 4 Dynamic policy effect analysis results.

Model	(1)	(2)
Treat × year09	0.134*	0.135*
	(0.074)	(0.075)
Treat × year10	0.154**	0.148*
	(0.078)	(0.080)
Treat × year11	0.141	0.139
	(0.089)	(0.089)
Treat × year12	0.153	0.147
	(0.094)	(0.096)
Treat × year13	0.144	0.134
	(0.095)	(0.096)
Treat × year14	0.182*	0.170*
	(0.097)	(0.098)
Treat × year15	0.178*	0.165*
	(0.098)	(0.099)
Treat × year16	0.233**	0.219**
	(0.104)	(0.106)
Treat × year17	0.196*	0.181*
	(0.103)	(0.105)
Treat × year18	0.189*	0.171
	(0.103)	(0.105)
Treat × year19	0.187*	0.167
	(0.103)	(0.105)
Treat × year20	0.206**	0.187*
	(0.103)	(0.105)
Obs	27,982	4,155
R-squared	0.918	0.918
Controls	Y	Y
Province FE	Y	Y
Year FE	Y	Y
Firm FE	Y	Y

Ps: Robust standard errors in parentheses, $^{**}p < 0.05$, $^{*}p < 0.1$.

TABLE 5 Dynamic sliding window test results.

Model	2 Years		3Years	
Model	(1)	(2)	(3)	(4)
DID	0.106***	0.092**	0.133***	0.124***
	(0.017)	(0.018)	(0.016)	(0.019)
Obs	5,044	593	9,333	1,221
R-squared	0.963	0.961	0.957	0.958
Controls	Y	Y	Y	Y
Province FE	Y	N	Y	N
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y

Ps: Robust standard errors in parentheses, $^{***}p < 0.01$, $^{**}p < 0.05$.

TABLE 6 Counterfactual test results.

Model	Pre 1		Pre 2	
Model	(1)	(2)	(3)	(4)
DID	0.019	0.002	0.019	0.002
	(0.052)	(0.051)	(0.052)	(0.051)
Obs	28,181	4,190	28,181	4,190
R-squared	0.693	0.680	0.693	0.680
Controls	Y	Y	Y	Y
Province FE	Y	N	Y	N
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y

Ps: Robust standard errors in parentheses.

before and after the policy is introduced. Therefore, referring to the research method of Shi and Li (2020), the difference in corporate TFP in different periods was tested by changing the time window width before and after the introduction of ISDHP. Specifically, 2 and 3 years are selected as the window width for the dynamic sliding window test.

The test results are shown in Table 5. Changing the width of the time window does not change the direction of the impact of ISDHP on corporate TFP. It indicates that the estimation results of the benchmark model are robust, again supporting the theoretical hypothesis H_{1a}.

4.3.2 Counterfactual test

To make the benchmark regression results credible, this paper advances the ISDHP time by 1 year (Pre1) and 2 years (Pre2) and conducts a counterfactual test on the average treatment effect of RIP on SDHEC's corporate TFP.

The results are shown in Table 6 below. When we advance the ISDHP time by 1 year and 2 years, the effect of RIP on corporate TFP is not statistically significant. It stated that when ISDHP was not implemented, RIP did not have any significant impact on SDHMC's corporate TFP. Therefore, the baseline model regression results are robust, which again supports the theoretical hypothesis H_{1a}.

4.3.3 Placebo test

Although DID estimates can mitigate potential unobservable confounders to some extent, self-selection bias may still exist in the treatment groups. Therefore, referring to the research of Huang and Chen (2022b), and Wang et al. (2021), we further avoid this bias by conducting multiple random sampling experiments. Specifically, we randomly sample 1,000 times to obtain a virtual experimental group and a control group and apply the benchmark estimation model to identify policy effects. The results of the placebo test were examined by plotting the kernel density curve and the distribution of policy effect coefficients as shown in Figure 2. It shows the distribution of

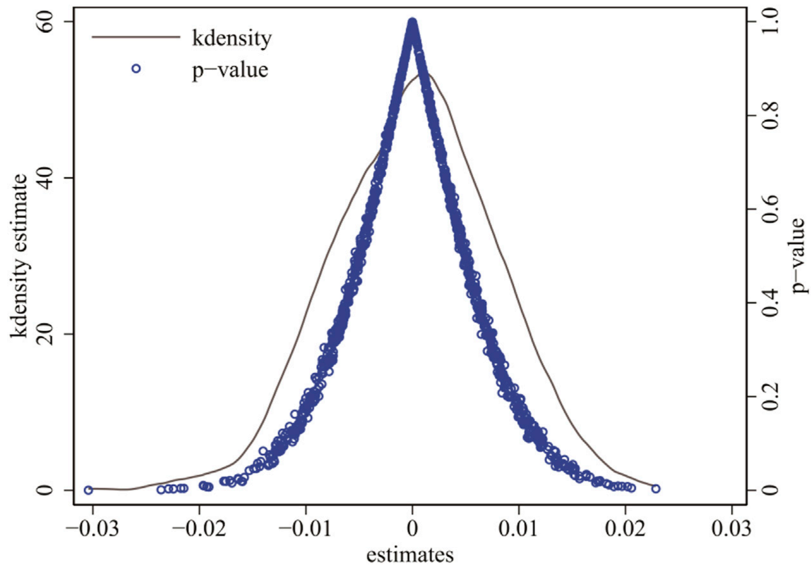

FIGURE 2
Placebo test. (PS: Figure is the plot of kernel density and p-value distribution of coefficients estimated with random sample 1,000 times based on the benchmark estimation.)

TABLE 7 Baseline regression with different dependent variables.

Variables	*tfp_op*		*tfp_xie*		*tfp_liao*	
Model	(1)	(2)	(3)	(4)	(5)	(6)
DID	0.199***	0.188*	0.182***	0.169**	0.098***	0.088
	(0.003)	(0.097)	(0.003)	(0.081)	(0.003)	(0.047)
Obs	28,298	4,211	15,797	2,275	15,686	2,269
R-squared	0.867	0.866	0.945	0.950	0.865	0.868
Controls	Y	Y	Y	Y	Y	Y
Province FE	Y	N	Y	N	Y	N
Year FE	Y	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y	Y

Ps: Robust standard errors in parentheses, ***p < 0.01, **p < 0.05, *p < 0.1.

TABLE 8 DDD estimation result.

Model	(1)	(2)	(3)	(4)
Variables	*tfp_lp*	*tfp_op*	*tfp_xie*	*tfp_liao*
DDD	0.026***	0.115***	0.036***	0.004
	(0.003)	(0.003)	(0.004)	(0.003)
DID	0.156***	0.155***	0.171***	0.091***
	(0.002)	(0.002)	(0.003)	(0.003)
YGA	0.074***	−0.015***	0.123***	0.123***
	(0.002)	(0.002)	(0.001)	(0.001)
Obs	27,982	28,298	15,797	15,686
R-squared	0.918	0.868	0.946	0.865
Controls	Y	Y	Y	Y
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y

Ps: Robust standard errors in parentheses, ***p < 0.01.

DID term coefficients in the random sampling estimation results. It can be found that most of the sampling estimation coefficients still have a low pass rate at the 10% confidence level, that is, the significance of the placebo sampling results fails. It indicates that the policy effect of the ISDHP does not exist significantly in the random sampling simulation, that is, the baseline estimate results pass the placebo test.

4.3.4 Change the dependent variable

Based on the practice of Zhang & Shen (2020), and Yang (2015), we change the dependent variable for robustness testing, and re-identified and estimated the benchmark model (1). This processing method can exclude the influence of unobservable confounding factors that may be ignored by the LP method.

The estimation results are shown in Table 7. Columns (1), (3), and 5) are the analysis results of different dependent variables using the benchmark model 1) to estimate policy

TABLE 9 Ownership heterogeneity estimation results.

Model	(1)	(2)	(3)	(4)
Variables	*tfp_lp*	*tfp_op*	*tfp_xie*	*tfp_liao*
*DID*SOE*	0.280***	0.254***	0.212***	0.095***
	(0.018)	(0.016)	(0.013)	(0.024)
DID(1-SOE)*	0.097***	0.155***	0.161***	0.099***
	(0.014)	(0.013)	(0.016)	(0.021)
Obs	27,982	28,298	15,797	15,686
R-squared	0.918	0.868	0.945	0.865
Controls	Y	Y	Y	Y
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y
F(H_{SOE})	35.11	12.31	3.31	0.01
p-value (H_{SOE})	0.000***	0.001***	0.079*	0.931

Ps: Robust standard errors in parentheses, $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

TABLE 10 Industry chain linkage mechanism estimation results.

Variables	*Plv*		*Ply*	
Model	(1)	(2)	(3)	(4)
DID	0.051***		-0.079***	
	(0.002)		(0.004)	
*DID*SOE*		0.115***		-0.126***
		(0.025)		(0.017)
DID(1-SOE)*		0.044***		-0.041***
		(0.005)		(0.012)
Obs	29,203	29,203	29,203	29,203
R-squared	0.859	0.859	0.895	0.893
Controls	Y	Y	Y	Y
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y
F(H_{SOE})		6.05		23.72
p-value (H_{SOE})		0.020**		0.000***

Ps: Robust standard errors in parentheses, $^{***}p < 0.01$, $^{**}p < 0.05$.

effects. It finds that the estimated results of the three groups of dependent variables are all significantly positive at the 1% confidence level. It shows that the promotion effect of ISDHP on corporate TFP is still significant under various measurement methods. The benchmark estimation results are robust, and hypothesis H_{1a} is verified again.

In addition, we also estimate the sample from Guangdong Province alone. Columns (2), (4), and 6) are the analysis results of different dependent variables. The estimated results are significant when the sample is limited to Guangdong Province. It supports the theoretical hypothesis H_{1a} again.

4.3.5 Control the confounding effects of the guangdong-Hong Kong-Macao greater bay area

We construct policy dummy variables for the Guangdong-Hong Kong-Macao Greater Bay Area and incorporate them into the benchmark model to control for confounding effects. The estimated results are shown in Table 8.

$$tfp\_lp_{ijt} = \delta \underbrace{Post_t \times Treat_i \times YGA_{pq}}_{DDD} + \lambda \underbrace{Post_t \times Treat_i}_{DID} + \gamma YGA_{pq} + \sum_k \eta_k X_{jk(t-1)} + Firm_i + Province_j + Year_t + \varepsilon_{ijt} \tag{3}$$

Columns 1) to 4) in Table 8 are the estimated results of different dependent variables. The results are all significantly positive at the 1% level. It shows that after controlling the confounding effects of the Guangdong-Hong Kong-Macao Greater Bay Area, the ISDHP still has a positive effect on corporate TFP. It verifies hypothesis H_{1a} again and verifies the robustness of the benchmark estimation results.

4.4 Ownership heterogeneity

Ownership is an important factor affecting the innovation and development of firms in China (Huang & Chen, 2022b). State-owned enterprises and private enterprises may enjoy different "treatment" in the face of government policies. Therefore, we performed estimation analyses of all fabrications as significant sources of heterogeneity. Drawing on the practice of Jiang (2022), we apply a DDD estimation model to investigate ownership heterogeneity. This model can not only directly show the difference in the policy effect coefficient, but also can be achieved by testing H_{SOE}: $\gamma_1 = \gamma_2$. The test model is as follows:

$$tfp\_lp_{ijt} = \gamma_1 DID_{it} \times SOE_{it} + \gamma_2 DID_{it} \times (1 - SOE_{it}) + \theta SOE_{it} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + year_t + \varepsilon_{ijt} \tag{4}$$

The estimated results are shown in Table 9. Columns (1)–4) are the estimated results of ISDHP policy effects on enterprises of different ownerships, respectively, with different dependent variables. The results show that the policy effect coefficients of state-owned listed companies are all larger than those of private listed companies. The three H_{SOE}: $\gamma_1 = \gamma_2$ tests all reject the null hypothesis. It shows that the state-owned listed companies in the economic circle get more TFP promotion effect under ISDHP. The difference between the two coefficients is significant. The general explanation for this difference in policy effects is that private enterprises may be subject to "policy discrimination" in

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spatial planning policies. The resource allocation department is more inclined to prefer policy resources to state-owned listed companies. It is difficult for private enterprises to enjoy the same "policy treatment" as state-owned enterprises, which is in line with China's actual national conditions.

