Research Topics

Progress towards achieving cross-regional carbon mitigation targets

Edited by
Kangyin Dong, Xiucheng Dong, Xiaohang Ren and Yukun Shi

Published in
Frontiers in Energy Research

ISSN 1664-8714
ISBN 978-2-83251-500-6
DOI 10.3389/978-2-83251-500-6

About Frontiers

Frontiers is more than just an open access publisher of scholarly articles: it is a pioneering approach to the world of academia, radically improving the way scholarly research is managed. The grand vision of Frontiers is a world where all people have an equal opportunity to seek, share and generate knowledge. Frontiers provides immediate and permanent online open access to all its publications, but this alone is not enough to realize our grand goals.

Frontiers journal series

The Frontiers journal series is a multi-tier and interdisciplinary set of open-access, online journals, promising a paradigm shift from the current review, selection and dissemination processes in academic publishing. All Frontiers journals are driven by researchers for researchers; therefore, they constitute a service to the scholarly community. At the same time, the *Frontiers journal series* operates on a revolutionary invention, the tiered publishing system, initially addressing specific communities of scholars, and gradually climbing up to broader public understanding, thus serving the interests of the lay society, too.

Dedication to quality

Each Frontiers article is a landmark of the highest quality, thanks to genuinely collaborative interactions between authors and review editors, who include some of the world's best academicians. Research must be certified by peers before entering a stream of knowledge that may eventually reach the public - and shape society; therefore, Frontiers only applies the most rigorous and unbiased reviews. Frontiers revolutionizes research publishing by freely delivering the most outstanding research, evaluated with no bias from both the academic and social point of view. By applying the most advanced information technologies, Frontiers is catapulting scholarly publishing into a new generation.

What are Frontiers Research Topics?

Frontiers Research Topics are very popular trademarks of the *Frontiers journals series*: they are collections of at least ten articles, all centered on a particular subject. With their unique mix of varied contributions from Original Research to Review Articles, Frontiers Research Topics unify the most influential researchers, the latest key findings and historical advances in a hot research area.

Find out more on how to host your own Frontiers Research Topic or contribute to one as an author by contacting the Frontiers editorial office: frontiersin.org/about/contact

Progress towards achieving cross-regional carbon mitigation targets

Topic editors
Kangyin Dong — University of International Business and Economics, China
Xiucheng Dong — University of International Business and Economics, China
Xiaohang Ren — Central South University, China
Yukun Shi — University of Glasgow, United Kingdom

Citation
Dong, K., Dong, X., Ren, X., Shi, Y., eds. (2023). *Progress towards achieving cross-regional carbon mitigation targets*. Lausanne: Frontiers Media SA.
doi: 10.3389/978-2-83251-500-6

Table of contents

frontiers in Energy Research

ORIGINAL RESEARCH
published: 03 May 2021
doi: 10.3389/fenrg.2021.683166

Check for updates

How Does Industrial Structure Upgrading Affect the Global Greenhouse Effect? Evidence From RCEP and Non-RCEP Countries

*Jiajia Dong[1], Yue Dou[2,3], Qingzhe Jiang[2,3] and Jun Zhao[2,3]**

[1] Metropolitan College, Boston University, Boston, MA, United States, [2] School of International Trade and Economics, University of International Business and Economics, Beijing, China, [3] UIBE Belt & Road Energy Trade and Development Center, University of International Business and Economics, Beijing, China

This study empirically investigates the impact of industrial structure upgrading on global carbon dioxide (CO_2) emissions by employing a balanced dataset of 73 countries over the period 1990–2019. After conducting a series of empirical tests, we used the fixed effect (FE) and random effect (RE) methods to estimate the econometric model, and divided the full sample data into two subsamples, i.e., Regional Comprehensive Economic Partnership (RCEP) countries and non-RCEP countries, for heterogeneous analysis. This study also examines the mediating role of technological innovation in the relationship between industrial structure upgrading and global CO_2 emissions. The main findings indicate that: (1) both industrial structure upgrading and technological innovation show significant negative impacts on CO_2 emissions in the global panel, the RCEP countries, and the non-RCEP countries; (2) industrial structure upgrading not only affects CO_2 emissions directly, but also has an indirect impact on global CO_2 emissions by promoting technological innovation; and (3) the environmental Kuznets curve (EKC) hypothesis is verified in this study; in other words, both economic growth and CO_2 emissions exhibit a significant inverted U-shaped relationship in the global panel, the RCEP countries, and the non-RCEP countries. Finally, we highlighted some important policy implications with respect to promoting industrial structure upgrading and mitigating the greenhouse effect.

Keywords: industrial structure upgrading, greenhouse effect, RCEP and non-RCEP countries, mediating effect model, global analysis

OPEN ACCESS

Edited by:
Xiaohang Ren,
Central South University, China

Reviewed by:
Jiang Hongdian,
Beijing Institute of Technology, China
Li Jizheng,
Central University of Finance and Economics, China
Hui Li,
Beijing Institute of Technology, China

Correspondence:
Jun Zhao
zhaojun4768@163.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *20 March 2021*
Accepted: *07 April 2021*
Published: *03 May 2021*

Citation:
Dong J, Dou Y, Jiang Q and Zhao J (2021) How Does Industrial Structure Upgrading Affect the Global Greenhouse Effect? Evidence From RCEP and Non-RCEP Countries. Front. Energy Res. 9:683166. doi: 10.3389/fenrg.2021.683166

INTRODUCTION

The past few decades have witnessed unparalleled economic growth due to rapid industrialization across the globe. According to the statistics from the former British Petroleum company (BP, 2020), along with this boom in economics, the primary energy consumption has increased nearly twofold worldwide, from 7,820.7 million tons of oil equivalent (Mtoe) in 1990 to 13,301.4 Mtoe in 2019. This rapid increase in energy consumption has triggered tremendous challenges related to the global environmental pressures (Cheng et al., 2019; Dong et al., 2020a; Zhao et al., 2021a), particularly the greenhouse effect. To be specific, global carbon dioxide (CO_2) emissions increased from 21,331.5 million tons (Mt) in 1990 to 34,169.0 Mt in 2019 (BP, 2020). Since CO_2 is the main contributor to the greenhouse effect, lowering CO_2 emissions has become a critical issue that needs to be addressed all over the world. Many scholars have investigated the driving factors of CO_2 emissions; among these, industrial structure upgrading has been widely accepted as an effective pathway to realize low-carbon development (Du et al., 2012; Tian et al., 2019; Zhao et al., 2020a; Ren et al., 2021). In this study, the definition of industrial structure upgrading is that the national industrial structure shifts from low value-added labor-intensive industries to high value-added technology-intensive industries; in other words, industrial structure upgrading refers to the process or trend of the transformation of the industrial structure from a low-level form to the high-level form. From the perspective of changes in the national industrial structure, industrial structure upgrading means that the national economic barycenter moves from primary industry to secondary industry, and then to tertiary industry. Since this process is usually accompanied by the development of high-tech industries, many scholars believed that it can mitigate environmental pressure caused by CO_2 emissions (Cheng et al., 2018; Peng et al., 2018; Zhou et al., 2018). However, to the best of our knowledge, the existing literature on the impact of industrial structure upgrading on CO_2 emissions is based mainly on Chinese cases, and very few studies on this issue are obtained from the global perspective.

Recently, the signing of the largest Free Trade Agreement (FTA) – the Regional Comprehensive Economic Partnership (RCEP) agreement – has attracted attention worldwide. The signing of the RCEP agreement provides a favorable platform to promote friendly exchanges, strengthen cooperation, and jointly promote the transformation of industrial structure and achieve carbon emission reduction targets. Its member countries cover 10 Association of Southeast Asian Nations (ASEAN) countries and include China, Japan, South Korea, Australia, and New Zealand. The member countries of the RCEP agreement account for nearly half of the world population and comprise the most diverse membership structure in the world. Under the framework of the RCEP, China and other RCEP member countries will accelerate the formation of an expanded version of the "world factory," and the agglomeration effect of the industrial chain and the supply chain will be further amplified. Based on the above circumstances, the signing of the RCEP can significantly boost the high-end manufacturing industry chains of member countries, which plays an important role in their national industrial structure upgrading. Thus, the organization of the RCEP countries may have the most development potential. Furthermore, since several RCEP countries (e.g., Japan, South Korea, and Singapore) have relatively higher technology levels, the technology spillover effect might be stronger among the RCEP countries. These factors indicate that heterogeneity may exist between the RCEP countries and the non-RCEP countries in the nexus between industrial structure upgrading and CO_2 emissions. However, very few studies have systematically examined the impact of technological innovation on the industrial structure upgrading–CO_2 nexus, and heterogeneity is often overlooked in the existing literature.

To fill the academic gaps discussed earlier, this study first investigates the impact of industrial structure upgrading on global CO_2 emissions by employing a balanced panel dataset covering 73 countries for the period 1990–2019, and then divides the full sample into two subsamples (i.e., the RCEP and non-RCEP countries) to examine the heterogeneous impact of industrial structure upgrading on CO_2 emissions. This study also investigates the mediating effect of technological innovation in the industrial structure upgrading–CO_2 emissions nexus. Accordingly, this study contributes to the existing literature in the following three aspects. (1) From the global perspective, after a series of tests, we empirically investigated the impact of industrial structure upgrading on CO_2 emissions and then identified the specific causal relationship between industrial structure and its determinants, which provides more generalized policy implications for reducing global CO_2 emissions. (2) By dividing the full sample into two subregions, i.e., RCEP and non-RCEP countries, we examined the heterogeneous impact of industrial structure upgrading on CO_2 emissions. This not only effectively provides evidence for policymakers to implement specific policies for carbon reduction, but also helps the RCEP countries to develop a low-carbon economic growth pattern. (3) To identify the internal impact channels between industrial structure upgrading and CO_2 emissions, we conducted the mediation effect in the industrial structure upgrading–CO_2 nexus by considering technological innovation as mediating variable, which can help advance our understanding of the impact mechanism between industrial structure upgrading and CO_2 emissions and facilitate the formulation of more compatible policies to reduce CO_2 emissions.

The remainder of this study is organized as follows. The "Literature review and research gap" section covers the literature review. The "Econometric model, method, and data" section provides the empirical model, estimation strategy, and data. The "Empirical results" section reports the empirical results. The "Further discussion on the mediating effect between industrial structure upgrading and CO_2 emissions" section further discusses the mediating effect between industrial structure upgrading and CO_2 emissions. The "Conclusions and policy implications" section concludes this study and provides some implications.