5 Mechanism analysis

5.1 Industry chain mechanism

5.1.1 Industry chain linkage mechanism

To test whether ISDHP exerts its policy effect by affecting the linkage of the industrial chain, we use *Plv* and *Ply* to test the mechanism:

$$\underset{\{Ply_{ijt}\}}{Plv_{ijt}} = \beta \underbrace{Post_t \times Treat_i}_{DID_{it}} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + Year_t + \varepsilon_{ijt} \quad (5)$$

The estimated results are shown in Table 10. Columns 1) and 3) are the estimated results. The results in column 1) show that ISDHP helps to improve the production length of the forward linkage of the industrial chain. The estimated coefficient is significant at the 1% level, indicating that ISDHP significantly improves the upstream degree of local enterprises in the global industrial chain. The results in column 3) show that ISDHP helps to shorten the production length of backward linkages in the industrial chain. The estimated coefficient is significant at the 1% level, indicating that ISDHP significantly reduces the downstream degree of territorial enterprises in the global industrial chain. On the one hand, it proves that the industrial chain climbing effect is an important mechanism for ISDHP on corporate TFP. That is, hypothesis H_{2a} is proved. On the other hand, the results show that under the ISDHP, industrial integration has gradually advanced. It will help the SDHEC to absorb the technology diffusion of developed countries through import and export trade. This gradually improves the upstream level of local enterprises participating in the global industrial chain and leads to independent innovation. The dependence on the import of intermediate goods from developed economies is gradually reduced, the domestic industrial chain is continuously strengthened, and the downstream degree is significantly reduced.

Secondly, columns 2) and 4) are the estimation results of the DDD estimation model. We found that the estimated coefficients of *DID*SOE* and *DID**(1-*SOE*) were both significant at the 1% level. The H_{SOE} test showed that there was a significant difference between the two coefficients. It means that ISDHP can better promote the upstream status of state-owned listed companies in the global industrial chain. It can also shorten the downstream status of local state-owned listed companies in the global industrial chain.

TABLE 11 Industry chain linkage mechanism estimation results.

Variables	*Plv_d*		*Plv_o*	
Model	**(1)**	**(2)**	**(3)**	**(4)**
DID	0.021***		0.030**	
	(0.001)		(0.011)	
*DID*SOE*		0.000		0.088**
		(0.007)		(0.032)
*DID**(1-*SOE*)		0.028***		-0.016
		(0.004)		(0.018)
Obs	29,203	29,203	29,203	29,203
R-squared	0.861	0.858	0.863	0.859
Controls	Y	Y	Y	Y
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y
F(H_{SOE})		25.85		14.57
p-value (H_{SOE})		0.000***		0.001***

Ps: Robust standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$.

The possible explanation is that under ISDHP, state-owned listed companies have more policy support than private listed companies. It enables state-owned listed companies to have certain policy advantages over private enterprises in the process of import and export trade. Thus, the process of absorbing advanced technologies is earlier, wider, or even faster. Then, state-owned entities can perform better in the global industrial chain and value chain.

In addition, based on the research of Wang (2017b), we also decompose *Plv* into forward link pure domestic production length *Plv_d* and international production length *Plv_o*. We use these two decomposition quantities to estimate the ISDHP policy. The estimation model is as follows:

$$\underset{\{Plv\_o_{ijt}\}}{Plv\_d_{ijt}} = \beta \underbrace{Post_t \times Treat_i}_{DID_{it}} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + Year_t + \varepsilon_{ijt} \quad (6)$$

The estimated results are shown in Table 11. Columns 1) and 3) are the estimated results of different dependent variables. The estimated coefficients are significant at the level of 1 and 5%, respectively. This indicates that ISDHP has significantly improved the pure domestic production length *Plv_d* and the international production length *Plv_o* of the forward linkage of local enterprises. It means that whether the domestic connection or the international connection, ISDHP has shown a significant positive promotion effect, which verifies hypothesis H_{2a} again.

Columns 2) and 4) are the results of the ownership heterogeneity estimation. The results show that the domestic linkages are mainly driven by private listed companies, while the

TABLE 12 Industry chain position mechanism estimation results.

Variables	POS		POS_APL	
Model	(1)	(2)	(3)	(4)
DID	0.058***		0.023***	
	(0.001)		(0.000)	
*DID*SOE*		0.106***		0.048***
		(0.010)		(0.003)
*DID**(1-*SOE*)		0.052***		0.020***
		(0.002)		(0.001)
Obs	29,203	29,203	29,203	29,203
R-squared	0.863	0.863	0.873	0.873
Controls	Y	Y	Y	Y
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y
F(H_{SOE})		20.39		62.40
p-value (H_{SOE})		0.000***		0.000***

Ps: Robust standard errors in parentheses, ***p < 0.01.

TABLE 13 Green innovation mechanism estimation results.

Variables	GAP		GAPR	
Model	(1)	(2)	(3)	(4)
DID	0.222***		0.036***	
	(0.006)		(0.001)	
*DID*SOE*		-0.027		-0.004
		(0.052)		(0.053)
*DID**(1-*SOE*)		0.181***		0.208***
		(0.007)		(0.006)
Obs	13,686	13,686	13,686	13,687
R-squared	0.238	0.239	0.058	0.228
Controls	Y	Y	Y	Y
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y
F(H_{SOE})		19.60		18.81
p-value (H_{SOE})		0.000***		0.000***

Ps: Robust standard errors in parentheses, ***p < 0.01.

international linkages are mainly driven by state-owned listed companies. The estimated coefficients are significant at the levels of 1 and 5%, respectively. Private enterprises are relatively small in scale compared to state-owned enterprises, and their competitiveness in participating in international trade is weaker. Therefore, private enterprises are more inclined to distribute production activities in the domestic production network. While state-owned enterprises will choose to embed some production activities in the international production division network in international trade.

5.1.2 Industry chain position mechanism

In addition, we also use the position index to further examine how ISDHP affects the position of the industry chain to the promotion of corporate TFP. We use *POS* and *POS_APL* to measure the industrial chain position index. Then, we construct the following model to continue testing the mechanism:

$$\underset{POS\_APL_{ijt}}{POS_{ijt}} = \beta \underbrace{Post_t \times Treat_i}_{DID_{it}} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + Year_t + \varepsilon_{ijt} \tag{7}$$

Theoretically, the larger the *POS* and *POS_APL* values, the stronger the international competitiveness of the company. The estimation results are shown in Table 12. Columns 1) and 3) are the estimation results of *POS* and *POS_APL* identified by applying the above model as dependent variables, respectively. The study found that ISDHP helps to promote local enterprises to climb to a higher upstream position in the process of participating in the international industrial chain. The estimated coefficients are all significant at the 1% level. On the one hand, it again demonstrates that the industrial chain climbing effect is an important mechanism for ISDHP to improve corporate TFP. That is, hypothesis H_{2a} has been verified again. On the other hand, the results show that ISDHP helps to obtain advanced technology diffusion from developed countries. It thereby improves corporate TFP and promotes enterprises to climb to the upstream position in the competition of the global industrial chain.

Secondly, columns 2) and 4) are the estimation results of the DDD estimation. The estimated coefficients of *DID*SOE* and *DID**(1-*SOE*) were both significant at the 1% level. The H_{SOE} test showed that there was a significant difference between the two coefficients. It shows that ISDHP can better promote the state-owned listed companies to climb the upstream position of the global industrial chain. The possible explanation is still that ISDHP is more conducive to the state-owned listed companies to climb the global industrial chain. Compared with state-owned companies, private listed companies have relatively weaker policy advantages and resource support. Thus, they are weaker than state-owned listed companies in participating in international competition. Therefore, the policy promotion effect is not as good as that of state-owned units, but the policy promotion effect still exists and is significant.

5.2 Green innovation mechanism

We use *GAP*, which is the logarithm of the number of green patent applications of listed companies plus 1, to measure the

TABLE 14 Innovation mechanism estimation results.

Variables	*APT*		*GPT*	
Model	(1)	(2)	(3)	(4)
DID	0.169***		0.016*	
	(0.009)		(0.008)	
*DID*SOE*		0.302***		-0.124**
		(0.061)		(0.053)
DID(1-SOE)*		0.165***		0.010
		(0.006)		(0.007)
Obs	22,834	22,834	22,489	22,489
R-squared	0.778	0.778	0.793	0.793
Controls	Y	Y	Y	Y
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y
F(H_{SOE})		5.07		6.14
p-value (H_{SOE})		0.032**		0.017**

Ps: Robust standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$.

TABLE 15 Market competition mechanism estimation results.

Variables	*HHI*		*LenC*	
Model	(1)	(2)	(3)	(4)
DID	−0.046***		−0.008***	
	(0.001)		(0.001)	
*DID*SOE*		−0.007		−0.025***
		(0.007)		(0.003)
DID(1-SOE)*		−0.051***		−0.007***
		(0.003)		(0.001)
Obs	16,268	16,268	16,268	16,268
R-squared	0.954	0.954	0.801	0.801
Controls	Y	Y	Y	Y
Province FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y
F(H_{SOE})		20.95		23.01
p-value (H_{SOE})		0.000**		0.000***

Ps: Robust standard errors in parentheses, ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

level of corporate green innovation. In addition, we also use the ratio of the number of green patent applications of listed companies to the number of patents applied for in the year, *GAPR*, as a proxy variable for green innovation to conduct robustness tests.

The estimation results are shown in Table 13. Columns 1) and 3) are the estimation results when GAP and GAPR are the dependent variables, respectively. The results show that, after controlling for multidimensional fixed effects, RIP has a positive effect on corporate green innovation. The estimated coefficient is significant at the 1% confidence level. The above results for the first time confirm the significant promotion effect of China's RIP on corporate green innovation from the enterprise level. It confirms the role of green innovation as an intermediary mechanism in RIP on corporate TFP, which verified hypothesis H_3.

Besides, we further analyzed the ownership heterogeneity of this mechanism using the DDD method, and the results are shown in columns 2) and 4) of Table 13. The results show that the policy effect coefficients of state-owned listed companies are smaller than those of private listed companies. The H_{SOE} test rejects the null hypothesis. This shows that the private listed companies get more green innovation promotion effects under ISDHP, and the coefficient difference is significant. The environmental protection integration policy in RIP is a mandatory regulatory policy. Compared with state-owned listed companies, private listed companies will face greater policy constraints. This drives private enterprises to have greater incentives for green decision-making, which in turn improves the level of green innovation.

5.3 Innovation mechanism

Innovation synergy or innovation integration is an important part of ISDHP. We use the total number of patents applied for by listed companies in the year *APT* and the total number of patents granted in the year *GPT* to measure the level of enterprise innovation. Then, we construct the following model to verify the hypothesis H_4:

$$\underset{GPT_{ijt}}{APT_{ijt}} = \beta \underbrace{Post_t \times Treat_i}_{DID_{it}} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + Year_t + \varepsilon_{ijt} \tag{8}$$

The estimation results are shown in Table 14. Columns 1) and 3) are the estimation results of *APT* and *GPT* used as dependent variables to identify the above models. The study found that ISDHP helps to promote the innovation level of local enterprises, and the estimated coefficients are all significant at the 1% level. On the one hand, it proves that the innovation effect is an important mechanism for ISDHP to improve corporate TFP. That is, it is assumed that H_4 is proved. On the other hand, the results show that ISDHP helps to improve the level of technological innovation of enterprises in the circle, and then enhances corporate TFP.

Columns 2) and 4) are the estimation results of the DDD estimation. The estimated coefficients of *DID*SOE* and *DID**(1-*SOE*) in column 2) were both significant at the 1% level. The estimated coefficients were significantly different through the H_{SOE} test. That is, the estimated coefficients of *DID*SOE* were

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significantly greater than that of *DID**(1-*SOE*). It shows that ISDHP is more conducive to the state-owned listed companies in the circle. The *DID*SOE* of column 4) is significantly negative at the 5% level, but the estimated coefficient of *DID**(1-*SOE*) is not significant. The H_{SOE} test proves that the two coefficients are significantly different. It shows that the ISDHP is not conducive to increasing the number of patents granted by state-owned listed companies in the circle.