LITERATURE REVIEW AND RESEARCH GAP

Research on the Impact of Industrial Structure Upgrading on CO_2 Emissions

In recent years, a growing body of scholars has shed light on the impact of industrial structure upgrading on CO_2 emissions. For instance, based on the STIRPAT framework, Li et al. (2017) found a significant negative correlation between industrial structure upgrading and CO_2 emissions in China. By employing a dataset covering 50 cities in China, Li et al. (2018) investigated the impact of industrial structure change on CO_2 emissions, and proposed that industrial structure change can significantly reduce CO_2 emissions. Furthermore, Tian et al. (2019) utilized the methods of input–output analysis (IOA) and structural decomposition analysis (SDA) to investigate the impact of industrial structure change on CO_2 emissions in southwest China. Their empirical results show that secondary industries (e.g., construction and manufacturing) are the main contributors of CO_2 emissions, and that industrial structure upgrading is conducive to carbon reduction, assertions that are supported by many other scholars who have also conducted analyses based on Chinese case (Chen et al., 2011; Yang et al., 2014; Chang, 2015; Liu et al., 2015; Zhang et al., 2020).

Additionally, some other researchers have examined the relationship between industrial structure and CO_2 emissions at the provincial level. For example, Zhang and Ren (2011) found a long-run equilibrium relationship between industrial structure and CO_2 emissions in Shandong Province and stated that industrial structure change could unidirectionally affect CO_2 emissions. Considering potential nonlinear characteristics, Wei and Zhang (2020) examined the threshold effect of industrial structure upgrading on CO_2 emissions based on the panel smooth transition regression model in Chinese 30 provinces for the period 1997–2015. The results indicate that the increase in the proportion of tertiary industry has an obvious positive impact on CO_2 emissions, while the increased proportion of the secondary industry would slow down the trend of CO_2 emissions. It is obvious that the current literature on the nexus between industrial structure and CO_2 emissions is based mainly on the Chinese case. Thus, the earlier conclusions have limitations, and their policy implications are not generalized for most global countries. In addition, very few studies have mentioned the impact of external shocks (e.g., the signing of the RCEP) on the nexus observed, which may cause the estimation bias and make the results inaccurate.

Research on the Determinants of CO_2 Emissions

In addition to industrial structure upgrading, some other factors have been found to contribute significantly to CO_2 emissions. These factors include technological innovation, economic growth, trade openness, and population size. Specifically, many scholars have investigated the impact of technological innovation on CO_2 emissions and consistently concluded that technological innovation can significantly mitigate CO_2 emissions (York et al., 2003; Zhao et al., 2010; Irandoust, 2016; Yii and Geetha, 2017; Cheng et al., 2020). As for the economic growth–CO_2 nexus, scholars in this field have largely accepted the well-known environmental Kuznets curve (EKC) hypothesis proposed by Grossman and Krueger (1993). The Kuznets curve clearly depicts an inverted U-shaped relationship between economic growth and CO_2 emissions (Zhang et al., 2017; Balado-Naves et al., 2018; Dong et al., 2018a; Leal and Marques, 2020). With regard to the impact of trade openness on CO_2 emissions, there has been some disparity among various studies. Some scholars believed that trade openness would produce more CO_2 emissions due to its positive impact on the production of goods in a country, which requires massive energy consumption and leads to more CO_2 emissions (Ertugrul et al., 2016; Ahmed et al., 2017). However, other researchers reached an opposing conclusion based on empirical results, which indicate that trade openness can reduce CO_2 emissions (Gozgor, 2017; Ho and Iyke, 2019; Lv and Xu, 2019). These scholars argued that trade openness is conducive to expanding the technology spillover effect between global countries, which consequently improves their national energy efficiency. Moreover, many scholars have investigated the role of population in CO_2 emissions, and claimed that population has a significantly positive impact on CO_2 emissions (Ghazali and Ali, 2019; Wang et al., 2019; Dong et al., 2020b). Other factors are also considered as contributing to CO_2 emissions. These include population aging (Menz and Welsch, 2012; Wang et al., 2017; Yu et al., 2018), natural gas consumption (Alkhathlan and Javid, 2013; Saboori and Sulaiman, 2013; Dong et al., 2018b), and urbanization (Liu and Bae, 2018; Bai et al., 2019). However, these variables are not considered in this study.

Literature Gap

Based on the literature review discussed earlier, although many scholars have examined the nexus between industrial structure upgrading and CO_2 emissions, certain research gaps still exist. First, to the best of our knowledge, earlier studies on the nexus between industrial structure upgrading and CO_2 emissions were based mainly on Chinese case; very few studies investigated the impact of industrial structure upgrading on CO_2 emissions from a global perspective, which can provide more generalized evidence for policymakers to implement effective policies for carbon reduction. Second, the existing literature neglects the influence of the signing of the RCEP on the nexus between industrial structure upgrading and CO_2 emissions. In other words, few studies explore the heterogeneity between RCEP and non-RCEP countries on this issue, which may cause bias in the estimation results. Third, very few studies have explored the impact mechanism of industrial structure upgrading on CO_2 emissions. In particular, the role of technological innovation in the industrial structure upgrading–CO_2 nexus remains unclear.

ECONOMETRIC MODEL, METHOD, AND DATA

Econometric Model

To explore the impact of industrial structure upgrading on CO_2 emissions, this study conducts an empirical analysis by constructing an econometric model, where CO_2 emissions are utilized as the dependent variable, and industrial structure upgrading is used as the core independent variable. Based on the literature review discussed earlier, technological innovation, economic growth, trade openness, and population size are introduced as control variables. Furthermore, to verify the EKC hypothesis in this study, we also introduced the quadratic term of economic growth into the model. Therefore, the multivariate framework can be written as follows:

$$CO_{2it} = f(ISU_{it}, Tec_{it}, Pgdp_{it}, Pgdp_{it}^2, Tra_{it}, Pop_{it}) \qquad (1)$$

where subscripts i and t represent the country and year, respectively. CO_2 represents the CO_2 emissions of each country, *ISU* indicates industrial structure upgrading, *Tec* denotes technological innovation, *Pgdp* refers to economic growth, *Tra* means trade openness, and *Pop* represents the population of each country.

Furthermore, to eliminate possible heteroscedasticity in the model, this study takes all the variables in Eq. (1) into logarithmic form as follows:

$$LnCO_{2it} = \beta_0 + \beta_1 LnISU_{it} + \sum_{k=2}^{6} \beta_k LnX_{it} + \varepsilon_{it} \quad (2)$$

where β_0 and ε_{it} denote the constant and random error terms, respectively. β_1–β_6 are the coefficients to be estimated. *X* stands for a vector that contains a series of control variables, i.e., technological innovation, economic growth and its square term, trade openness, and population size.

Estimation Strategy

To investigate the impact of industrial structure upgrading on CO_2 emissions across the globe, the estimation strategies in this study consist of four steps: (1) the Breusch–Pagan Lagrange multiplier (LM) test and the Pesaran cross-sectional dependence (CD) test are simultaneously conducted to examine CD within the panel data (see the "CD tests" section); (2) two panel unit root tests, i.e., the Pesaran cross-sectionally augmented Dickey–Fuller (CADF) and cross-sectionally augmented Im, Pesaran, and Shin (CIPS) tests, are utilized to examine the stationarity of the selected variables (see the "Panel CADF and CIPS unit root tests" section); (3) both the fixed effect (FE) and random effect (RE) estimation methods are employed to estimate the impact of industrial structure upgrading on CO_2 emissions (see the "FE and RE estimates" section); and (4) to detect the causal relationship between all the variables, the Dumitrescu–Hurlin (D-H) causality test is conducted in this study (see the "D-H panel causality test" section).

CD Tests

Since countries around the world are more linked due to the rapid globalization of trade and economics, a shock affecting one country might cause economic fluctuations in other countries. This means CD may exist in the global panel data, which can cause biased and even inconsistent estimates of the econometric model (Dong et al., 2019, 2021; Jiang et al., 2020). Therefore, to obtain consistent estimations, this study first conducts two CD tests, that is, the Breusch–Pagan LM test developed by Breusch and Pagan (1980) and the Pesaran CD test proposed by Pesaran (2004) to examine the existence of CD in the panel data.

Panel CADF and CIPS Unit Root Tests

Before estimating the parameters in the model, it is necessary to ensure that all the selected variables in this study are stable. Considering the potential CD in the panel data, two updated panel unit root tests (i.e., the Pesaran CADF and CIPS tests) are conducted to examine the stationarity of the variables. To be specific, the Pesaran CIPS test is proposed by Pesaran (2007) and the test statistics for the Pesaran CIPS can be obtained as follows:

$$\Delta Y_{it} = \gamma_i + \alpha_i Y_{i,t-1} + \beta_i \overline{Y}_{t-1} + \sum_{l=0}^{P} \gamma_{il} \Delta \overline{Y}_{t-l} + \sum_{l=1}^{P} \gamma_{il} \Delta Y_{i,t-l} + \varepsilon_{it} \quad (3)$$

where $\overline{Y}_{t-l}$ and $\Delta \overline{Y}_{t-l}$ represent the cross-sectional averages of lagged levels and first differences of individual series, respectively. From the CADF, the CIPS test statistics can be calculated as follows:

$$CIPS = \frac{1}{N} \sum_{i=1}^{n} CADF_i \quad (4)$$

where $CADF_i$ represents the *t*-statistic in the CADF regression defined by Eq. (3).

FE and RE Estimates

Considering multiple individuals are involved in the panel data, the different individual effects in the econometric model might cause bias in the process of estimation. Thus, we employed two conventional static panel data estimation approaches (i.e., the FE and RE methods) to calculate the estimated parameters in Eq. (2). Moreover, both the FE and RE estimation methods could avoid the problem of omitted variables by eliminating the impact from individual effects. Technically, the FE model is suitable for the conditions where the individual factors are correlated with some independent variables, while the RE model is appropriate for the situation where the individual factors are irrelevant with all the independent variables. Based on this, before applying the two estimation methods, it is necessary to figure out which method fits the panel data in this study. Following the specification test principle proposed by Hausman (1978), we utilized the Hausman test to identify the more effective estimates. Specifically, the null hypothesis of the Hausman test is a non-correlation between individual factors and the independent variables, which means the RE estimates are more effective. Additionally, to detect whether the signing of the RCEP affects the nexus between industrial structure upgrading and CO_2 emissions, this study further estimates the econometric model based on two subsamples (i.e., the RCEP countries and the non-RCEP countries). By comparing the estimation results of the full panel sample and the two subsamples, we conducted a heterogeneous analysis of the impact of industrial structure upgrading on CO_2 emissions.

D-H Panel Causality Test

The causal relationship between CO_2 emissions and their determinants cannot be verified merely from a regression equation. Thus, Granger (1969) proposed a causality test to examine causalities between the selected variables in the empirical model. The results of the causality tests are particularly useful for policymakers to formulate specific policies. Since CD may exist in the panel data, the D-H panel causality test developed by Dumitrescu and Hurlin (2012) is used in this

TABLE 1 | Description of all the selected variables.

Variable	Definition	Data source
CO_2	Carbon dioxide (CO_2) emissions	BP (2020)
ISU	Ratio of the added value of the tertiary industry to the secondary industry	World Bank (2020)
Tec	Proportion of total gross domestic product (GDP) to energy consumption	BP (2020) and World Bank (2020)
Pgdp	Per capita GDP	World Bank (2020)
Tra	Proportion of total import and export to GDP	World Bank (2020)
Pop	Population	World Bank (2020)

study. The test can also deal with the heterogeneity in the slope coefficients in the model.

Variable Measurements and Data

This study employs a balanced panel dataset covering 73 countries over the period 1990–2019 to investigate the impact of industrial structure upgrading on CO_2 emissions. Notably, other countries are not considered due to unavailability of data. Moreover, considering the potential heterogeneity between the RCEP countries and the non-RCEP countries, this study further divides the full panel into two subsamples, the RCEP countries (12 countries) and the non-RCEP countries (61 countries); the specific countries are highlighted in **Appendix Table A1**.

The data on CO_2 emissions (denoted as CO_2) are sourced from the BP Statistical Review of World Energy (BP, 2020). Industrial structure upgrading (denoted as *ISU*) is calculated by the ratio of the added value of tertiary industry to secondary industry, and the data are obtained from the World Development Indicators (WDI) published by the World Bank (2020). Technological innovation (denoted as *Tec*) is measured by the proportion of gross domestic product (GDP) to energy consumption, where the data on energy consumption are obtained from BP (2020), while the data on GDP are obtained from the World Bank (2020). Economic growth (denoted as *Pgdp*) is expressed by per capita GDP, trade openness (denoted as *Tra*) is measured by the ratio of total imports and exports to GDP, and population (denoted as *Pop*) is measured by the national population of each country. The data on economic growth, trade openness, and population were collected from the World Bank (2020). In sum, the detailed description of the variables is listed in **Table 1**, while the descriptive statistics (i.e., mean value, SD, maximum value, and minimum value) of the variables are illustrated in **Table 2**.

EMPIRICAL RESULTS

Results of CD Tests

The estimation results of the CD tests for the global panel and the two subsamples are all reported in **Table 3**. As the table shows, the statistics of the Breusch–Pagan LM tests and the Pesaran CD tests are all larger than the critical values at the 1% significance level, which confirms strong CD for the full panel and the groups of the RCEP and non-RCEP countries. Therefore, when conducting the following empirical analysis, the CD in the three panels (i.e., the full panel and two subpanels) should be fully considered.

TABLE 2 | Descriptive statistics of all the selected variables (after logarithm).

Panel	Variables	Obs.	Mean	SD	Min	Max
Global panel	$LnCO_2$	2,190	4.711829	1.383155	1.938211	9.192767
	LnISU	2,190	0.5621893	0.5177519	−2.082297	2.007518
	LnTec	2,190	−1.692787	0.481996	−3.646372	−0.4831987
	LnPgdp	2,190	9.355232	1.254396	6.018994	11.62597
	$LnPgdp^2$	2,190	89.09316	22.92353	36.22828	135.1632
	LnTra	2,190	4.238189	0.6477828	−3.863269	6.080681
	LnPop	2,190	16.79474	1.563094	12.85278	21.0581
RCEP countries	$LnCO_2$	360	5.652064	1.430734	2.858019	9.192767
	LnISU	360	0.4523649	0.3778658	−0.3387244	1.178982
	LnTec	360	−1.70509	0.3221202	−3.053031	−0.815232
	LnPgdp	360	8.885996	1.462949	6.071393	10.98654
	$LnPgdp^2$	360	81.0952	25.91471	36.86182	120.704
	LnTra	360	4.264086	0.7599114	2.741244	6.080681
	LnPop	360	18.01789	1.748463	14.92971	21.0581
Non-RCEP countries	$LnCO_2$	1,830	4.555271	1.306878	1.938211	8.680018
	LnISU	1,830	0.5859982	0.5396149	−2.082297	2.007518
	LnTec	1,830	−1.697604	0.5064509	−3.646372	−0.4831987
	LnPgdp	1,830	9.448844	1.189417	6.018994	11.62597
	$LnPgdp^2$	1,830	90.6946	21.98763	36.22828	135.1632
	LnTra	1,830	4.220192	0.6262307	−3.863269	6.012154
	LnPop	1,830	16.5691	1.402305	12.85278	19.60925

SD, Min, and Max denote standard deviation, minimum, and maximum, respectively.

Results of the Panel CADF and CIPS Unit Root Tests

Following the discussions earlier, the CD is verified in both the full panel and the two subpanels (the RCEP and non-RCEP countries). Thus, the panel CADF and CIPS unit root tests are valid and more suitable in this study to examine the stationarity of the selected variables. The results of the two tests for the full panel and the two subsamples of the RCEP and non-RCEP countries are listed in **Table 4**. From the table, the variables of the full panel sample are not all stable at the level; however, after taking the first-order difference, all the series data are stable due to the significant statistics of the panel unit root tests. Similar results are obtained for the subsamples of the RCEP countries and non-RCEP countries. Therefore, the selected variables in this study are integrated of order [i.e., I (1)], for both the full sample data and the two subsamples. This ensures stable estimation of the empirical model and avoids the problem of spurious regression. To sum up, the econometric model we built in this study is valid and reliable for the full panel sample and the two subsamples, respectively, due to the same order of integration of the selected variables in the three samples.

TABLE 3 | Results of the cross-sectional dependence tests.

Panel	Breusch–Pagan LM test	Pesaran CD test
Global panel	21,667.50***	7.734***
RCEP countries	1,241.25***	3.784***
Non-RCEP countries	19,384.64***	3.950***

****indicates statistical significance at the 1% level.*

TABLE 4 | Results of the panel CADF and CIPS unit root tests.

Panel	Variables	Pesaran CADF test		Pesaran CIPS test	
		Level	1st difference	Level	1st difference
Global panel	$LnCO_2$	−2.249	−3.767***	−2.234	−2.358***
	LnISU	−2.354	−3.803***	−2.221	−4.864***
	LnTec	−2.274***	−3.887***	−2.453***	−5.154***
	LnPgdp	−2.496**	−3.223***	−2.511	−3.894***
	$LnPgdp^2$	−2.398	−3.171***	−2.395	−3.856***
	LnTra	−3.197***	−4.215***	−2.657**	−4.761***
	LnPop	−2.701***	−3.977***	−2.037	−3.313***
RCEP countries	$LnCO_2$	−2.234	−3.041***	−2.016	−4.511***
	LnISU	−2.377	−3.384***	−2.495	−4.996***
	LnTec	−1.784	−2.967***	−1.740	−4.090***
	LnPgdp	−1.580	−3.494***	−1.677	−4.408***
	$LnPgdp^2$	−1.575	−3.475***	−1.858	−4.292***
	LnTra	−2.058	−3.236***	−2.267	−4.522***
	LnPop	−3.487***	−4.656***	−2.421	−2.786**
Non-RCEP countries	$LnCO_2$	−2.302	−3.879***	−2.220	−5.280***
	LnISU	−2.361	−3.922***	−2.275	−4.870***
	LnTec	−2.354***	−4.058***	−2.538***	−5.334***
	LnPgdp	−2.535**	−3.215***	−2.609	−3.869***
	$LnPgdp^2$	−2.466*	−3.166***	−2.494	−3.815***
	LnTra	−3.297***	−4.275***	−2.676**	−4.838***
	LnPop	−3.016***	−3.870***	−2.141	−3.281***

****, **, and * indicate statistical significance at the 1, 5, and 10% levels, respectively. Optimal lag lengths were selected automatically using the Schwarz information criteria.*

Results of the Industrial Structure Upgrading–CO_2 Nexus

Estimates for the Global Panel

Based on the empirical analysis earlier, this study then investigates the nexus between industrial structure upgrading and CO_2 emissions by estimating Eq. (2) for the global panel. Furthermore, technological innovation may have a significant impact on industrial structure upgrading–CO_2 emissions. To verify this, we first eliminated technological innovation in Eq. (2) and then reestimated the model by introducing it into an empirical framework. The results of the FE and RE estimates are displayed in **Table 5**. Specifically, the first and second columns of the table report the estimation results for the empirical model without technological innovation based on the FE and RE methods, respectively; the third and fourth columns of the table present the results of the FE and RE estimates for the model with technological innovation, respectively. Also, the estimation results of the Hausman tests are reported in the table. From the table, the FE estimates are more effective due to the significant statistics of the Hausman tests for the model both before and after technological innovation is introduced. Therefore, the FE estimates are considered the benchmark estimation results for the global panel. Notably, the results of the RE estimates are basically consistent with the FE estimates, which indicates that the estimation results of Eq. (2) are robust and stable.

As for the impact of industrial structure upgrading on global CO_2 emissions, it is obvious that industrial structure

TABLE 5 | Results of the FE and RE estimates for the full sample.

Variable	FE estimation	RE estimation	FE estimation	RE estimation
LnISU	−0.140***	−0.144***	−0.041***	−0.045***
	(−7.86)	(−7.97)	(−3.93)	(−4.31)
LnTec			−1.054***	−1.026***
			(−65.32)	(−66.18)
LnPgdp	2.226***	2.205***	2.125***	2.166***
	(19.27)	(19.02)	(31.96)	(32.49)
$LnPgdp^2$	−0.108***	−0.104***	−0.063***	−0.067***
	(−16.21)	(−15.57)	(−16.09)	(−17.26)
LnTra	−0.087***	−0.081***	−0.024***	−0.019***
	(−7.99)	(−7.38)	(−3.75)	(−3.05)
LnPop	1.161***	1.036***	1.092***	1.084***
	(45.11)	(48.33)	(73.57)	(84.86)
_Cons	−25.556***	−23.655***	−29.597***	−29.429***
	(−42.81)	(−41.30)	(−84.78)	(−85.89)
Obs.	2,190	2,190	2,190	2,190
R^2	0.7335	0.7653	0.9008	0.9072
Hausman	112.56 (0.0000)		76.82 (0.0000)	

**** indicates statistical significance at the 1% level; the values in parentheses represent t-statistics.*

upgrading can significantly reduce CO_2 emissions. This is rational because, with rapid industrialization around the world, industrial structure upgrading appears as a shift from secondary to tertiary industries. To the best of our knowledge, the secondary industry usually has the characteristics of high pollution and high emissions, while the tertiary industry shows the advantages of high added value and low pollution (Zhao et al., 2021b). The secondary industries consist mainly of industry and construction, which are the main contributors of CO_2 emissions in the world. However, the tertiary industries are dominated mainly by the service sectors (e.g., computer services and software, information transmission, and financial), which are more efficient and emit low carbon. Accordingly, the promotion of transformation from secondary industry to tertiary industry can play an important role in carbon emission reduction; in other words, industrial structure upgrading is conducive to carbon reduction. Thus, it is necessary for policymakers to promote the shift of industrial structure from secondary to tertiary industries, which will reduce CO_2 emissions and achieve green economic development. Furthermore, it is noteworthy that when technological innovation is introduced into the empirical model, the estimated coefficient of industrial structure upgrading (i.e., *ISU*) shrinks a lot. This indicates that the impact of industrial structure upgrading on CO_2 emissions might be attributed partly to technological innovation. At the same time, accelerating technological innovation can significantly reduce CO_2 emissions. In other words, industrial structure upgrading may not only affect CO_2 emissions directly, but also influence CO_2 emissions through technological innovation.