5.4 Market competition mechanism

We use *HHI* and *LI* to measure the level of market competitiveness of enterprises, and then investigate the mechanism role between ISDHP and corporate TFP. To test the above mechanism, that is, the hypothesis H_5, we construct the following model:

$$\underset{LenC_{ijt}}{HHI_{ijt}} = \beta \underbrace{Post_t \times Treat_i}_{DID_{it}} + \sum_k \rho_k X_{jk(t-1)} + Firm_i + Province_j + Year_t + \varepsilon_{ijt} \quad (9)$$

Theoretically, the lower the *HHI* and *LI* values of listed companies, the higher the actual competitiveness level. Thus, the *DID* coefficient should be negative. The estimation results are shown in Table 15. Columns (1) and (3) are the estimation results of *HHI* and *LI* as dependent variables. The *DID* estimation coefficients of the two models were both significantly negative at the 1% level. On the one hand, it demonstrates that market competitiveness is an important mechanism for ISDHP on corporate TFP. Hypothesis H_5 was verified. On the other hand, it also shows that ISDHP can promote corporate TFP by improving the market competitiveness of enterprises.

In addition, columns 2) and 4) are the estimation results of the DDD estimation. The estimated coefficient of *DID**(1-*SOE*) of column 2) is significantly negative at the 1% level. The estimated coefficients of *DID*SOE* and *DID**(1-*SOE*) in column 4) are both significantly negative at the 1% level. The estimated coefficients of the two models *DID*SOE* and *DID**(1-*SOE*) are significantly different through the H_{SOE} test. That is, the estimated coefficient of *DID*SOE* is significantly larger than that of *DID**(1-*SOE*). It shows that ISDHP is more conducive to the state-owned enterprises to gain more market competitiveness. It is also in line with China's actual national conditions.

6 Conclusion and recommendations

Based on the quasi-natural experiment of ISDHP in China, this research is the first paper to examine the impact of RIP on corporate TFP from the perspective of the industrial chain. Our research provides new perspectives and new ideas for the research on the influencing factors of corporate TFP, RIP, and industrial chain linkage in emerging economies. Based on an empirical study by applying a multi-dimensional fixed-effects DID model, we found that: Firstly, ISDHP has a positive impact on corporate TFP. Moreover, the policy effect shows a more significant TFP improvement effect in the state-owned enterprise group. It is consistent with the conclusions of the existing literature (Li et al., 2022). Secondly, the level of the industrial chain linkage is an important mechanism for RIP to improve corporate TFP. It is mainly achieved by improving the upstream degree of local enterprises embedded in the global industrial chain. However, existing research lacks to explore the micro-policy effects of regional integration from this perspective. Further research finds that the RIP can also improve the corporate TFP by enhancing the level of corporate green innovation, innovation, and market competitiveness. Corporate ownership has a significant heterogeneity moderating effect on different mechanisms. The TFP of state-owned listed companies is significantly more positively affected by policy effects than private enterprises. Overall, China's ISDHP has achieved its goal of improving corporate TFP. The above research provides ideas for subsequent scholars to introduce micro-effect evaluation similar to RIP in other emerging economies.

Although from the perspective of the industrial chain, this paper provides an econometric empirical analysis from SDHEC in China for the TFP improvement effect of ISDHP, however, it is subject to several limitations: ① Although this study investigates the policy effects of RIP on corporate TFP in SDHEC. However, due to the limitations of the sample of listed companies, it is difficult to reflect the more general effect of RIP truly and comprehensively. There will be some sample bias. ②This study attempts to explore the policy effect mechanism from the perspective of the industrial chain. However, due to the close economic ties between the cities of SDHEC, our research inevitably ignores the spatial correlation of policy effects. Future research can consider the following ideas for improvement: ① Match the Chinese industrial enterprise database data with the customs database data and try to re-examine policy effects using microdata. It can improve the confidence of the analysis and reduce possible sample bias. ② The MRIO data can be used to construct the spatial weight matrix, and then to perform spatial DID analysis on the micro data. It will identify the spatial effects of policy and increase the credibility of the research.

In conclusion, our findings support the positive impact of China's ISDHP on industrial chain climbing, corporate innovation, market competition, and corporate TFP. Therefore, it is necessary to increase the policy design of these key mechanism factors. ①According to the requirements of industry chain supply chain segmentation, strengthen more specialized personnel training. Cultivate cross-field, cross-industry, and interdisciplinary human capital, and give play to the role of compound talents as the "glue" between the industrial chain and supply chain. Build a modern financial service system that adapts to the modernization of the industrial chain and supply chain. ②Cultivate a group of technologically advanced "little giant" enterprises with a leading role. Give full play to its main role in key technological breakthroughs and innovation. Play its leading role in creating new markets. ③ By establishing a negative list for the integration of economic circles. Clarify the boundaries of the role of the market and the government in the practice of regional integration. Build a more free market competition environment to reduce the distortion of factor allocation between regions, within and between industry chains by administrative intervention. Give full play to the decisive role of the market in the allocation of factors.

However, our research results show that the existing ISDHP has certain problems. The policy effect of RIP appears ownership discrimination, showing a significant "state-owned tilt" feature. Therefore, it is necessary to establish and improve the information disclosure and supervision system for non-listed companies based on the existing information disclosure system of listed companies in the future ISDHP practice. Besides, taking measures such as introducing NGO supervision, reducing the probability of local government ownership discrimination, and achieving a balanced development of "state-owned" and "private".

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

Methodology, CG; software, CG; data curation, CG and HD; writing—original draft preparation, HD and CG; writing—review and editing, HD, CG, and HY; visualization, CG and HD; supervision, HD, CG, and HY; project administration, HD and CG; funding acquisition, HD and CG. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The effects of energy taxes level on greenhouse gas emissions in the environmental policy measures framework

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Over the last decades, all countries have pursued an ambitious climate policy, thus showing a growing concern about climate change, global warming, greenhouse gas (GHG) emissions, or environmental taxes. Water, air, and soil pollution caused by gas emissions directly affect human health, but also the economies of states. As people's ability to adapt to novel changes becomes increasingly difficult, globally, they are constantly trying to reduce their greenhouse gas emissions in a variety of ways. Environmental taxes, in general, and energy taxes, in particular, are considered effective tools, being recommended by specialists, among other instruments used in environmental policy. The aim of this research is to assess, empirically, the influence of environmental taxes levels on greenhouse gas emissions in 28 European countries, with a time span between 1995 and 2019. Regarding the empirical research, the proposed methods are related to Autoregressive Distributed Lag (ARDL) models in panel data and also at country level. At panel level, we used the estimation of non-stationary heterogeneous panels and also the dynamic common-correlated effects model with heterogeneous coefficients over cross-sectional units and time periods. The results obtained show that the increase in environmental taxes leads, in most countries, to a decrease in greenhouse gas emissions. To test the robustness of our results, we have included supplementary economic and social control variables in the model, such as gross domestic product (GDP), population density, exports, or imports. Overall, our paper focuses on the role of environmental policy decisions on greenhouse gas emissions, the results of the study showing, in most cases, an inverse impact of the taxation level on the reduction of gas emissions.

KEYWORDS

greenhouse gas (GHG) emissions, environmental policy, environmental taxes, economic development, European countries

Introduction

The interest of people and governments in global warming and climate change has grown in recent years. The increase in temperature on our planet is mainly generated by greenhouse gas (GHG) emissions. The European Union has stated over the years that preventing climate change is one of its top priorities, thus encouraging other countries to adopt this strategy (Trends and Projections in Europe 2021 — European Environment Agency). It has supported, from the outset, the reduction of greenhouse gas emissions by at least 20% until 2020 (compared to 1990) and then 40%–60% until 2040. Also, another strategic goal of the EU is to reduce greenhouse gas emissions by up to 80% until 2050.

The issue of the impact of economic growth on the environment has been discussed at length by a number of economists. Thus, among the first studies that analyzed this topic is *The Limits to Growth* by (Meadows et al., 1974). Their results showed that the rates of some variables such as population growth, resource use, and pollution level increased depending on the trajectory of the exponential function. Economic growth requires higher energy consumption, and more efficient use of energy requires a higher level of economic growth. Thus, studies (Iwata et al., 2011; Fujii and Managi, 2013) have shown that the energy sector is considered to be the strongest determinant of greenhouse gas (GHG) emissions.

The interest of the world's population in the risks of climate change has grown since the first decade of the 21st century, following evidence of human influence on the climate system. Currently, European countries face two major dilemmas (Wang et al., 2021), namely economic development and environmental conservation. In Europe, the main industries underlying economic development play an important role in increasing the level of greenhouse gas emissions (Smith et al., 2021; Zhang et al., 2021; Zhao et al., 2021). The current policy of the states of the world is used as a tool in reducing the level of gas emissions. Thus, various taxes are implemented (Shahzad, 2020) in order to reduce the level of pollution. Although the pandemic created both social and economic problems, it also led to the creation of a new commitment by European countries. Thus, the United Nations Framework Convention on Climate Change established the "joint mobilization of $ 100 billion annually starting up 2020 to improve the quality of the environment" (UN Agenda 2030). By implementing traffic restrictions during the pandemic, a "brake" was put on the level of gas emissions. In 2019 there were the highest temperatures ever recorded, and in 2020 there was a 6% decrease in gas emissions. However, as the global economy recovers from the pandemic, gas emissions are expected to increase (Climate Change—United Nations Sustainable Development). We can say that the pandemic played an important role in achieving the goal of SDG 13-Climate Action. Thus, we can consider that the current crisis is an opportunity for a change towards a sustainable economy, which will help all people, as well as the planet. In other words, the various economic and social problems caused by environmental pollution have led European governments to take action. Thus, the concern of officials automatically translates into the desire of researchers to observe the effects of these measures on the economic and social life.

It is known that energy, in addition to providing personal comfort and mobility, is essential to the generation of industrial and commercial prosperity. But energy production and consumption have a negative impact on the environment through greenhouse gas (GHG) emissions, polluting gases, waste generation and oil spills. All these pressures contribute to climate change, damage natural ecosystems and the human environment, and have adverse effects on human health. The main human activity that emits CO_2 is the burning of fossil fuels (coal, natural gas and oil) for energy and transport. Our research focuses only on greenhouse gas emissions from electricity generation. The types of fossil fuels used to generate electricity emit different amounts of CO_2. Also, many industrial processes use electricity and therefore indirectly result in CO_2 emissions. Fossil fuels are still dominant in the fuel mix: around 77% of Europe's energy needs are met by oil, natural gas and coal. Nuclear energy provides 14%, and the remaining 9% is provided by renewable energy source (Energy-European Environment Agency, 2022).

Changes in CO_2 emissions from burning fossil fuels are influenced by many long-term and short-term factors, including population growth, economic growth, changing energy prices, new technologies, changing behavior and seasonal temperatures. Energy was and still is a policy priority and represents a main area of development that was the object of the targets of the Europe 2020 Strategy: 20% of Europe's energy consumption was to come from renewable energies, and energy efficiency was to increase all the time by 20% (Energy-European Environment Agency, 2022).

There is a consensus, globally, that an increase in greenhouse gas emissions into the atmosphere is causing climate change. To challenge this problem, governments around the world have committed to controlling greenhouse gas emissions. One driver of carbon dioxide emissions is energy production. In this context, the study investigates the extent to which decision makers in different countries can rely on increased energy taxes to reduce pollution as part of environmental policies.

In the present study, the level of energy taxes, measured as total amount of energy tax revenue in millions of euros for all NACE activities plus households, non-residents and not allocated, was taken as an independent variable, in order to test their financial leverage role regarding reducing greenhouse gas emissions within environmental policies. In other words, the purpose of our study is to test the influence of energy taxes imposed at the European level during the period 1995–2019 on greenhouse gas (GHG) emissions. In addition to the independent variable, i.e., energy taxes, several control variables are also identified: imports, exports, population density, and the results of the study show a possible inverse impact of the taxation level on the reduction of gas emissions (GHG).