As for the control variables, the estimated coefficients of technological innovation (i.e., *Tec*), economic growth (i.e., *Pgdp*), trade openness (i.e., *Tra*), and population (i.e., *Pop*) are all significant, and their signs basically coincide with the actual conditions. Specifically, both technological innovation and trade openness can significantly reduce global CO_2 emissions due to their negative estimated coefficients. This is rational because both of them can improve production efficiency and optimize the production procedure, which are conducive to reducing energy use while maintaining the current production level. Since energy use is the main source of CO_2 emissions, the decline in energy utilization will certainly slow the growth of CO_2 emissions. As for economic growth, this study confirms the EKC hypothesis according to the positive coefficient of economic growth and the negative of its quadratic term, which indicates that an inverted U-shaped relationship exists between economic growth and CO_2 emissions. Specifically, during the initial stage, rapid economic growth is anchored by massive energy consumption, which is accompanied by large amounts of CO_2 emissions. However, as national economic growth rises to a certain level, the environmental regulation tends to be more intensified, considering the consequences of the greenhouse effect. Furthermore, public awareness of energy conservation and emission reduction tends to be greater when their income level improves. These factors result in a downward trend of CO_2 emissions after economic growth crosses a certain value (i.e., a turning point). The results also indicate that population has a significantly positive impact on CO_2 emissions. This is because rapid population growth causes more demand for energy consumption, particularly for some developing countries whose energy efficiency is relatively low. This certainly would cause more CO_2 emissions and would not mitigate the greenhouse effect.

Estimates for RCEP and Non-RCEP Countries

After estimating the causal nexus between industrial structure upgrading on CO_2 emissions based on the global panel, this study further reestimates the benchmark model [i.e., Eq. (2)] based on the two subsamples (i.e., the RCEP and non-RCEP countries), respectively. The estimation results are listed in **Table 6**. Similarly, the FE and RE estimates are simultaneously employed

TABLE 6 | Results of the FE and RE estimates across RCEP and non-RCEP countries.

Variable	RCEP countries				Non-RCEP countries			
	FE estimation	RE estimation	FE estimation	RE estimation	FE estimation	RE estimation	FE estimation	RE estimation
LnISU	−0.622*** (−9.24)	−0.616*** (−8.99)	−0.289*** (−4.66)	−0.290*** (−4.31)	−0.143*** (−8.06)	−0.148*** (−8.18)	−0.041*** (−4.11)	−0.046*** (−4.57)
LnTec			−0.640*** (−12.50)	−0.563*** (−10.63)			−1.071*** (−62.14)	−1.039*** (−63.41)
LnPgdp	1.752*** (12.49)	1.601*** (11.34)	1.955*** (16.64)	1.745*** (13.89)	1.390*** (9.34)	1.392*** (9.31)	1.979*** (23.60)	1.997*** (23.85)
LnPgdp^2	−0.060*** (−6.57)	−0.045*** (−5.08)	−0.065*** (−8.50)	−0.046*** (−5.90)	−0.068*** (−8.12)	−0.065*** (−7.77)	−0.055*** (−11.81)	−0.059*** (−12.56)
LnTra	0.090*** (2.88)	0.087*** (2.78)	0.078*** (3.00)	0.102*** (3.73)	−0.086*** (−7.86)	−0.082*** (−7.38)	−0.020*** (−3.25)	−0.018*** (−2.87)
LnPop	1.435*** (17.21)	1.111*** (24.29)	1.664*** (23.25)	1.177*** (34.64)	1.130*** (43.54)	1.034*** (44.76)	1.054*** (72.26)	1.050*** (79.61)
_Cons	−30.999*** (−19.60)	−25.021*** (−26.07)	−37.762*** (−26.60)	−28.607*** (−34.20)	−20.695*** (−28.97)	−19.391*** (−27.34)	−28.296*** (−67.64)	−28.051*** (−67.10)
Obs.	360	360	360	360	1,830	1830	1,830	1,830
R^2	0.9251	0.9217	0.9486	0.9415	0.5816	0.5782	0.8689	0.8686
Hausman	20.83 (0.0000)		91.08 (0.0000)		126.53 (0.0000)		56.05 (0.0000)	

**** indicates statistical significance at the 1% level; the values in parentheses represent t-statistics.*

for the models before and after technological innovation is introduced into the empirical framework. And from the results of the Hausman tests, the FE estimates are still preferred as the benchmark estimations for both the RCEP and non-RCEP countries.

As for the RCEP countries, industrial structure upgrading still has a significantly negative impact on CO_2 emissions, which is consistent with the results for the global panel. However, compared with the estimated results in for the full sample, the absolute value of the coefficient of industrial structure upgrading is larger, which indicates that the impact of industrial structure upgrading on CO_2 emissions is greater for the RCEP countries. This might be because, among the RCEP countries, some developed countries (e.g., Australia, Japan, South Korea, and Singapore) are at or near the stage of post-industrial society. This means most of these countries have successfully shifted their national structure of manufacturing industry from capital-intensive industries to technology-intensive industries; thus, these countries have relatively higher technology levels. At the same time, people's lifestyles in these countries are more modernized. Additionally, the signing of the RCEP will greatly strengthen the links among member countries, and the technology spillover among these countries will be stronger than in other countries. Based on this, the marginal effect of industrial structure upgrading on carbon reduction in the RCEP countries is larger than that of countries in other regions. Furthermore, similar to the global panel, it is obvious that the coefficient of industrial structure upgrading shrinks after technological innovation is introduced into the model. This implies that the impact of industrial structure upgrading on CO_2 emissions is affected by technological innovation. The significance and signs of the coefficients of other control variables are consistent with those of the global panel, which is in line with the actual conditions of the RCEP countries.

With respect to the non-RCEP countries, the significance and absolute values of the coefficients of the independent variables are almost the same as the global panel. This implies that, in both RCEP and non-RCEP countries, the upgrading of industrial structure is conducive to the realization of carbon emission reduction targets. Furthermore, the evident difference of the coefficients between the RCEP countries and other global countries highlights the significance of the signing of the RCEP on the nexus between industrial structure upgrading and CO_2 emissions. To conclude, the impact of industrial structure upgrading on CO_2 emissions is heterogeneous between the RCEP countries and the non-RCEP countries. Thus, policymakers should adjust measures to local conditions when implementing policies for carbon reduction.

Results of the D-H Panel Causality Test

The results of the D-H panel causality tests for the global panel and the two subpanels are listed in **Table 7**. In addition, to clearly display the causal relationships between the selected variables, we also depicted the causality flows in **Figure 1**. As the figure shows, bidirectional causality runs between any two of the variables for the global panel and non-RCEP countries, which indicates that the correlations between global CO_2 emissions and their determinants are getting much closer due to the tightening link of economic activities and environmental quality. However, as for the RCEP countries, the causality is unidirectional, running from technological innovation to CO_2 emissions and from technological innovation to economic growth. The varying causal relationships among the different samples again verify the existence of heterogeneity between the RCEP and non-RCEP countries. This implies that policymakers should implement specific policies to reduce CO_2 emissions.

TABLE 7 | Results of the D-H panel causality tests.

No.	Null hypothesis	Global panel	RCEP countries	Non-RCEP countries
1	$CO_2 \neq ISU$	10.6670***	2.4883**	10.8423***
2	$ISU \neq CO_2$	5.9878***	5.0732***	4.3272***
3	$CO_2 \neq Tec$	12.8061***	**1.6112**	13.2951***
4	$Tec \neq CO_2$	13.4503***	10.1314***	10.3388***
5	$CO_2 \neq Pgdp$	16.3706***	5.6822***	15.3820***
6	$Pgdp \neq CO_2$	28.3127***	8.0857***	27.9788***
7	$CO_2 \neq Tra$	9.5072***	5.5456***	7.9908***
8	$Tra \neq CO_2$	8.2962***	7.2113***	6.2760***
9	$CO_2 \neq Pop$	16.7422***	5.8843***	15.6906***
10	$Pop \neq CO_2$	118.6812***	36.1528***	113.7162***
11	$ISU \neq Tec$	9.8457***	3.9790***	7.8265***
12	$Tec \neq ISU$	13.4682***	7.5276***	11.0135***
13	$ISU \neq Pgdp$	12.9607***	8.0659***	10.1502***
14	$Pgdp \neq ISU$	24.4579***	3.3408***	25.7790***
15	$ISU \neq Tra$	6.7946***	3.0476***	5.9177***
16	$Tra \neq ISU$	14.5310***	1.7441*	14.9620***
17	$ISU \neq Pop$	8.8039***	6.0073***	7.0548***
18	$Pop \neq ISU$	57.0425***	24.9258***	51.4670***
19	$Tec \neq Pgdp$	19.2548***	9.7838***	16.5903***
20	$Pgdp \neq Tec$	18.7063***	**0.7298**	20.1565***
21	$Tec \neq Tra$	17.1287***	5.9009***	15.6492***
22	$Tra \neq Tec$	11.0380***	4.5273***	10.2248***
23	$Tec \neq Pop$	28.5423***	11.6420***	25.7641***
24	$Pop \neq Tec$	78.7734***	34.6920***	70.7939***
25	$Pgdp \neq Tra$	17.8907***	5.9571***	17.4372***
26	$Tra \neq Pgdp$	15.9392***	9.9106***	12.3349***
27	$Pgdp \neq Pop$	31.9762***	4.5973***	32.9312***
28	$Pop \neq Pgdp$	108.6138***	42.4640***	100.0639***
29	$Tra \neq Pop$	16.5841***	12.4774***	12.6310***
30	$Pop \neq Tra$	38.9820***	25.7122***	31.1771***

*The values in bold denote the Wald statistics, and A≠B indicates that A does not cause B. ***, **, and * indicate statistical significance at the 1, 5, and 10% levels, respectively.*

FURTHER DISCUSSION ON THE MEDIATING EFFECT BETWEEN INDUSTRIAL STRUCTURE UPGRADING AND CO_2 EMISSIONS

Estimation Model

To effectively investigate the impact of industrial structure upgrading on CO_2 emissions, it is necessary to explore the specific impact mechanism behind the observed relationship. Furthermore, based on the discussions on the estimation results in the "Results of the industrial structure upgrading–CO_2 nexus" section, the coefficient of industrial structure upgrading changes a lot after technological innovation is introduced into the empirical model, which indicates that technological innovation might be a mediating factor between industrial structure upgrading and CO_2 emissions. To verify this, this study further conducts a mediating effect analysis on the nexus between industrial structure upgrading and CO_2 emissions. Following the work by Zhao et al. (2020b), we constructed the mediating effect model as follows:

$$LnCO_{2it} = \alpha_0 + \alpha_1 LnISU_{it} + \sum_{k=2}^{5} \alpha_k LnX_{it} + \varepsilon_{it} \quad (5)$$

$$LnTec_{it} = \phi_0 + \phi_1 LnISU_{it} + \sum_{k=2}^{5} \phi_k LnX_{it} + \varepsilon_{it} \quad (6)$$

$$LnCO_{2it} = \delta_0 + \delta_1 LnISU_{it} + \delta_2 LnTec_{it} + \sum_{i=3}^{6} \delta_k LnX_{it} + \varepsilon_{it} \quad (7)$$

where X indicates a vector of control variables, including economic growth and its square term, trade openness, and population. ε_{it} represents the random disturbance term in three equations [i.e., Eqs. (5)–(7)]. The logic of the mediating effect model lies in that the direct effect of industrial structure upgrading on CO_2 emissions is reflected from the parameter δ_1 in Eq. (7), and the indirect effect through technological innovation is valid if the parameters ϕ_1 in Eq. (6) and δ_2 in Eq. (7) are simultaneously significant. Also, to detect whether the impact mechanism varies with different panel data, we conducted a mediating effect analysis based on the global panel and the two subsamples (i.e., the RCEP and non-RCEP countries), respectively.