The methodology is presented in the section titled Data and Methodology, and is based on methods proposed by Blackburne and Frank (2007), Ditzen (2018, 2019). The proposed approaches are applicable on panels in which the number of cross-sectional observations (N) and the number of time-series observations (T) are both large. The methodologies also control the dynamic non-stationary data in panels by using an error correction model with pooling and/or averaging coefficients (for example the PMG estimator relies on a combination of pooling and averaging). The second method supplementary accounts for unobserved heterogeneity across units, and uses instrumental variables in case of endogenous variables. The results in the latter showed some volatility regarding the robustness of interest variable (*entax*)—a positive association in one model implied, that suggests possible dissimilar impacts at unit level. Further testing on splitted dataset by GDP *per capita* reveals that impact is differentiated by level of development. Based on previous findings (suspecting diverse effects on different countries), we continued the investigation at country level, using ARDL methodology, that confirmed some positive association in a limited number of countries.

The novelty of the research lies in the fact that the period under analysis is extensive and current (the last year analyzed is 2019), and the recent methodology is applied to a large number of countries (28 developed and emerging European countries). Our study uses latest available data (at Eurostat, June 2022), but the necessity of strongly balanced, needed for the methodologies (calculations of unit root tests and some panel ARDL), conducted to the removal of some years and countries. The gap covered by our study is that the research results demonstrate that increasing energy taxes cannot be generalized as an environmental policy measure to reduce greenhouse gas emissions. The latest methodology used (Ditzen, 2018; Ditzen, 2019; Ditzen, 2021) is also new, and also few encountered in the GHG literature. The suggestion for policymakers in different countries is that they should increasingly focus on promoting and supporting the deployment of green energy sources.

Materials and methods

Literature review

The idea of sustainable development is being promoted in Europe, and EU Member States are committed to meeting the goals of the UN Agenda. However, in the case of this paper, we will consider countries in the EU, as well as non-EU countries. Thus, there is a discussion and dilemma about whether or not to choose to reduce CO_2 emissions through taxation. Thus, a paper Lenzen and Dey (2002) indicates that a policy focused on reducing energy consumption and the effect of the evening brings socio-economic benefits that consist in increasing employment and income, but also in reducing imports. These authors use the input-output analysis that allowed the quantification of both direct and indirect effects of spending to be quantified. Thus, the six studies undertaken indicated other areas of expenditure in which energy consumption and greenhouse gas emissions are reduced; increasing the mobilization of the workforce by shifting the final consumption of the current model of an alternative, environmentally motivated substitute. Studies Metcalf (2009) show that increasing concentrations of greenhouse gases in recent years are influencing climate change and global warming over the next hundred years. This is mainly due to the fact that greenhouse gases persist in the atmosphere for hundreds of years and these emission levels will have a significant effect on the atmosphere for centuries to come. Similarly Onofrei et al. (2017), Haites (2018), and Mihalciuc and Grosu (2021) analyzed the same topic.

Śleszyński (2014) analyzed the problems related to the correct definition of environmental taxes. In his paper, four tax groups were addressed: taxes on energy, taxes on means of transport, taxes on air pollution, and taxes on natural resources. The author concluded that it is difficult to introduce adequate tax benefits for people who behave appropriately towards the environment. A study Lapinskienė et al. (2015) analyzed the relationship between greenhouse gases and the main aspects of economic development, based on a data panel of 20 EU member states from 1995–2011. The results of the study showed that higher energy rates, nuclear heat production and the level of development contribute to reducing the level of greenhouse gas emissions. The same author also points out that during the 2008 crisis, greenhouse gas emissions decreased.

Beck et al. (2015) conducted an analysis of the distribution of the tax based on a general equilibrium model, which can estimate the impact of the tax on both expenditures and revenues. They concluded that the carbon tax is "very progressive," which shows that the incidence of taxes is more on wages and partly on energy prices. A study Lapinskienė et al. (2017) analyzed the relationship between economic growth and greenhouse gas emissions, based on a panel of data from 22 European Union member states. The data analysis period is 1995–2014. Proxy variables included in the study include GDP *per capita*, GHG (total emissions), energy taxes, energy consumption, etc. The results of the study showed that a number of factors analyzed (energy consumption, energy taxes, R&D taxes) can be applied to adjust the EKC (Environmental Kuznets Curve) trend in the region and to adjust climate change policy. The authors believe that the approximation of the effects on GHGs of economic growth and various external factors can be seen as an instrument that supports a country's strategic decision. This view is shared by another paper (Lu, 2017) on the situation in Asia. Thus, for the entire sample of 16 Asian countries, there is a short-term two-way causality between energy consumption and greenhouse gas emissions, between GDP and greenhouse gas emissions, and between growth and energy consumption (Borozan, 2019). investigated in his paper the role of energy-related taxes for residential energy consumption in European economies. Thus, he used the panel quantile regression methods for annual data of variables. The results show that an increase in energy taxes and energy prices has a positive effect on the environment, generated by lower energy consumption of households.

Another study Asghar et al. (2020), conducted at the micro level, evaluates sustainable corporate performance based on the areas of financial, social and environmental performance. Financial and economic performance was assessed through financial reports and surveys, and social and environmental performance were quantified by survey questionnaires for seven multi-factor performance domains, based on Weisbord's six-box model. The study period was 2011–2015, and data were collected from 517 employees in 19 banks in Pakistan. The results of the study show that the total effect of performance (economic, social and environmental) is much stronger than the individual impact on the performance of the sustainable company. This is a clear indication of the mediating role of social performance, but also of the environment for evaluating the performance of the sustainable company and highlights the importance that the social and environmental dimensions have begun to have in recent years. A study Ghazouani et al. (2020) shows that there is a positive and significant impact of the adoption of the carbon tax on stimulating the reduction of carbon emissions. Thus, the propensity score matching method is used for developed EU countries. The results of the study support the hypothesis that environmental tax regulations and technological innovation in European economies help to achieve higher revenues, but also to reduce greenhouse gas emissions. Based on the consensus that export diversification contributes to the development of less developed countries, Mania (2020) investigated the effect of export diversification on CO_2 emissions in the context of a Kuznets environmental curve hypothesis in 98 developed and developing countries in the period 1995–2013. Using short-term (Generalized System of Methods) and long-term (Cumulative Average Group) estimation methods, the author finds that the Kuznets environmental curve is valid and that export diversification has a positive effect on CO_2 emissions. And a reduction in carbon emissions can be achieved even in a pandemic through policies (Lahcen et al., 2020).

Several recent studies Ghazouani et al. (2021) and Sharma et al. (2021) argue that environmental regulations, taxes, and energy policies can be used as effective tools for achieving a climate without emissions and cleaner energy sources in Europe. And other authors (Adebayo et al., 2021; Rehman et al., 2021) promote the same opinion through their work for Asian countries.

We have been able to observe various opinions that largely support the hypothesis that taxes are a tool to reduce greenhouse gas emissions (Armeanu et al., 2018; Hussain et al., 2022; Wei et al., 2022). But when the goal is economic growth, the price paid can be a decrease in the quality of the environment, in the context in which most economies are still dependent on fossil fuels (Khan, 2021). It also promotes the idea of investing in new, unpolluted technologies (Rokhmawati, 2021). However, in the current period the biggest changes are given by the IT industry. Thus, the most recent opinion of international researchers (Zhao et al., 2021) is that the development of digital finance should be promoted in order to reduce carbon emissions. These authors used balanced panel data at the provincial level in China from 2011 to 2018 to observe the link between digital financing and carbon emissions. The results show that digital financing has a significant inhibitory effect on carbon emissions. Thus, policy formulations should focus on removing barriers to the development of digital finance. Because global carbon is considered to be the main contributor to global warming, global policymakers are pursuing a series of fiscal policies to reduce carbon emissions (Tu et al., 2022). The largest carbon emitter on our planet is China, which is why the government has introduced a number of environmental regulations. These include the introduction of the environmental protection tax and the emissions trading system in order to reduce carbon emissions and improve the quality of the environment. Desiring to conduct an analysis of the effect of the carbon tax on the economic environment, the authors developed a general equilibrium stochastic system structured in four departments: households, enterprises, government and the environment. The results of the analysis showed that, as a result of the introduction of the carbon tax, the level of environmental quality has improved considerably and the other economic variables have been significantly reduced. Thus, improving environmental efficiency in the emissions sector leads to sustainable environmental development, but to the detriment of economic development (Apetri and Mihalciuc, 2019; Brodny and Tutak, 2020; Li et al., 2022). Out of a desire to address these issues caused by climate change and global warming, policymakers around the world have focused on adopting carbon-based tax reduction policies. In 2008, British Columbia implemented a carbon tax for the first time and by 2012, the tax had reached a level of \$ 30/tCO_2, managing to cover three-quarters of all greenhouse gas emissions in the province. Therefore, a study Murray and Rivers (2015) analyzed the effect of tax on emissions with evening effect, economy and revenue. The results showed that the implementation of the tax led to a decrease of 5%–15%. The models also showed that the tax had negligible effects on economic performance. Despite the fact that the public initially opposed the implementation of this tax, it is now fully supported.

Carattini et al. (2015) investigated the reasons why individuals and some states adopt or accept behaviors and policies to reduce emissions, despite climate change. Although the vast majority of governments avoid engaging in coordinated international policies, various individual local and environmental actions, such behaviors have become increasingly available lately. The authors believe that trust and social values can help reduce these problems. Henseler et al. (2020) analyzed the implementation of the nitrogen tax. The results of the study showed that the implementation of this tax is more economically efficient than the option to withdraw it from the agricultural circuit. Despite this, differences in effectiveness and efficiency require an adjustment of the nitrogen tax rate to achieve the desired level of reduction.

A number of authors Burtraw et al. (2003), Cox et al. (2018), and McLaren (2020) have analyzed the problem of eliminating greenhouse gases. This is not just a theoretical issue, raising a number of important questions for politics, governance and finance. Similarly, Bispo et al. (2017) analyzed the problem. Agriculture is an important source of greenhouse gases, which demonstrates its contribution to global warming. Stetter and Sauer (2022) analyzed whether GHGs can be attenuated at the micro level. The authors analyzed a number of farms, regarding the ratio of emissions dynamics to performance. Data were processed for the period 2005–2014, including Bavarian farms in the sample. The results of the study showed that the performance of micro emissions improved over time.

Other authors Cooper (2009) analyzed the proposal to implement a common tax for all global greenhouse gas emissions. Similarly, Kotnik et al. (2014) analyzed the governmental effect of environmental taxes on greenhouse gases, using data from 19 EU member states. The results of the study showed that the effect of taxes on GHG emissions is negative. Emissions and removal of CO_2 through natural processes should balance, without anthropogenic impacts. Since the Industrial Revolution, starting around 1750, human activities have contributed substantially to climate change by adding CO_2 and other heat-trapping gases, namely greenhouse gases, to the atmosphere. In Europe, the peak of energy consumption occurred in 2006; in 2010, energy consumption was reduced by approximately 4%, a decrease partially explained by the economic crisis of that period (Energy—European Environment Agency). These aspects can also be analyzed based on Figure 1.

It can be observed that in the year 2020, the decrease in CO_2 emissions from the burning of fossil fuels corresponded to a decrease in energy consumption as a result of the decrease in economic activity, production and travel, in response to the coronavirus pandemic (US EPA, 2015).

Another study Morley (2012) that analyzed EU member states and Norway found that there is a significant negative impact between environmental taxes and pollution, but not between environmental taxes and energy consumption. The results of the research suggest that the countless exemptions for energy-consuming sectors have had only a limited effect. Thus, the policy promoted by these states does not have direct effects in reducing the level of pollution, but rather pollution is reduced through cleaner technologies. The impact of fiscal instruments on environmental degradation is a research topic that has been analyzed from various approaches.

According to a study by Lacko and Hajduová (2018) higher taxes do not have a positive impact on environmental efficiency or the performance of EU countries. The researchers of this paper used two DEA models—CCR and BCC—and the efficiency was verified by a double bootstrap procedure. Thus, the results show that the efficiency of the environment does not necessarily depend on the classic variables existing on EUROSTAT. Indices such as environmental taxes, waste management, resource productivity and freight management should also be taken into account in policies. Therefore, there are other factors that influence climate change, including changes in technology. These researchers also argue that less environmentally efficient countries should develop their own policies to mitigate the impact of climate change. This view is shared by other papers (Apergis et al., 2018; Johansen et al., 2018) also from 2018.

Zioło et al. (2020) consider that among the most important challenges facing governments today are climate change and environmental pollution. Given that environmental risks are associated with specific costs and expenses, in order to

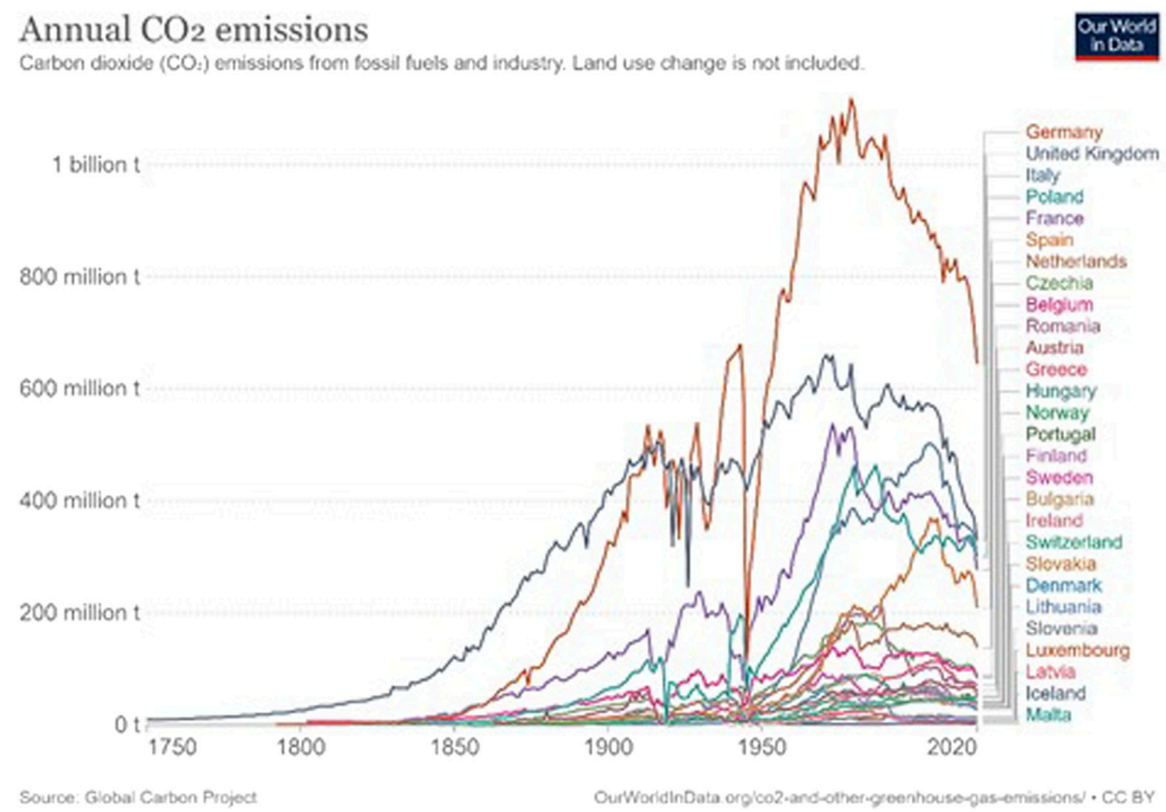

FIGURE 1
Evolution of CO_2 emissions for the countries included in the sample in the period 1750–2020. Own processing after Global Carbon Project (Ritchie et al., 2020).

mitigate their negative effects, the financial system has a particularly important role to play, as it creates the necessary instruments that allocate and redistribute public resources. The impact on market participants is materialized in the obligation to pay environmental taxes. The authors analyzed the link between public spending and environmental protection. The analysis period is 2008–2017, focusing on the economies of Central and Eastern Europe and the most developed economies in Western Europe. The results of the study demonstrate the existence of a strong relationship between fiscal instruments and greenhouse gas emissions, in the sense that they lead to improved environmental quality. The author pointed out that, in terms of environmental taxes, their impact varied from country to country, their implementation being particularly useful in countries with higher greenhouse gas emissions, whereas in countries with lower emissions, the impact was insignificant.

In a 1996–2016 study of OECD countries, using the ARDL model, a group of authors (He et al., 2021) demonstrate that the introduction of energy taxes improves energy efficiency only in the short term and not for all sampled countries.

Related to the Research Hypotheses we want to demonstrate that there is an inverse relation between identified variables: energy taxes and greenhouse gas emissions. In this case, the null hypothesis is that.

H_0: There is no influence of the level of energy taxes on greenhouse gas emissions, meaning that the coefficient of the variable (enTAX) is not statistically significant (p-value is above 0.1, at 10% level) or in other words, that the coefficient can have zero (0) value. If the coefficient value is negative and statistically significant (the p-value is below 0.1 and the sign is minus), the conclusion is that there is an inverse influence of the energy taxes (enTAX) and greenhouse gas emissions (GHGEbss).

We have primarily analyzed the effect of *entax* to *GHG* using panel ARDL (Blackburne and Frank, 2007). The results are stable and statistically significant, suggesting the decreasing of the dependent variable (on long—run) when increasing the energy taxes. In a second phase, we have changed the methodology to control for common correlated effects, using a more actual and newest method (Ditzen, 2018; Ditzen, 2019; Ditzen, 2021). The results are volatile (in one model) regarding the control variable. In this stage, we have suspected different impact in different countries, so we have sliced the dataset in two (using GDP *per capita*) to further control and improve the robustness. The new set of results shows that the effect is different on types of countries (developed or developing), being in line with other cited studies. Based on previous findings (volatility of some methodologies and different results in sliced data), in a final stage, we have used simple/individual ARDL methodology to analyze the impact at country level. The results confirm that there are different effects by countries, which is also in line with studies that we have cited. The main conclusion is that taxes used as instruments to combat GHG are not enough to combat GHG emissions, further leverages (expand the green technologies, use public subsidies to finance them and so on) are needed.

TABLE 1 Variables definition, sources and economic literature usage.

Variable symbol	Variable name, description and units	Source
Country	Country—The sample includes 28 countries	Kotnik et al. (2014), Lapinskienė et al. (2017), Lu (2017), Zioło et al. (2020), Sharma et al. (2021), and Zhao et al. (2021)
Year	Year—The time period is 1995–2019	Lapinskienė et al. (2017), Lu (2017), Sharma et al. (2021), and Zhao et al. (2021)
GHGEbss	Greenhouse gas emissions by source sector (source: EEA) [SDG_13_10]—Greenhouse gases (CO_2, N_2O in CO_2 equivalent, CH_4 in CO_2 equivalent, HFC in CO_2 equivalent, PFC in CO_2 equivalent, SF_6 in CO_2 equivalent, NF_3 in CO_2 equivalent) in Tones *per capita*	Cooper (2009), Morley (2012), Kotnik et al. (2014), Murray and Rivers (2015), Lapinskienė et al. (2017), Lu (2017), Armeanu et al. (2018), Adebayo et al. (2021), Ghazouani et al. (2021), Khan (2021), Rehman et al. (2021), Sharma et al. (2021), Hussain et al. (2022), and Wei et al. (2022)
enTAX	Energy Taxes—total amount of energy tax revenue in millions of euro for all NACE activities plus households, non-residents and not allocated	Cooper (2009), Kotnik et al. (2014), Śleszyński (2014), Murray and Rivers (2015), Lapinskienė et al. (2017), Borozan (2019), Ghazouani et al. (2020); Zioło et al. (2020), and Tu et al. (2022)
gdp	Gross Domestic Product—Main GDP aggregates *per capita* [NAMA_10_PC], Gross domestic product at market prices, expressed in current prices, purchasing power standard (PPS, EU27 from 2020) *per capita*	Lapinskienė et al. (2017) and Lu (2017)
pop	Population—Population density by NUTS 3 region (loc/km^2)	Burciu et al. (2010), Ghazouani et al. (2020), Andrew Mejia (2021), and D'Orazio and Dirks (2022)
exp	Exports—Exports of goods and services, in current prices, million units of national currency	Mania (2020) and Tu et al. (2022)
imp	Imports—Imports of goods and services, in current prices, million units of national currency	Lenzen and Dey (2002)

Source: own processing.

TABLE 2 Descriptive statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
GHGEbss	700	10.64643	8.225827	−0.9	49.2
enTAX	700	8.304807	12.67874	0.02344	50.57345
Gdp	700	24.54912	12.11744	4.6212	79.6348
Pop	700	17.05333	24.41028	0.27	159.51
Exp	700	10.5707	39.84777	0.004125	388.686
Imp	700	10.02998	37.88869	0.002924	377.6796
logGDP	700	9.985576	0.518721	8.43841	11.28521
logEXP	700	12.02313	1.898941	6.022236	17.4757
logIMP	700	12.00622	1.842614	5.678123	17.44697

Source: own processing.

Data and methodology

The study on the effects of energy taxes level on greenhouse gas emissions (GHGEbss) under environmental policy measures, in the period 1995–2019, extracting from the total population represented by the states of the world only 28 European countries (Austria, Belgium, Bulgaria, Switzerland, the Czeck Republic, Germany, Denmark, Greece, Spain, Finland, France, Hungary, Ireland, Iceland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Norway, Poland, Portugal, Romania, Sweden, Slovenia, Slovakia, the United Kingdom). The sample was limited to this number depending on the availability of data collected from the EUROSTAT database.

The data analysis methods used refer to the estimation of non-stationary heterogeneous panels (Blackburne and Frank, 2007) and furthermore (for robust results) the dynamic model of common effects correlated with heterogeneous coefficients on cross-sectional units and time periods (Ditzen, 2018; Ditzen, 2019; Ditzen, 2021). To test the validity of our findings, we added additional economic and social control variables to the model, such as gross domestic product (GDP), population density, imports, and exports.

Data description

The identified variables, their description, but also the sources of other studies performed that took into account the variables identified in our study are presented in Table 1.

After preliminary data processing, the summary of descriptive statistics is presented in Table 2.

The dataset has 700 observations, with a time length of 25 years, between 1995 and 2019. The unit panel refers to 28 countries from the European Union. The dependent interest variable GHGEbss has an average mean of 10.65, and the independent interest variable is enTAX, which has an average mean of 8.30.

The panel data statistics are presented in Supplementary Appendix Table SA1. There is enough variability in data to consider panel models (different fixed or random effects for countries). As visual representation, the boxplot Supplementary Appendix Figure SA1 enforces the previous conclusion.

The results are in line with graphical analysis (see Supplementary Appendix Figure SA2), which confirm that in developed countries (Germany, France, Netherlands, United Kingdom) there is a clear negative inverse relation, while in some countries (Island or Finland for example) there is no visual impact of the energy environmental taxes on greenhouse gas emissions (GHGEbss).

The inverse relationship can be visually identified as in Supplementary Appendix Figure SA3 [using geopandas python package (Jordahl et al., 2020)], showing that, usually, in countries with higher levels of taxes (right blue chart) there are reduced correspondent levels of greenhouse gas emissions (left orange chart).

Methodology

The methodology is related to our data, which is panel type. The general pooled Ordinary Least Squares (OLS), presented in Eq. 1, is generally not usable in panel data, as it does not account for differences in individual means related to country specifics, as in our case. The panel data general model, which pulls out, for instance the fixed effects (μ_i) from error term as in Eq. 2, do not account for the existence of lag—dependent variables, as one encountered in economics (such as Gross Domestic Product—GDP, for instance, in our case).

$$Y_t = \beta_1 + \beta_2 X_t + \varepsilon_t \quad (1)$$

$$Y_{it} = \beta_1 + \beta_2 X_{it} + \mu_i + \epsilon_{it} \quad (2)$$

Another problem related to the linear regression model is that it requires variables X and Y to be stationary in covariance. The presence of non-stationarity in the data needs to be checked, so the choice of methodology is related to the fact that in time series and panel data, variables are usually co-integrated. The presence of cointegration between variables forces us to choose an error-correction model (ECM), which is stationary. To test the stationarity in the panels, we used a variety of tests (for unit roots) in the panel dataset (Harris and Tzavalis, 1999; Hadri, 2000; Choi, 2001; Levin et al., 2002; Im et al., 2003; Breitung and Das, 2005). Most of the tests have the null Hypothesis H_0: *all the panels contain a unit root*. Another one (Hadri, 2000) has the null hypothesis H_0: *all the panels are* (*trend*) *stationary*. Usually, economic variables of time-series type on long-term are non-stationary, so autoregressive distributed lag (ARDL) models should be used.