Empirical Results

The estimation results of the mediating effect model are reported in **Table 8**. In this table, Models (1)–(3) correspond to Eqs. (5)–(7), respectively. As the table shows, the coefficients of industrial structure upgrading in Eqs. (5) and (6) and

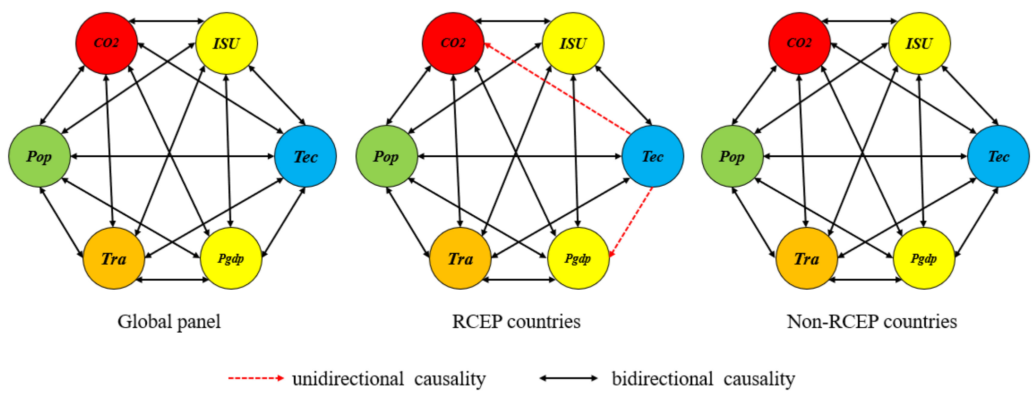


FIGURE 1 | Results of causality movements for the full panel and two subpanels.

TABLE 8 | Results of the mediating effect between industrial structure upgrading and CO_2 emissions.

Variable	Global panel			RCEP countries			Non-RCEP countries		
	Model (1)	Model (2)	Model (3)	Model (1)	Model (2)	Model (3)	Model (1)	Model (2)	Model (3)
LnISU	−0.140*** (−7.86)	0.094*** (6.81)	−0.041*** (−3.93)	−0.622*** (−9.24)	0.521*** (8.84)	−0.289*** (−4.66)	−0.143*** (−8.06)	0.095*** (6.91)	−0.041*** (−4.11)
LnTec			−1.054*** (−65.32)			−0.640*** (−12.50)			−1.071*** (−62.14)
LnPgdp	2.226*** (19.27)	−0.096 (−1.07)	2.125*** (31.96)	1.752*** (12.49)	0.317*** (2.59)	1.955*** (16.64)	1.390*** (9.34)	0.550*** (4.78)	1.979*** (23.60)
LnPgdp^2	−0.108*** (−16.21)	0.043*** (8.32)	−0.063*** (−16.09)	−0.060*** (−6.57)	−0.007 (−0.87)	−0.065*** (−8.50)	−0.068*** (−8.12)	0.012* (1.81)	−0.055*** (−11.81)
LnTra	−0.087*** (−7.99)	0.060*** (7.10)	−0.024*** (−3.75)	0.090*** (2.88)	−0.019 (−0.70)	0.078*** (3.00)	−0.086*** (−7.86)	0.062*** (7.26)	−0.020*** (−3.25)
LnPop	1.161*** (45.11)	−0.065*** (−3.26)	1.092*** (73.57)	1.435*** (17.21)	0.358*** (4.91)	1.664*** (23.25)	1.130*** (43.54)	−0.071*** (−3.54)	1.054*** (72.26)
_Cons	−25.556*** (−42.81)	−3.832*** (−8.27)	−29.597*** (−84.78)	−30.999*** (−19.60)	−10.57*** (−7.64)	−37.762*** (−26.60)	−20.695*** (−28.97)	−7.099*** (−12.84)	−28.296*** (−67.64)
Obs.	2,190	2,190	2,190	360	360	360	1,830	1,830	1,830
R^2	0.7335	0.6488	0.9008	0.9251	0.7145	0.9486	0.5816	0.6906	0.8689

**** and * indicate statistical significance at the 1 and 10% levels, respectively; the values in parentheses represent t-statistics.*

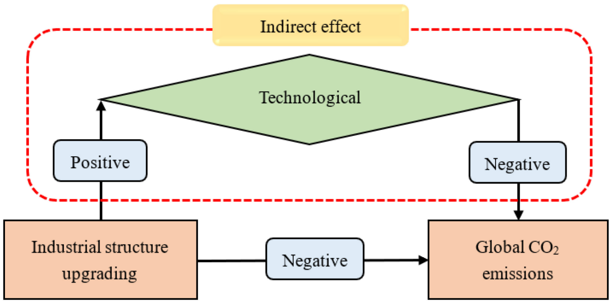


FIGURE 2 | The specific impact mechanism between industrial structure upgrading and CO_2 emissions.

technological innovation in Eq. (7) are all significant, no matter which sample data are employed. Thus, industrial structure upgrading not only affects CO_2 emissions directly, but can also indirectly affect CO_2 emissions through technological innovation. Specifically, industrial structure upgrading can significantly promote the development of technological innovation, while technological innovation has a significantly negative impact on CO_2 emissions. This is rational because industrial structure upgrading means the booming of service sectors, such as information transmission and financial; these industries, compared with secondary industries, are technology and knowledge intensive, and their current boom is accelerating the process of national technological innovation. Similar to the discussions in the "Results of the industrial structure upgrading–CO_2 nexus" section, technological innovation can significantly reduce CO_2 emissions. Therefore, the indirect impact of industrial structure upgrading on CO_2 emissions is negative.

In addition, it is worth noting that the specific impact mechanism between industrial structure upgrading and CO_2 emissions of RCEP countries is slightly different from that of global countries and non-RCEP countries. Specifically, for RCEP countries, the coefficient of industrial structure in Eq. (6) is larger than that of the global panel and the non-RCEP countries. This verifies the existence of a technology spillover effect among the RCEP countries, which again indicates that the impact of industrial structure upgrading on CO_2 emissions is heterogeneous between the RCEP countries and non-RCEP countries; the specific impact mechanism between industrial structure upgrading and CO_2 emissions is presented in **Figure 2**.

CONCLUSION AND POLICY IMPLICATIONS

By employing a balanced panel dataset of 73 countries over the period 1990–2019, this study empirically investigates the impact of industrial structure upgrading on CO_2 emissions across the globe. After conducting a series of empirical tests, this study uses the conventional panel data estimation methods, i.e., the FE and the RE methods. Moreover, we also explored the impact mechanism between industrial upgrading and CO_2 emissions by employing the mediating effect model. And to detect heterogeneity between the RCEP and non-RCEP countries, we also conducted a series of comparative analyses on industrial structure upgrading–CO_2 emissions nexus. Several interesting findings are highlighted as follows.

First, upgrading industrial structure can significantly reduce global CO_2 emissions, which provides new evidence for policymakers to promote this process to reduce carbon emissions. Furthermore, the marginal impact of upgrading industrial structure on CO_2 reduction is larger for the RCEP countries, which indicates that heterogeneity exists in the nexus between industrial structure upgrading and CO_2 emissions.

Second, this study verifies the EKC hypothesis; in other words, an inverted U-shaped relationship exists between economic growth and global CO_2 emissions. Thus, there exists a threshold value (i.e., a turning point) between economic growth and CO_2 emissions, and CO_2 emissions increase initially and then decline as the economic growth crosses the threshold value.

Third, technological innovation is verified as a significant mediating variable between industrial structure upgrading and CO_2 emissions. To be specific, upgrading industrial structure not only affects CO_2 emissions directly, but can also have an indirect impact on CO_2 emissions through technological innovation. Furthermore, the different estimation results between the RCEP countries and non-RCEP countries again verify the existence of heterogeneity in the relationship between industrial structure upgrading and CO_2 emissions.

Based on the findings earlier, several policy implications are provided as follows.

First, since upgrading industrial structure contributes significantly to carbon mitigation, it is necessary for policymakers to implement effective and specific policies to encourage the development of the modern service industry and limit the expansion of secondary industries, especially those with high energy consumption. For example, the government can provide targeted subsidies to promote the development of service industries and set a series of environmental regulations for high-emission secondary industries to promote energy conservation and carbon reduction. The government also should work to eliminate traditional high-polluting sunset industries, formulate relevant promotion measures for emerging sunrise industries, provide sufficient scientific R&D funds, and lay a solid foundation for the subsequent sustainable and green transformation of industrial structure. Furthermore, as for the RCEP countries, it is helpful to expand the technology spillover effect among the relevant countries by promoting technology trade among these countries.

Second, although economic growth is anchored by massive energy consumption and carbon emissions, CO_2 emissions would eventually show a downward trend due to technology development fueled by economic growth. This emphasizes the importance of the green economy to a certain extent. Thus, governments of various countries should strive to promote environmental protection while maintaining sustained economic growth. Furthermore, new industrialization paths should be developed by changing the patterns of the industry. Specifically, the percentage of high-tech industries, such as information transmission and financial, should be improved to accelerate economic development and upgrade the national industrial structure.

Third, technological innovation should be promoted due to its role in the mediation effect mechanism between industrial structure upgrading and CO_2 emissions. Some low-carbon and high-efficiency technologies should be improved through development, demonstration, and promotion. For example, governments should encourage enterprises to establish scientific management systems to improve information levels and operational efficiencies. Moreover, R&D technologies for clean, renewable energy and exploration technologies for natural gas, coal bed methane, and shale gas should also be promoted to rationalize the energy consumption structure.