At country level (when no panel data is used) the following ARDL model is used (see Pesaran et al., 2001; Hassler and Wolters, 2006; Kripfganz and Schneider, 2016; Kripfganz and Schneider, 2020) as in (3,3').

$$y_t = c_0 + c_1 t + \sum_{i=1}^{p} \phi_i y_{t-i} + \sum_{i=0}^{q} \beta_i' \mathbf{x}_{t-i} + \gamma' \mathbf{z}_t + u_t \quad (3)$$

$$\Delta y_t = c_0 + c_1 t + \pi_y y_{t-1} + \pi_x \mathbf{x}_{t-1} + \sum_{i=1}^{p-1} \psi_{yi} \Delta y_{t-i} + \omega' \Delta \mathbf{x}_t + \sum_{i=1}^{q-1} \psi_{xi}' \Delta \mathbf{x}_{t-i} + \gamma' \mathbf{z}_t + u_t, \quad (3a)$$

For panel data, we used the PMG estimator (Pesaran et al., 1999; Blackburne and Frank, 2007; Chudik and Pesaran, 2015), assuming an autoregressive distributive lag (ARDL), as in (3). Considering that the variables in (4) are, stationary in first-difference I (1) and cointegrated, then the error term is an I (0) process for all *i*. Furthermore, this implies an error correction model in which the short-run dynamics of the variables in the system are influenced by the deviation from equilibrium [as in (5)].

$$\mathbf{y_{it}} = \sum_{j=1}^{p} \boldsymbol{\lambda_{ij}} \mathbf{y_{i,t-j}} + \sum_{j=0}^{q} \boldsymbol{\delta_{ij}'} \mathbf{X_{i,t-j}} + \boldsymbol{\mu_i} + \boldsymbol{\epsilon_{it}}, \quad (4)$$

$$\Delta \mathbf{y_{it}} = \boldsymbol{\phi_i}\left(\mathbf{y_{i,t-1}} - \boldsymbol{\theta_i'} \mathbf{X_{it}}\right) + \sum_{j=1}^{p-1} \boldsymbol{\lambda_{ij}^{*}} \mathbf{n} \Delta \mathbf{y_{i,t-1}} + \sum_{j=0}^{q-1} \boldsymbol{\delta_{ij}'^{*}} \Delta \mathbf{X_{i,t-j}} + \boldsymbol{\mu_i} + \boldsymbol{\epsilon_{it}}, \quad (5)$$

where:

$$\boldsymbol{\phi_i} = -\left(1 - \sum_{j=1}^{p} \boldsymbol{\lambda_{ij}}\right),\ \boldsymbol{\theta_i} = \sum_{j=0}^{q} \boldsymbol{\delta_{ij}} \Big/ \left(1 - \sum_{k} \boldsymbol{\lambda_{ik}}\right), \text{ and } \boldsymbol{\lambda_{ij}^{*}} = -\sum_{m=j+1}^{p} \boldsymbol{\lambda_{im}}, \quad (6)$$

i = 1, 2, ..., *N* is the number of groups; t = 1, 2, . . ., *T* is the number of periods; X is a k × 1 vector of explanatory variables; $\delta_{it} = it$ is the k × 1 coefficient vectors; $(p, q_1, \ldots, q_k)$ are A.R.D.L. lags; *ij* are scalars; *i* is the group-specific effect.

To further control for dynamic common-correlated effects the methodology proposed by J. Ditzen is used (as in Ditzen, 2018; Ditzen, 2019; Ditzen, 2021). In a dynamic panel [as in (5)], where the idiosyncratic errors are cross-sectionally weakly dependent, the lagged dependent variable is no longer strictly exogenous. The estimator is consistent if $p_T = \lfloor \sqrt[3]{T} \rfloor$ lags of the cross-section averages is added as in (7).

$$\mathbf{y_{it}} = \boldsymbol{\alpha_i} + \boldsymbol{\lambda_i} \mathbf{y_{i,t-1}} + \boldsymbol{\beta_i'} \mathbf{x_{it}} + \sum_{l=0}^{p_T} \boldsymbol{\delta_{il}'} \bar{\mathbf{z}}_{t-l} + \mathbf{e_{it}} \quad (7)$$

where $\overline{\mathbf{Z}}_t = (\bar{y}_{t-1}, \bar{\mathbf{x}}_t)$. If λ_i and $\boldsymbol{\beta}_i$ are stacked into $\boldsymbol{\pi}_i = (\lambda_i, \boldsymbol{\beta}_i)$, the estimates are of form as in (8):

$$\hat{\boldsymbol{\pi}}_{MG} = \frac{1}{N} \sum_{i=1}^{N} \hat{\boldsymbol{\pi}}_i \quad (8)$$

The pooled mean group (PMG) estimator is an intermediate between "pure" pooled (homogenous coefficients) and MG (heterogeneous coefficients), the assumption being that "regressors have a homogeneous long-run effect and a heterogeneous short-run effect on the dependent variable," as in the previous methodology. Dynamic models allow the estimation of the long-term. The equation is transformed in an error-correction model (ECM), as in (9), also noted in tables from section *Robustness tests of our results* as "ec".

$$\Delta y_{i,t} = \mu_i - \phi_i \left[y_{i,t-1} - \theta_{1,i} x_{i,t} \right] - \beta_{1,i} \Delta x_{i,t} + \sum_{l=0}^{p_T} \gamma_{i,l}' \bar{z}_{t-l} + e_{i,t} \quad (9)$$

The initial empirical results (based on ECM, no cross-sectionally corrected) and the robustness test (sectionally—corrected estimates) are presented as follows.

Results and discussion

Preliminary tests

The correlation matrix in Supplementary Appendix Table SA2 suggests an inverse relation between our interest variables: environmental taxes and greenhouse gas emissions (GHGEbss), as expected. We found that there is a higher correlation between imports and exports (.9969), so the series will be interchanged using them as control (variables). The correlation between imports and exports shown in Supplementary Appendix Table SA3, and the necessity to use them separately in models, is confirmed by the variance inflation factor table below (an accepted value is under 5, when two variables are concomitantly used, the variance is inflated—the value is 92.96).

The results for unit root tests Levin-Lin-Chu, Im-Pesaran-Shin, Harris-Tzavalis, Breitung, Hadri Lagrange multiplier stationarity test regarding the dependent variable—greenhouse gas emissions (GHGbss)—are presented in Supplementary Appendix Table SA4.

TABLE 3 Pooled mean group (PMG) results, ECT and long-run coefficients.

Indep. vars	Dependent variable: GHGEbss				
	(1)	(2)	(3)	(4)	(5)
ECT (ϕ_i)	*−0.160****	*−0.203****	*−0.195****	*-0.189****	*-0.186****
	(0.0324)	*(0.0419)*	*(0.0410)*	*(0.0392)*	*(0.0406)*
enTAX	−1.028***	−0.440***	−1.154***	−0.222***	−0.182***
	(0.0865)	(0.0363)	(0.103)	(0.0362)	(0.0301)
logGDP		0.703***	0.703***	2.202***	2.296***
		(0.250)	(0.270)	(0.441)	(0.380)
Pop			−0.0690***	−0.0825***	−.0769***
			(0.0250)	(0.0242)	(0.0267)
logEXP				−0.289	
				(0.192)	
logIMP					−0.285*
					(0.172)
Observations	672	672	672	672	672

Source: own processing.
Note: methodology PMG estimator (Pesaran et al., 1999; Blackburne and Frank, 2007; Chudik and Pesaran, 2015) and implemented in Stata by Blackburne and Frank (2007); the independent variables are logarithmic value of GDP *per capita*—logGDP (1), added population—pop (2), added the logarithmic value of exports—logEXP (3), added logarithmic value of imports—logIMP (4). *** $p < .01$, ** $p < .05$, * $p < .1$.

The null hypothesis for Levin-Lin-Chu is Ho: Panels contain unit roots, for Im-Pesaran-Shin is H0: All panels contain unit roots, for Harris-Tzavalis is H0: Panels contain unit roots, for Breitung is H0: Panels contain unit roots, for Hadri Lagrange multiplier stationarity test is H0: All panels are stationary.

For the variable GHGEbss in levels, all five of the unit root tests mentioned above suggest that the variable is not stationary in levels (adjusted t* statistic: 0.3207, p-value: 0.6258; Zt-tilde-bar: 4.5822, p-value: 1.0000; z statistic: 2.4333, p-value: 0.9925; lambda: 3.1747, p-value: 0.9993), z: 57.4943, p-value: 0.0000). For the variable in first-difference d.GHGEbss, all five of the unit root tests mentioned above suggest that the variable is stationary in first-difference (adjusted t* statistic: −8.9126; p-value: 0.0000, Zt-tilde-bar: −13.7223, p-value: 0.0000; z statistic: −39.9634, p-value: 0.0000), lambda: −9.9048, p-value: 0.0000; z: −0.9760, p-value: 0.8355).

For the other variables, the results also suggest non-stationarity in levels, but are stationary in first-difference, so a first-difference model is necessary (the full explanations are available on demand).

The results for tests Kao, Pedroni, Westerlund are presented in the following. The null hypothesis for Kao, Pedroni, Westerlund, is H0: No cointegration with some alternative hypothesis. The alternative hypothesis of the Kao and the Pedroni tests is H1: the variables are cointegrated in all panels. In the Westerlund test, the alternative hypothesis is that the variables are cointegrated in some of the panels.

The cointegration tests results between greenhouse gas emissions and environmental taxes are presented in Supplementary Appendix Table SA5.

The statistics for Kao (cointegration) test, regarding the co-integration between GHGEbss and enTAX (Modified Dickey-Fuller t, Dickey-Fuller t, Augmented Dickey-Fuller t, Unadjusted modified Dickey Fuller t, Unadjusted Dickey-Fuller t) are: 2.6917, 2.8630, 3.2710, 1.4777, 1.4734, with the following p-values: 2.6917, 2.8630, 3.2710, 1.4777, 1.4734. Based on the above statistics and p-values (statistically representative at 5% level), we can conclude that the variables are cointegrated in accordance with three tests.

In conclusion, regarding the statistics for all the tests, we found that in five of ten, at 5% level, and seven of ten at 10% level, the null hypothesis could be rejected, so the alternative can be considered (*Ha: All panels are cointegrated*).

The other statistics (available on demand) also suggest cointegration between variables implied.

The existence of cointegration between variables, corroborated with non-stationarity in levels concludes the necessity of using error-correction models (ECM).

Pooled mean group—PMG models

The results for the long - run coefficients (θ_i'), in ECM model are presented in Table 3. Every column noted to one to five represents a model, starting with *entax* as independent varaible, and recursively adding new independent variables to the new models implied (logarithmic value of GDP *per capita*—logGDP, population—pop, logarithmic value of exports—logEXP, logarithmic value of imports—logIMP).

The independent variables, noted as X_{it} are coded in the first column. The coefficient for the first model (with standard errors in brackets), where only the interest variable (enTAX) and one control variable (logGDP) are modeled, are available in column no.1 (model one). Every column heading represents the number of one model.

In the long run, the relationship between the variables *enTAX, GDP, imp and GHGEbss* is as expected. The error-correction term (ECT) is negative and statistically significant at 1% level, showing the expected cointegration in considered variables, for all of the models implied. The statistical interpretation is that on every unit of time, the short-run relationship is corrected by 0.16 units. For the other models (2–4) the correction is 0.203, 0.195, 0.189, and 0.186 for achieving long-run cointegration.

The statistical interpretation, for example for *enTAX*, is that a unit change in environmental energy taxes is associated with a 1.028 (0.44, −1.154, 0.222, and 0.182 in other models) decrease in greenhouse gas emissions in the long-run, at the 1% significance level, on average *ceteris paribus*. In this case, greenhouse gas emissions and energy (environmental) taxes display an *inelastic inverse relationship*.

The interpretation of the coefficients is the same for all other variables implied, a negative sign having an inverse effect on dependent variable, while a positive one has a direct (growing) impact. The short-run coefficients have the same logic, the table results being available in the Supplementary Appendix.