However, this study provides only preliminary empirical evidence on the industrial structure upgrading–CO_2 nexus, and there exist some limitations. One such limitation is the empirical method. In this study, we employed the static regression model (e.g., FE and RE estimation), and in future research, we tend to consider the dynamic linkage between industrial structure upgrading and CO_2 emissions. Another limitation is that it would be interesting to focus on the industrial structure rationalization, but the upgrading of the industrial structure shows the importance of the tertiary industry. However, the secondary industry is also indispensable. Therefore, how to realize the rational allocation of industrial structure is also crucial.

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/s.

AUTHOR CONTRIBUTIONS

JD contributed to datacuration, methodology, and software. YD contributed to conceptualization and wrote the original draft. QJ contributed to conceptualization and wrote, reviewed, edited, and supervised. JZ contributed to conceptualization, methodology, validation, investigation, wrote, reviewed, and edited. All authors contributed to the article and approved the submitted version.

FUNDING

This article is supported by the National Social Science Foundation of China (Grant No. 18VDL017) and the Innovation Methods Special Foundation of the Chinese Ministry of Science and Technology (Grant No. 2018IMO40100). Certainly, all remaining errors are our own.

REFERENCES

Ahmed, K., Rehman, M. U., and Ozturk, I. (2017). What drives carbon dioxide emissions in the long-run? Evidence from selected South Asian Countries. *Renew. Sust. Energ. Rev.* 70, 1142–1153. doi: 10.1016/j.rser.2016.12.018

Alkhathlan, K., and Javid, M. (2013). Energy consumption, carbon emissions and economic growth in Saudi Arabia: an aggregate and disaggregate analysis. *Energ. Policy* 62, 1525–1532. doi: 10.1016/j.enpol.2013.07.068

Bai, Y., Deng, X., Gibson, J., Zhao, Z., and Xu, H. (2019). How does urbanization affect residential CO_2 emissions? An analysis on urban agglomerations of China. *J. Clean. Prod.* 209, 876–885. doi: 10.1016/j.jclepro.2018.10.248

Balado-Naves, R., Baños-Pino, J. F., and Mayor, M. (2018). Do countries influence neighbouring pollution? A spatial analysis of the EKC for CO_2 emissions. *Energ. Policy* 123, 266–279. doi: 10.1016/j.enpol.2018.08.059

Breusch, T. S., and Pagan, A. R. (1980). The lagrange multiplier test and its applications to model specification in econometrics. *Rev. Econ. Stud.* 47, 239–253. doi: 10.2307/2297111

Chang, N. (2015). Changing industrial structure to reduce carbon dioxide emissions: a Chinese application. *J. Clean. Prod.* 103, 40–48. doi: 10.1016/j.jclepro.2014.03.003

Chen, S., Jefferson, G. H., and Zhang, J. (2011). Structural change, productivity growth and industrial transformation in China. *China Econ. Rev.* 22, 133–150. doi: 10.1016/j.chieco.2010.10.003

Cheng, C., Ren, X., Dong, K., Dong, X., and Wang, Z. (2020). How does technological innovation mitigate CO_2 emissions in OECD countries? Heterogeneous analysis using panel quantile regression. *J. Environ. Manag.* 280:111818. doi: 10.1016/j.jenvman.2020.111818

Cheng, C., Ren, X., Wang, Z., and Yan, C. (2019). Heterogeneous impacts of renewable energy and environmental patents on CO_2 emission-evidence from the BRIICS. *Sci. Total Environ.* 668, 1328–1338. doi: 10.1016/j.scitotenv.2019.02.063

Cheng, Z., Li, L., and Liu, J. (2018). Industrial structure, technical progress and carbon intensity in China's provinces. *Renew. Sust. Energ. Rev.* 81, 2935–2946. doi: 10.1016/j.rser.2017.06.103

Dong, K., Dong, X., and Dong, C. (2019). Determinants of the global and regional CO_2 emissions: what causes what and where? *Appl. Econ.* 51, 5031–5044. doi: 10.1080/00036846.2019.1606410

Dong, K., Dong, X., and Jiang, Q. (2020a). How renewable energy consumption lower global CO_2 emissions? Evidence from countries with different income levels. *World Econ.* 43, 1665–1698. doi: 10.1111/twec.12898

Dong, K., Dong, X., and Ren, X. (2020b). Can expanding natural gas infrastructure mitigate CO_2 emissions? Analysis of heterogeneous and mediation effects for China. *Energ. Econ.* 90:104830. doi: 10.1016/j.eneco.2020.104830

Dong, K., Sun, R., Jiang, H., and Zeng, X. (2018a). CO_2 emissions, economic growth, and the environmental Kuznets curve in China: what roles can nuclear energy and renewable energy play? *J. Clean Prod.* 196, 51–63. doi: 10.1016/j.jclepro.2018.05.271

Dong, K., Sun, R., Li, H., and Liao, H. (2018b). Does natural gas consumption mitigate CO_2 emissions: testing the environmental Kuznets curve hypothesis for 14 Asia-Pacific countries. *Renew. Sust. Energ. Rev.* 94, 419–429. doi: 10.1016/j.rser.2018.06.026

Dong, K., Dong, X., Jiang, Q., and Zhao, J. (2021). Valuing the greenhouse effect of political risks: the global case. *Appl. Econ.* 53, 1–15. doi: 10.1080/00036846.2021.1883543

Du, L., Wei, C., and Cai, S. (2012). Economic development and carbon dioxide emissions in China: provincial panel data analysis. *China Econ. Rev.* 23, 371–384. doi: 10.1016/j.chieco.2012.02.004

Dumitrescu, E. I., and Hurlin, C. (2012). Testing for Granger non-causality in heterogeneous panels. *Econ. Model.* 29, 1450–1460. doi: 10.1016/j.econmod.2012.02.014

Ertugrul, H. M., Cetin, M., Seker, F., and Dogan, E. (2016). The impact of trade openness on global carbon dioxide emissions: evidence from the top ten emitters among developing countries. *Ecol. Indic.* 67, 543–555. doi: 10.1016/j.ecolind.2016.03.027

Ghazali, A., and Ali, G. (2019). Investigation of key contributors of CO_2 emissions in extended STIRPAT model for newly industrialized countries: a dynamic common correlated estimator (DCCE) approach. *Energ. Rep.* 5, 242–252. doi: 10.1016/j.egyr.2019.02.006

Gozgor, G. (2017). Does trade matter for carbon emissions in OECD countries? Evidence from a new trade openness measure. *Environ. Sci. Pollut. R.* 24, 27813–27821. doi: 10.1007/s11356-017-0361-z

Granger, C. W. J. (1969). Investigating causal relations by econometric models and cross-spectral methods. *Econometrica* 37, 424–438. doi: 10.2307/1912791

Grossman, G. M., and Krueger, A. B. (1993). "Environmental impacts of a North American free trade agreement," in *The US-Mexico free Trade Agreement*, ed. P. Barber (Cambridge, MA: MIT Press), doi: 10.3386/w3914

Hausman, J. A. (1978). Specification tests in econometrics. *Econometrica* 46, 1251–1271. doi: 10.2307/1913827

Ho, S., and Iyke, B. (2019). Trade openness and carbon emissions: evidence from central and eastern European countries. *Rev. Econ.* 70, 41–67. doi: 10.1515/roe-2018-0001

Irandoust, M. (2016). The renewable energy-growth nexus with carbon emissions and technological innovation: evidence from the Nordic countries. *Ecol. Indic.* 69, 118–125. doi: 10.1016/j.ecolind.2016.03.051

Jiang, H., Dong, X., Jiang, Q., and Dong, K. (2020). What drives China's natural gas consumption? Analysis of national and regional estimates. *Energ. Econ.* 87:104744. doi: 10.1016/j.eneco.2020.104744

Leal, P. H., and Marques, A. C. (2020). Rediscovering the EKC hypothesis for the 20 highest CO_2 emitters among OECD countries by level of globalization. *Int. Econ.* 164, 36–47. doi: 10.1016/j.inteco.2020.07.001

Li, L., Lei, Y., Wu, S., He, C., Chen, J., and Yan, D. (2018). Impacts of city size change and industrial structure change on CO_2 emissions in Chinese cities. *J. Clean Prod.* 195, 831–838. doi: 10.1016/j.jclepro.2018.05.208

Li, W., Wang, W., Wang, Y., and Qin, Y. (2017). Industrial structure, technological progress and CO_2 emissions in China: analysis based on the STIRPAT framework. *Nat. Hazards* 88, 1545–1564. doi: 10.1007/s11069-017-2932-1

Liu, N., Ma, Z., and Kang, J. (2015). Changes in carbon intensity in China's industrial sector: decomposition and attribution analysis. *Energ. Policy* 87, 28–38. doi: 10.1016/j.enpol.2015.08.035

Liu, X., and Bae, J. (2018). Urbanization and industrialization impact of CO_2 emissions in China. *J. Clean. Prod.* 172, 178–186. doi: 10.1016/j.jclepro.2017.10.156

Lv, Z., and Xu, T. (2019). Trade openness, urbanization and CO_2 emissions: dynamic panel data analysis of middle-income countries. *J. Int. Trade. Econ. Dev.* 28, 317–330. doi: 10.1080/09638199.2018.1534878

Menz, T., and Welsch, H. (2012). Population aging and carbon emissions in OECD countries: accounting for life-cycle and cohort effects. *Energ. Econ.* 34, 842–849. doi: 10.1016/j.eneco.2011.07.016

Peng, B., Tu, Y., Elahi, E., and Wei, G. (2018). Extended Producer Responsibility and corporate performance: effects of environmental regulation and environmental strategy. *J. Environ. Manag.* 218, 181–189. doi: 10.1016/j.jenvman.2018.04.068

Pesaran, M. H. (2004). General diagnostic tests for cross section dependence in panels. *Cambridge Working Papers in Economics*. Paper No. 0435. doi: 10.17863/CAM.5113

Pesaran, M. H. (2007). A simple panel unit root test in the presence of cross-section dependence. *J. Appl. Econ.* 22, 265–312. doi: 10.1002/jae.951

Ren, X., Cheng, C., Wang, Z., and Yan, C. (2021). Spillover and dynamic effects of energy transition and economic growth on carbon dioxide emissions for the European Union: a dynamic spatial panel model. *Sustain. Dev.* 29, 228–242. doi: 10.1002/sd.2144

Saboori, B., and Sulaiman, J. (2013). Environmental degradation, economic growth and energy consumption: evidence of the environmental Kuznets curve in Malaysia. *Energ. Policy* 60, 892–905. doi: 10.1016/j.enpol.2013.05.099

Tian, X., Bai, F., Jia, J., Liu, Y., and Shi, F. (2019). Realizing low-carbon development in a developing and industrializing region: impacts of industrial structure change on CO_2 emissions in southwest China. *J. Environ. Manag.* 233, 728–738. doi: 10.1016/j.jenvman.2018.11.078

Wang, S., Wang, J., Li, S., Fang, C., and Feng, K. (2019). Socioeconomic driving forces and scenario simulation of CO_2 emissions for a fast-developing region in China. *J. Clean. Prod.* 216, 217–229. doi: 10.1016/j.jclepro.2019.01.143

Wang, Y., Kang, Y., Wang, J., and Xu, L. (2017). Panel estimation for the impacts of population-related factors on CO_2 emissions: a regional analysis in China. *Ecol. Indic.* 78, 322–330. doi: 10.1016/j.ecolind.2017.03.032

Wei, W., and Zhang, M. (2020). The non-linear impact of industrial structure on CO_2 emissions in China. *Appl. Econ. Lett.* 27, 576–579. doi: 10.1080/13504851.2019.1644419

World Bank (2020). *World Development Indicators*. Available online at: https://databank.worldbank.org/source/world-development-indicators/preview/on

Yang, Y., Cai, W., and Wang, C. (2014). Industrial CO_2 intensity, indigenous innovation and R&D spillovers in China's provinces. *Appl. Energy* 131, 117–127. doi: 10.1016/j.apenergy.2014.06.033

Yii, K. J., and Geetha, C. (2017). The nexus between technology innovation and CO_2 emissions in Malaysia: evidence from granger causality test. *Energy Procedia* 105, 3118–3124. doi: 10.1016/j.egypro.2017.03.654

York, R., Rosa, E. A., and Dietz, T. (2003). STIRPAT, IPAT and ImPACT: analytic tools for unpacking the driving forces of environmental impacts. *Ecol. Econ.* 46, 351–365. doi: 10.1016/S0921-8009(03)00188-5

Yu, Y., Deng, Y. R., and Chen, F. F. (2018). Impact of population aging and industrial structure on CO_2 emissions and emissions trend prediction in China. *Atmos. Pollut. Res.* 9, 446–454. doi: 10.1016/j.apr.2017.11.008

Zhang, B., Wang, B., and Wang, Z. (2017). Role of renewable energy and non-renewable energy consumption on EKC: evidence from Pakistan. *J. Clean Prod.* 156, 855–864. doi: 10.1016/j.jclepro.2017.03.203

Zhang, F., Deng, X., Phillips, F., Fang, C., and Wang, C. (2020). Impacts of industrial structure and technical progress on carbon emission intensity: evidence from 281 cities in China. *Technol. Forecast. Soc. Change* 154:119949. doi: 10.1016/j.techfore.2020.119949

Zhang, X., and Ren, J. (2011). The relationship between carbon dioxide emissions and industrial structure adjustment for Shandong Province. *Energy Proc.* 5, 1121–1125. doi: 10.1016/j.egypro.2011.03.197

Zhao, J., Dong, C., Dong, X., and Jiang, Q. (2020a). Coordinated development of industrial structure and energy structure in China: its measurement and impact on CO_2 emissions. *Clim. Res.* 81, 29–42. doi: 10.3354/cr01607

Zhao, J., Jiang, Q., Dong, X., and Dong, K. (2020b). Would environmental regulation improve the greenhouse gas benefits of natural gas use? A Chinese case study. *Energ. Econ.* 87:104712. doi: 10.1016/j.eneco.2020.104712

Zhao, J., Jiang, Q., Dong, X., and Dong, K. (2021a). Assessing energy poverty and its effect on CO_2 emissions: the case of China. *Energ. Econ.* 97:105191. doi: 10.1016/j.eneco.2021.105191

Zhao, J., Shahbaz, M., Dong, X., and Dong, K. (2021b). How does financial risk affect global CO_2 emissions? The role of technological innovation. *Technol. Forecast. Soc. Change* 168:120751. doi: 10.1016/j.techfore.2021.120751

Zhao, M., Tan, L., Zhang, W. G., Ji, M. H., Liu, Y., and Yu, L. Z. (2010). Decomposing the influencing factors of industrial carbon emissions in Shanghai using the LMDI method. *Energy* 35, 2505–2510. doi: 10.1016/j.energy.2010.02.049

Zhou, C., Wang, S., and Feng, K. (2018). Examining the socioeconomic determinants of CO_2 emissions in China: a historical and prospective analysis. *Resour. Conserv. Recy.* 130, 1–11. doi: 10.1016/j.resconrec.2017.11.007

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.

APPENDIX

TABLE A1 The specific countries of RCEP and non-RCEP countries.

Region	Provinces
RCEP countries (12 countries)	Australia, China, India, Indonesia, Japan, South Korea, Singapore, New Zealand, Thailand, Philippines, Vietnam, Malaysia
Non-RCEP countries (61 countries)	Argentina, Australia, Brazil, France, Germany, Italy, Mexico, the Netherlands, Russian Federation, Saudi Arabia, Spain, Switzerland, Turkey, the United Kingdom, the United States, Denmark, Ukraine, Uzbekistan, Israel, Iraq, Iran, Bulgaria, Croatia, Canada, Hungary, North Macedonia, South Africa, Qatar, Luxembourg, Ecuador, Kazakhstan, Colombia, Turkmenistan, Venezuela, Bangladesh, Pakistan, Greece, Latvia, Norway, Czech Republic, Morocco, Slovakia, Slovenia, Chile, Belgium, Poland, Ireland, Estonia, Sweden, Belarus, Kuwait, Peru, Lithuania, Romania, Finland, Portugal, Azerbaijan, Algeria, Egypt, the United Arab Emirates, Oman

TABLE A2 Abbreviation list.

Abbreviations			
ASEAN	Association of Southeast Asian Nations	GDP	Gross domestic product
BP	former British Petroleum	IOA	Input–output analysis
CADF	Cross-sectionally augmented Dickey–Fuller	LM	Lagrange multiplier
CD	Cross-sectional dependence	Mt	Million tons
CIPS	Cross-sectionally augmented Im, Pesaran, and Shin	Mtoe	Million tons of equivalent oil
CO_2	Carbon dioxide	RCEP	Regional Comprehensive Economic Partnership
D-H	Dumitrescu–Hurlin	RE	Random effect
EKC	Environmental Kuznets curve	SDA	Structural decomposition analysis
FE	Fixed effect	WDI	World Development Indicators
FTA	Free Trade Agreement		

frontiers in Energy Research

ORIGINAL RESEARCH
published: 11 May 2021
doi: 10.3389/fenrg.2021.681334

The Green Innovation Effect on Heavy-Polluting Enterprises Under the Environmental Protection Law

Leqian Ouyang and Daming You*

Business College, Central South University, Changsha, China

One of the main purposes of the 2015 *Environmental Protection Law* (EPL) *of the People's Republic of China* is to boost the green innovation of the enterprises. Using heavy-polluting enterprises as examples, this paper uses the Difference-in-difference analysis (DDD) technique to analyze the influence of EPL on the green innovation of enterprises under fiscal decentralization and enterprise heterogeneity. Results show that EPL exerts a negative impact on the green innovation of heavy-polluting enterprises at the national level, as well as those in the central and western areas specifically. The only presence of positive motivation for green innovation is being found in the eastern area, although, the motivation seems to be insignificant. The negative impacts have been lasting in the long run, especially for the low-performance enterprises in the central areas. As for the targeted implementation of EPL in China, local governments should make the best use of financial power under fiscal decentralization. This balanced approach is designed to motivate enterprises in different regions with various performance levels to develop green innovation based on their different weaknesses and strengths.

Keywords: green innovation, environmental protection law, fiscal decentralization, DDD analysis, environmental regulation

OPEN ACCESS

Edited by:
Kangyin Dong,
University of International Business and Economics, China

Reviewed by:
Ma Yongjun,
Hunan University of Technology, China
Sihuan Li,
Huaihua University, China
Xiaohui Shu,
Huaihua University, China

****Correspondence:***
Leqian Ouyang
563331902@qq.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *16 March 2021*
Accepted: *09 April 2021*
Published: *11 May 2021*

Citation:
Ouyang L and You D (2021) The Green Innovation Effect on Heavy-Polluting Enterprises Under the Environmental Protection Law. Front. Energy Res. 9:681334. doi: 10.3389/fenrg.2021.681334

INTRODUCTION

Since its reform and opening up, rapid economic development has been experienced in China, but the task of conserving energy and reducing emissions has been unyielding. The *Environmental Protection Law* (EPL) *of the People's Republic of China* (Standing Committee of Twelfth National People's Congress of the People's Republic of China, 2015), January 1, 2015, was declared to establish and advocate coordination between economic development and environmental protection.

When compared to the former law, the number of articles in the EPL (SC-12th NPR, 2015) increased to 70, with larger environmental obligations and harsher punishments for polluting enterprises. These EPL articles delineated the environmental supervision responsibilities of local governments at all levels. Hence, it has become the most stringent environmental protection law in China. Heavy-polluting enterprises are the main targets of this restraint. The EPL (SC-12th NPR, 2015) clearly stipulates that pollutant-discharging enterprises and other operators shall take measures to prevent and control pollution and hazards such as waste gas, wastewater, waste residue, medical waste, dust, malodorous gas, and radioactive substances produced during production or other activities.

In the process of execution, the legal effect of the EPL (SC-12th NPR, 2015) can be realized through the regulation of two levels of government. It is determined by the fiscal decentralization system, which has an "economic decentralization and political centralization" characteristic. On one side, in the background of economic decentralization, the local governments have a certain decision-making power upon formulating local laws and regulations and implementing and supervising the behavior of enterprises; on the other side, in the background of political centralization, the central government evaluates the performance of the local officials, which has gradually added environmental indicators such as emissions cuts in recent years. In detail, the EPL (SC-12th NPR, 2015) clearly proposes that the State Council should set the national pollutant discharge standards and the local governments can set the relevant pollutant discharge standards at their discretion, but that they must be stricter than the national standards; pollutant discharging enterprises shall observe both the national total emission control system and regional key pollutant emission control system; if the polluters illegally discharge pollutants, they will be fined in accordance with the law. If they exceed the pollutant discharge standard or the total emission quota, the local government can order them to limit production, stop production for rectification, or suspend the business or close them down if the circumstances are serious; the central and local governments should take measures to promote the trial use of clean energy, encourage enterprises to choose processes and equipment that discharge less pollutants, and improve pollution-free treatment technologies; governments at all levels will increase financial input in environmental protection and implement the environmental protection target responsibility system for local governments; the central government shall supervise the implementation of local emission reduction and punish the competent environmental protection departments of governments that are unable to effectively enforce the law.