Our results are confirmed by other studies (Dietz and Rosa, 1997; Ghazouani et al., 2020; Zioło et al., 2020; Adebayo et al., 2021; Andrew Mejia, 2021; D'Orazio and Dirks, 2022; Tu et al., 2022), in the sense that an increase in energy taxes and imports leads to a decrease in greenhouse gas emissions (GHG), while an increase in GDP has a negative effect on the quality of the environment. On the other hand, in the long run, the same cannot be said about population density and increasing exports, in the sense that an increase in them leads to a decrease in greenhouse gas emissions and not to an increase in them, as we would have expected. Thus, a study Tu et al. (2022) shows, by using a dynamic stochastic general equilibrium model, that once carbon taxes were introduced, the level of carbon emissions fell by 45% in China and the quality of the environment improved by 1.63 units, but with a decrease in production of 46%. The same positive effect of environmental taxes on improving the quality of the environment is confirmed by our study of European countries. In a grouping of developed and emerging countries in Europe, using the analysis of the main components, the results showed a positive relationship between rising energy taxes and environmental quality in developed countries (Germany is central) and a less significant relationship in emerging countries for 2008–2017 (Zioło et al., 2020). Studies show that since the introduction of the carbon tax in 2008 in British Columbia, greenhouse gas emissions have fallen by between 5% and 17% (Murray and Rivers, 2015). The results of the first model show that population density leads to a decrease in greenhouse gas emissions, on average, at the level of the analyzed sample. This can be explained by the fact that an increase in population does not necessarily translate into an increase in labor that will drive production, and has a negative long-term influence on the environment, at the level of the sample analyzed. Following the processing carried out, if we look at the influence of exports on the environment, we see that they lead to a decrease in greenhouse gas emissions, a result that can be explained by the fact that an increase in exports is not always generated by an increase in production, but the fact that much of the domestic production is destined for export. The balance of payments, which is in deficit (Balance of payment statistics, 2022), must also be taken into account, which means that imports are higher than exports. It should be noted that the sampled Central and Eastern European countries have an average of non-EU imports, especially from China, higher than the average of EU imports (China Imports - May 2022 Data—1981–2021 Historical—June Forecast—Calendar). In addition, the transport of imported goods is carried out rather by sea and, to a lesser extent, by land. Under these conditions, the results of the processing carried out also show that the influence of imports on the environment, at the level of the analyzed sample, is a positive one, in the sense that the greenhouse gas emissions decrease on average.

Testing the robustness of our findings

We further control for common-correlated effects by using the methodology proposed by J. Ditzen [as in (Ditzen, 2018; Ditzen, 2019; Ditzen, 2021)]. We control for interferences between countries, and also the situation when independent variables especially GDP, enTAX and pop are not considered as exogenous. Another advantage of the second methodology is that latest variables are instrumented by own first lags and in case of enTAX also by the first lag of logGDP (because higher GDP can lead to higher GHGbss, but also to higher taxes (enTAX)). As in table no. 3, every column noted from 6 to 11, represents a model with different independent variables considered.

In order to test the robustness of the pervious results, we have sliced the data into different data sets, using as criteria the sorted GDP *per capita* in 2019 (Supplementary Appendix Table SA6). The descriptive statistics are available on demand.

The coefficients with standard errors in brackets for long-run coefficients and ECT are presented in Table 4. Every column heading represents the number of the model conducted.

Regarding the second methodology, the results of the processing presented in Table 4 show that the long-run relationship appears to be present mainly in models of the splitted data (countries with lower *GDP per capita*) In these models, in the long-run, the relationship between the variables of interest—*GHGEbss, enTAX* (which explains 0.66 and 0.72 of *GHG* variation, by R-squared) and *GDP per capita* are as expected. For long-term processing, the density population, exports and imports negatively affect the quality of the environment. The statistical interpretation for *enTAX*, is that a unit change in environmental energy taxes is associated with a |−0.08| in model no. (6) and |−0.21| in model no. (7) decrease in greenhouse gas emissions in the long-run, at the 10% significance level, on average *ceteris paribus*. In this models, greenhouse gas emissions and energy (environmental) taxes display an inelastic inverse relationship., being in accordance to the results of other research (Dietz and Rosa, 1997; Ghazouani et al., 2020; Ghazouani et al., 2021; Mania, 2020; Andrew Mejia, 2021; D'Orazio and Dirks, 2022).

For the models (10) and (11), that implies countries with a lower GDP *per capita*, the statistical interpretation for enTAX, is that a unit change in environmental energy taxes is associated with |−1.448| and |−2.849| decrease in greenhouse gas emissions in the long-run, at the 10% significance level, on average ceteris paribus. In these models, greenhouse gas emissions and energy (environmental) taxes display an inelastic inverse relationship.

Some results are not statistically significant (some are sensitive to dataset and control variables—available on demand). The results appear in some cases sensitive regarding the control variables. We suspect that the impact could be different at country level, or, in some countries, there is no long-run co-integration, so further investigations to test the robustness of our models were conducted.

The results (standard errors in brackets) using sliced dataset are available in Table 5. Every column heading represents the number of the model conducted.

The results from Table 5 show that in countries with lower *GDP per capita* rates, the effect of energy taxes on GHG is negative and

TABLE 4 Pooled mean group PMG with common-correlated effects and instrumented variables.

Variables	(6)	(7)	(8)	(9)	(10)	(11)
ec (ϕ_i)	−0.905***	−0.998***	−0.807***	−0.914***	−0.950***	−0.932***
	(0.0481)	(0.0553)	(0.0573)	(0.0434)	(0.0688)	(0.0639)
enTAX	**−0.0791***	**−0.210***	−5.130	−4.711	−1.448	−2.849*
	(1.931)	**(2.034)**	(3.425)	(3.315)	(1.561)	(1.468)
logGDP	3.341	3.574	1.305	−1.084	−4.692	−6.013
	(2.482)	(2.418)	(3.179)	(3.087)	(4.337)	(4.621)
pop		1.410		0.317	1.637	2.117
		(2.970)		(1.797)	(2.775)	(2.375)
logEXP					0.122	
					(0.871)	
logIMP						0.235
						(1.074)
Observations	672	672	336	336	336	336
R-squared	0.660	0.719	0.593	0.654	0.751	0.759
Number of groups	28	28	14	14	14	14

Source: own processing.
Note: Note: methodology PMG estimator with common-correlated effects (Pesaran et al., 1999; Chudik and Pesaran, 2015; Ditzen, 2018; Ditzen, 2019; Ditzen, 2021) and implemented in Stata by Ditzen, 2019–2021; independent variable of interest: enTAX; the independent control variables are logarithmic value of GDP *per capita*—logGDP (6) (8); added population—pop (7), (9); added the logarithmic value of exports—logEXP (10), added logarithmic value of imports—logIMP (11); models (6), (7) -full dataset; (8)–(11), models sliced dataset, *lower GDPpercapita*. *** $p < .01$, ** $p < .05$, * $p < .1$.

TABLE 5 Pooled mean group PMG—sliced data.

Variables	(12)	(13)	(14)	(15)	(16)	(17)	(18)
ECT (ϕ_i)	−0.183***	−0.209***	−0.282***	−0.186***	−0.232***	−0.284***	−0.328***
	(0.0443)	(0.0498)	(0.0578)	(0.0656)	(0.0726)	(0.0738)	(0.0893)
enTAX	−1.085***	−1.139***	−0.186***	−0.508***	−0.342***	−0.0495**	−0.0190
	(0.101)	(0.109)	(0.0399)	(0.0267)	(0.0534)	(0.0240)	(0.0220)
Pop			−0.0176			−0.500***	−0.258***
			(0.0252)			(0.0803)	(0.0754)
logGDP		0.840***	0.841**		−2.041***	−2.718***	0.750
		(0.287)	(0.367)		(0.596)	(0.580)	(0.607)
logEXP			−0.705***				−2.955***
			(0.146)				(0.433)
Constant	1.760***	0.155	2.124***	1.961*	7.069***	13.17***	15.78***
	(0.491)	(0.262)	(0.446)	(1.138)	(2.577)	(4.290)	(5.019)
Observations	336	336	336	336	336	336	336
Number of groups	14	14	14	14	14	14	14

Source: own processing.
Note: methodology PMG estimator (Pesaran et al., 1999; Blackburne and Frank, 2007; Chudik and Pesaran, 2015) and implemented in Stata by Blackburne and Frank (2007), sliced data; first dataset—high gdp countries dataset: independent variable of interest: enTAX (12); the independent control variables are logarithmic value of GDP *per capita*—logGDP (13), population—pop(14), logarithmic value of exports—logEXP (14); added logarithmic value of imports—logIMP, removed logEXP (15); second dataset—lower level of gdp countries dataset: independent variable of interest: enTAX; the independent control variables are logarithmic value of GDP *per capita*—logGDP(16), population—pop (17), logarithmic value of exports—logEXP (18). *** $p < .01$, ** $p < .05$, * $p < .1$.

statistically significant at least at 5% level, as shown by other studies (Hao et al., 2021; He et al., 2021). The results can be interpreted as above, greenhouse gas emissions and energy (environmental) taxes display an inelastic inverse relationship, but in some cases the coefficient is not statistically significant.

One possible explanation is that, in developed countries, the higher price for categories affected by the tax is still acceptable and affordable, not being the case in developing countries, where an increase in costs, indeed determines a reduce of the related "consumption". The results are in line with other research (Dietz and Rosa, 1997; Ghazouani et al., 2020; Ghazouani et al., 2021; Mania, 2020; Andrew Mejia, 2021; D'Orazio and Dirks, 2022).

In countries with higher values of GDP, it appears that the effect is not as expected, the coefficients being positive and not statistically significant.

The results obtained in some models (1–7) are in line with the research in the structural human ecology tradition, that theorizes that population levels are a key driver of environmental degradation (Dietz and Rosa, 1997). The models in our study shows that there is a positive relationship between population density and air pollution as in other studies (Andrew Mejia, 2021; Falk and Hagsten, 2021; D'Orazio and Dirks, 2022). The main culprits for the increase in pollution are the increase in energy consumption, income and population, and governments must take effective measures to combat this phenomenon (Ghazouani et al., 2020). A study conducted on nine developed countries in Europe for the period 1994–2018 (Ghazouani et al., 2021), which tested the influence of environmental taxes, GDP and urban population on greenhouse gas emissions, using FMOLS techniques and DOLS pointed out that the introduction of environmental taxes has a positive influence on reducing pollution, while the increase in GDP and the urban population leads to an increase in greenhouse gas emissions. Globally, the population is expected to grow, and this growth will put increasing pressure on the environment.

By applying the Arellano-Bover's two-step dynamic panel approach to a sample of EU and transition countries in the period 1995–2006, Morley (Morley, 2012) shows that the introduction of environmental taxes in the EU has had a positive effect on the reduction of pollution, but a limited effect on energy consumption, which suggests that the use of cleaner technologies would be the solution, a conclusion we reached in our study.

Sharma et al. (2021) conducted a study on BIMSTEC countries over a period of 35 years that looked at the influence of agricultural production on greenhouse gas emissions and showed that limiting agricultural production on a smaller scale can improve the quality of the environment. However, reducing agricultural production is not a solution; it requires the use of clean energy tools, upon the urging of SDG 7-*Ensure access to affordable, reliable, sustainable and modern energy for all*, a conclusion that also confirms the results of our study. However, ecological solutions largely involve research and development costs (Lapinskienė et al., 2017), which will be considered in a future study.

To explain the different results obtained on previous models (especially in 8–11), twenty eight (28) further models were conducted at country levels using ARDL (Kripfganz and Schneider, 2016; Kripfganz and Schneider, 2020), the results being presented in Table 6. In Table 6 every row represents the results of the model at country level.

The first coefficient in the ADJ section is the negative speed-of-adjustment coefficient ($-\boldsymbol{\alpha}$). The coefficients in the LR section are the long-run coefficients θ. Investigation on individual countries, as seen in Table 6, shows that in 18 cases ($\alpha < 0$ and $\theta < 0$—green color) from 28, the effect of energy taxes is negative, as expected. We consider that the country level individual analysis enforces the previous ECM results, where the effect is statistically significant only at 5% level [model (17) or not significant (18)].

The impact of energy taxes is different at country level, with higher negative impact on *GHGbss* in emergent economies. Even if the overall impact can be considered as negative, *no strong conclusion can be drawn.*

The main findings of the empirical analysis can be highlight as follows:

- the empirical analysis consists in 46 models, from which 28 are applied to country level;
- 25 of 41 models (using different methodologies) suggests an inverse relation between *GHG* and *enTAX*;
- at country level, from 24 long-term models (with $\alpha < 0$), in 18 models an inverse relation between *GHG* and *enTAX* is met;
- some results are sensitive to composition of the sample, the choose of the independent variables and methodology;
- in some countries with high levels of *GDP per capita*, the results suggest no evidence of long-run and inverse relationship, when some methodologies were used;
- in countries with lower levels of GDP *per capita* in the models implied, there is evidence of inverse relation and long-run cointegration;
- based on the previous findings, the use of environmental taxes appears to have limitations, at least in some developed countries;
- the results are in line with other studies, as we explain below.

The same methodology was used in other articles with similar results (Ntanos et al., 2018; Afolayan et al., 2020; Leitão and Balogh, 2020; Hao et al., 2021; He et al., 2021; Wolde-Rufael and Mulat-Weldemeskel, 2022). In a 1996–2016 study of OECD countries, using the ARDL model, a group of authors (He et al., 2021) demonstrate that the introduction of energy taxes improves energy efficiency only in the short term and not for all sampled countries. A study conducted on a sample of countries grouped into Belt and Road (B&R) and OECD countries for the period 1992–2015 (Sun et al., 2020) using the Common Correlated Effect Mean Group (CCEMG) and Augmented Mean Group (AMG) methods showed that increasing production has a significant positive effect on environmental pollution for all panels. The results also show that other factors, such as trade openness, urbanization and energy use, have been responsible for the recent increase in global carbon emissions. However, there are disparities in the estimated coefficients. The impact is greater in the OECD region than in the Belt and Road region. In these circumstances, it is suggested that efforts to promote a sustainable and low-carbon green environment should take these factors together when developing different policies.

Our study highlights the fact that the application of energy taxes to improve the quality of the environment cannot be generalized, being insufficient for the sustainable development of each individual country. As a consequence of this fact, we rally to the opinion that supports the increasingly accentuated orientation towards investments in renewable energy sources with a positive impact on

TABLE 6 ARDL model results at country level.

Model No.	Country	Error-correction term (-α) results				Long—Run results for enTAX			
		Coef.	Std.Err	z	*p*-value	Coef.	Std. Err	z	*p*-value
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
(19)	**AT**	**−0.2608**	**0.1527**	**−1.7075**	**0.1032**	**0.2476**	**0.5842**	**0.4238**	**0.6761**
(20)	BE	0.2547	0.1924	1.3233	0.2022	−0.9328***	0.1916	−4.8674	0.0001
(21)	**BG**	**−0.8174*****	**0.2047**	**−3.9926**	**0.0009**	**1.2397*****	**0.2637**	**4.7010**	**0.0002**
(22)	**CH**	**−0.5668*****	**0.1880**	**−3.0143**	**0.0068**	**−0.5879*****	**0.0966**	**−6.0801**	**0.000**
(23)	**CZ**	**−0.3572****	**0.1271**	**−2.8087**	**0.0112**	**−0.6331****	**0.2793**	**−2.2664**	**0.0352**
(24)	DE	0.1162	0.1238	0.9379	0.3600	−0.2429	0.1669	−1.4554	0.1618
(25)	**DK**	**−0.0336**	**0.0979**	**−0.3433**	**0.7349**	**7.1119**	**30.9357**	**0.2298**	**0.8205**
(26)	**EL**	**−0.326*****	**0.1035**	**−3.1497**	**0.0050**	**−1.246*****	**0.1971**	**−6.3188**	**0.000**
(27)	**ES**	**−0.1364***	**0.0764**	**−1.7840**	**0.0903**	**−0.499***	**0.2631**	**−1.8960**	**0.0732**
(28)	**FI**	**−1.2165*****	**0.3275**	**−3.7142**	**0.0014**	**−2.206*****	**0.2889**	**−7.6354**	**0.000**
(29)	FR	0.1333	0.0830	1.6050	0.1269	−0.0242	0.0789	−0.3068	0.7627
(30)	**HU**	**−0.1808****	**0.0760**	**−2.3767**	**0.0287**	**−0.7102**	**0.5498**	**−1.2917**	**0.2127**
(31)	**IE**	**−0.1841**	**0.1081**	**−1.7017**	**0.1043**	**−4.1057*****	**1.2293**	**−3.3396**	**0.0032**
(32)	**IS**	**−0.086**	**0.1491**	**−0.5768**	**0.5711**	**−128.0526**	**167.8692**	**−0.7628**	**0.4554**
(33)	**IT**	**−0.4223****	**0.1595**	**−2.6459**	**0.0159**	**−0.1811*****	**0.0266**	**−6.7978**	**0.000**
(34)	**LT**	**−0.4459*****	**0.1170**	**−3.8093**	**0.0011**	**1.5229**	**1.3602**	**1.1195**	**0.2768**
(35)	**LU**	**−0.0561**	**0.0713**	**−0.7860**	**0.4415**	**−17.6903**	**35.0720**	**−0.5044**	**0.6197**
(36)	**LV**	**−0.5469****	**0.2162**	**−2.5285**	**0.0199**	**8.1963*****	**1.3236**	**6.1924**	**0.0000**
(37)	**MT**	**−0.3462***	**0.1675**	**−2.0660**	**0.0520**	**−32.1537*****	**8.0080**	**−4.0151**	**0.0006**
(38)	**NL**	**−0.6723*****	**0.1840**	**−3.6535**	**0.0016**	**−0.4721*****	**0.0347**	**−13.5852**	**0.000**
(39)	**NO**	**−0.2608**	**0.1655**	**−1.5755**	**0.1325**	**−0.4928**	**0.7028**	**−0.7011**	**0.4921**
(40)	**PL**	**−0.4427*****	**0.1239**	**−3.5710**	**0.0020**	**0.0571**	**0.0450**	**1.2670**	**0.2204**
(41)	**PT**	**−0.4183****	**0.1526**	**−2.7400**	**0.0134**	**−1.7525**	**1.0341**	**−1.6947**	**0.1073**
(42)	**RO**	**−0.4529*****	**0.1166**	**−3.8840**	**0.0009**	**−0.5238*****	**0.1311**	**−3.9952**	**0.0007**
(43)	**SE**	**−0.2955***	**0.1444**	**−2.0454**	**0.0549**	**−0.6078**	**0.4152**	**−1.4638**	**0.1595**
(44)	**SI**	**−0.251***	**0.1431**	**−1.7536**	**0.0948**	**3.0031**	**1.8179**	**1.6519**	**0.1141**
(45)	**SK**	**−0.5335****	**0.1888**	**−2.8257**	**0.0108**	**−0.9987*****	**0.2206**	**−4.5266**	**0.0002**
(46)	UK	0.0554	0.0446	1.2387	0.2305	−0.3851	0.2538	−1.5170	0.1457

Source: own processing.

Note: methodology ARDL (Kripfganz and Schneider, 2016; 2020); dependent variable: *GHGEbss*; independent variable of interest: enTAX. *** $p < .01$, ** $p < .05$, * $p < .1$.

sustainable development (Karmaker et al., 2021; Wolde-Rufael and Mulat-Weldemeskel, 2022). Although ETR (Environmental Tax Reform) aim to internalize the external cost of pollution, it has not yet created a level playing field between "green" technologies and non-renewable energy sources (Arbolino and Romano, 2014; Cottrell et al., 2016; Takeda and Arimura, 2021).

Recent research (Edziah et al., 2022) on how greenhouse gas emissions could be controlled shows that in developing economies an important role in reducing gas emissions is played by exogenous technological factors in addition to the use of renewable energy. Exogenous technological factors include imports of machinery and equipment, foreign direct investment, and imports of research and development (R&D) knowledge. The study is carried out on 18 developing countries for the period 1995–2017, and using the dynamic specific common correlated effect estimator (DCCE) technique, it is found that the use of renewable energy, imports of machinery, and foreign direct investment significantly reduce carbon dioxide emissions, but in descending order. In contrast, the transfer of research and development (R&D) from abroad increases carbon dioxide emissions in the region.

Conclusion

Today's society enjoys a life marked by the evolution of innovation and technology, but the facilities conveyed by the technological implementations brought into discussion a new problem that humanity is facing, namely pollution. Thus, water, air and soil pollution caused by gas emissions directly affects human health as well as the economies. At European level, the sustainable development of countries, which includes the desire to reduce the level of pollution, is also needed, while the European legislation has different terms regarding greenhouse gas emissions. Under these conditions, it is the governments that must take measures to reduce pollution, fiscal policy being one of the most common instruments with a demonstrated positive impact on the environmental system. However, the implementation of environmental taxes as a macroeconomic policy measure must be done carefully, as their negative effect on long-term economic sustainability can be admitted. Specifically, when the macro-objective is economic growth, the effect on environmental quality is negative, given that economies are still dependent on fossil fuels.

Our study focuses on the effects of energy taxes level on greenhouse gas emissions under environmental policy measures in the period 1995–2019 on 28 European countries (both at panel and individual—country level). The key variable *entax* is only partially significant and is very sensitive to specification and method. The findings show that, in the long run, an increase in energy taxes and imports could be a positive factor that possibly decrease greenhouse gas emissions. On the other hand, energy taxes have different results on diverse countries (this conclusion being encountered in different studies cited in our paper), so this leverage could not be generalized and other instruments should be found and used. We have also found that an increase in GDP has a negative effect on the quality of the environment, while population density and increased exports lead to a decrease in greenhouse gas emissions (not as we would expect). This can be explained by the fact that population growth does not necessarily translate into an increase in labor that will drive production and has a negative long-term impact on the environment at the level of the sample analyzed. Then, the influence of exports on the environment is a positive one in our long-term study, in the sense that greenhouse gas emissions decrease as exports increase, being justified by the fact that an increase in exports is not always generated by an increase in production (it could be influenced by the proportion of the domestic production that is destined for export). The producers' decision to export also depends on the exchange rate (in countries that have not adopted the Euro), being, rather, a reallocation of the same production internally or externally (exports can also increase in case of decrease in production). We found that, in the short term, population density, exports and imports negatively affect the quality of the environment, being in accordance with the results of other research.

Our findings suggest that (environmental/energy) taxes have limited and different effects that vary by countries, other instruments being needed and concentrated efforts should be done. The balance between environmental and sustainable growth policies could be the solution to this problem, so the support for the implementation of green energy must be considered as a foundation for economic growth.

Among the novelty aspects brought by our study are the extended and recent analysis period (the last year analyzed being 2019), the large number of states included in the sample, but also the recently applied methodology. Clearly, the study also has limitations, and these take into account the size of the sample, which depended on the available data, as well as the variables taken into account (that appear to be volatile regarding the robustness of results when combining different control variables in the methodologies implied). Subsequent research will consider expanding the sample, introducing additional variables, especially from the perspective of economic or environmental indices, and/or including the period covered by the COVID-19 pandemic.

Given the results of the research, it can be considered that the paper will be useful to public officials in making environmental policy decisions. More specifically, the results of our study lead to the idea that the growth of energy taxes is not sufficient to reduce greenhouse gas emissions, the effects being different and related to a variety of factors (some of them impossible to be quantified). This leads to another fact, that decision makers have to increasingly focus on promoting and aiding the implementation of green energy sources (e.g., considering as leverages the subsidies or tax advantages related to the use of solar/wind energy or electric cars). Public officials (both on national and local levels) should also consider tax incentives and investment grants for the implementation and use of renewable energy to achieve a higher level of sustainable development.

The novelty of the paper lies, first of all, in the fact that the methodology applied is recent and considers different situations, with the results showing that increasing energy taxes alone cannot be generalized as an environmental policy measure to reduce greenhouse gas emissions, as policymakers have to focus on finding other solutions, such as the deployment of renewable energy sources.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: Eurostat Database.

Author contributions

BF: Concept, data, methodology, econometric analysis, literature review and writing. FB and MG: Conceptualization, data, literature review, and writing. ED and AS: Data, literature review, and writing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.965841/full#supplementary-material

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