Due to the pressure of emission reduction, the application of scientific and technological innovation in the environmental protection industry is more extensive than before. Research on green innovation is strongly supported by the EPL (SC-12th NPR, 2015). It also mentioned that the adoption of policies and measures in finance, taxation, price, and government procurement, among others, would encourage and support the development of environmental protection industries such as technological equipment for environmental protection, comprehensive utilization of resources, and environmental services. Furthermore, in 2017, President Jinping's address to the 19th National Congress of the Communist Party of China, promoted both green innovation and green finance.

"We will create a market-based system for green innovation, develop green finance, and spur the development of energy-saving and environmental protection industries as well as clean production and clean energy industries (Xi, 2017)."

President Jinping also assured the Congress that the state shall support scientific and technological research, development, and application as a "holistic approach" to conserving our mountains, rivers, forests, farmlands, lakes, and grasslands; implement the strictest possible systems for environmental protection; and develop eco-friendly growth models and ways of life. The president Jinping also promised environmental protection, encouraged the development of environmental protection industries, promoted the development of information technology for environmental protection, and increased the scientific and technological level of environmental protection. Therefore, looking at regulating pollution through measures aimed at a green transformation, the EPL (SC-12th NPR, 2015) serves as an instrument for environmental regulation working through administrative orders that make following environmental policies mandatory. Simultaneously, it may motivate enterprises to pay more attention to the effect of green innovation in emission reduction.

Above all, the EPL (SC-12th NPR, 2015) is of highly theoretical and practical value in many aspects including defining green innovation requirements for enterprises, shaping fiscal decisions of local governments, and establishing and implementing environmental regulation policies. The major contributions of this paper are as follows. We discuss how the EPL (SC-12th NPR, 2015) influences the green innovation of enterprises under fiscal decentralization and focus to present on the heterogeneity of enterprises in green innovation from different areas based on the different problems and performance as well. The difference between this study and the existing literature focusing on the regulating effect or interaction effect is that this study conducted a quasi-experiment analysis based on fiscal decentralization and used EPL (SC-12th NPR, 2015) to examine the efficiency of environmental regulations.

THE PROGRESS OF ENVIRONMENTAL REMEDIATION: A LITERATURE REVIEW

Facing all kinds of environmental regulations, the traditional neoclassical theory reckoned that the investment of enterprises in R&D (research and development) might be reduced to the high cost of environmental protection. Indeed, R&D investment was reduced, causing less innovation and poorer performance (Testa et al., 2011; Hottenrott and Rexh, 2015). Combined with microeconomic theory, Ziesemer (2013) indicated that environmental regulation was not always effective because enterprise innovation involved hidden interests beyond profit but environmental regulation did not. However, Porter (1991) praised the impact of environmental regulation on enterprise innovation from a dynamic aspect. For example, Lanjouw and Mody (1996) found that the number of patents on environmental remediation technology in the 1970s and 1980s increased based on higher environmental regulation through empirical data in America, Japan, and Germany. Nameroff et al. (2004) deemed that environmental regulation made by the government exerted considerable influence on the green innovation of polluting enterprises, because the external cost of competing in enterprise innovation was cut, thanks to the support from the government toward green products and services. Some scholars considered that the relationship between environmental regulation and enterprise innovation might switch between win-win and mutual restraint, as it might be affected by market conditions; game rules or strategies between regulated enterprises and the government;

the environment or the life cycle of enterprise innovation; or the political system (Darnall et al., 2008).

Compared with ordinary technology innovation, the green innovation of enterprises based on the extension of innovation theory dates back to the 1990s. Amy Dietterich, the Director of the Global Challenge Division of the World Intellectual Property Organization (WIPO) defines green innovation as being dependent on technological innovation. In a WIPO Magazine article published on March 2020, she defined WIPO GREEN as an "online marketplace for sustainable technology," which connects green innovators/providers with those seeking a green solution to a specific problem. This connection is achieved primarily through the WIPO GREEN database, which has more than 3,000 technologies, including prototypes and solutions that are on the market. Dietterich reported, "All featured technologies are available for license, collaboration, joint ventures and/or sale." This service is also free for inventors/innovators if they simply list the benefits of their technology when they register online to join 1,500 internal users from 63 countries, including enterprises, universities, and research institutions (Dietterich, 2020). For Kemp and Pontoglio (2011), their concept of green innovation was called "eco-innovation," which covered every aspect of environmental remediation technologies, including pollution through improved abatement technology, creating green products and cleaner and more efficient ways of processing them, green energy technology, and waste management. Song and Wang (2016) pointed out that enterprise innovation in technology with environmental protection features could boost its development through enhancing environmental quality. Furthermore, research into the causality of the effect of environmental regulation on green innovation was said to be on the rise. For instance, Calel and Dechezlepretre (2016) worked on the green innovation of enterprises from the perspective of environmental regulation in the environmental rights trading scheme.

Regional economy and innovation systems could not proceed without support from the government. In recent years, fiscal decentralization has become a fresh concept leading to discussion and research on its relationship to economic development and environmental issues, but no conclusion was established due to a wide range of different indicators, variables, sample sizes, time dimensions, area coverage, econometric models, and calculation methods in the empirical research. For example, Bernauer and Koubi (2013) thought that there are different degrees of public good concerned by governments, which set different fiscal expenditure for environmental benefits. Specifically, a government prioritizing people and the environment would focus on improving public services and the environment, while a money-seeking regime would be more likely to add to environmental deterioration. Halkos and Paizanos (2013) conducted research on the direct and indirect effects of fiscal decentralization on the environment and proved its long- and short-term impacts on environmental pollution. Fan and Zhang (2009) believed that resource allocation and efficiency could be optimized by delegating local financial power. This was a great opportunity for local governments to provide public services and relevant incentive policies in light of their own economic and environmental features, thereby creating an economic model that was suitable for indigenous resource distribution, which paved the way for the green innovation of enterprisers in products and technology. In this manner, talents and investment would pour into regions. Conversely, Zhang et al. (2017) and Zhao (2008) assumed that fiscal decentralization suppressed economic benefits, leading to competition distortions in local areas. Notably, economic development was crucial in the evaluation of officials, which means that problems including a race to the bottom of environmental regulation, unfair division of regional markets, overlapping economic projects, and shortsighted regional construction goals were always possibilities. These conditions were extremely unfavorable to the technology innovation of enterprises and the growth of totally green factor productivity.

Based on the existing literature, it is clear that most studies on environmental regulation and the green innovation of enterprises were from the perspective of industry or region at this stage, with little research considering enterprises as the subject at a micro level (the level of enterprises). As for the indicators of green innovation, they were always adjusted by multi-factor models in prior research because of their ambiguity. Researchers tend to consider various factors influencing green innovation, but in fact, the measurement of indicators such as the performance or the efficiency of green innovation might result in distorted understanding in empirical analysis. Thus, based on the WIPO GREEN classification, the number of green innovations in enterprises is measured as a specific indicator in this research. Heterogeneity is also a main factor, but when discussing the influence of environmental regulations on green innovation, some studies have ignored it. Given the effects of environmental regulations on entrepreneurial green innovation, the role of local fiscal decentralization has not attained an overall consensual evaluation, and the quasi-experimental treatment of fiscal decentralization as a political system perspective is relatively rare.

EFFECT OF THE GOVERNMENT ON GREEN INNOVATION

The Importance of Government Regulation

In order to bring more public interests or legal private interests, the government would use macro regulation to directly intervene in the market mechanism or indirectly the decision-making of the enterprises. The Public Interest Theory postulates that if enterprises do not comply with some rules, the government should guide and regulate them in a way such that public interests are protected so as to guarantee the growth of social welfare. As a public good, environment has strong externalities and cannot gain benefits in the short run, it is not suitable for reasonable decisions made by enterprises or individuals. Lacking government regulation, the supply of public goods cannot be met by free markets, so it is a good theoretical reason for the government to make environmental regulations.

The Institutional Basis of Green Innovation Based on the Theory of Fiscal Decentralization

The theory of fiscal decentralization (or fiscal federalism) went through two generations in public economics. First-generation fiscal federalism (FGFF) emphasized that the government enjoyed advantages in offering public goods and services, and the government could also rectify some market failures by setting a policy. Second-generation fiscal federalism (SGFF) introduced mechanisms, incentive compatibility, and mechanism design. SGFF focused on the impact of institution and government officials' incentives on fiscal decentralization. Without certain restraints, local governments might prefer to pursue their own maximum interests rather than public welfare. Hence, a "market-preserving" decentralization result was produced. "Federalism with Chinese characteristics" was put forward by Chinese scholars, who deemed that the fiscal decentralization mode in China under the system of political centralization and economic decentralization was closer to meeting the conditions of market-preserving federalism in SGFF. The majority of established research in public economics discusses regional economic and technological development from the perspective of fiscal decentralization, but the green innovation of enterprises spotlights the regional heterogeneity of the environment; hence, the decision-making and financial power of a government should exert a more evident impact on boosting the green innovation of enterprises. Accordingly, there is a credible theoretical basis for determining the influence of different fiscal decentralization degrees in various regions on the green innovation of enterprises.

Hypothesis 1: Environmental Regulation Encourages Green Innovation

The Porter hypothesis argues that a properly designed environmental regulation policy can trigger green innovation in an enterprise that generates an innovation offset effect, and then reaches a "win-win" situation that allows enterprises to improve environmental and economic performance (Porter, 1991). Ronacchia and Lambertini (2021) divided the Porter hypothesis into a "strong" and a "weak" version. The weak version states that environmental regulation will effectively induce enterprise innovation, and the strong version states that environmental regulation will help enterprises step up economic performance. The latter could be a theoretical basis for this study on the influence of legal regulation on the green innovation of enterprises.

Therefore, based upon the government regulation theory, the theory of fiscal decentralization, and Porter hypothesis, the following hypothesis is suggested:

Hypothesis 1: Under fiscal decentralization, implementing the EPL (SC-12th NPR, 2015) has a significantly positive impact on the green innovation of enterprises.

Hypothesis 2: Heterogeneity on Green Innovation

The concept of a regional innovation system, a theoretical extension of the national innovation system, was introduced in the early 1990s. It originated from technological trajectories, which referred to continuity and localization of existing learning (knowledge) and innovation, as well as knowledge creation (educational) institutions. Cooke et al. (2000) proposed that a regional innovation system consists of a knowledge application and exploitation sub-system with enterprises in the relevant industry as major innovators, as well as a knowledge generation and diffusion sub-system with some public organizations promoting the diffusion of innovation. The region is a pivotal ground for economic regulation at a meso level; thus, regional innovation is generated from the cross effect of the networking of regional innovators, local clusters, and research institutions (Lundvall and Borras, 1997). Meanwhile, the values, attitudes, rules, customs, and expectations in a region taken together with the so-called regional culture intensify the interaction and innovation of enterprises in the region. This theory explains explicitly the regional clusters and growth of innovation in the domain of geographical economics.

Built on the theory of fiscal decentralization and regional innovation system, hypothesis 2 is proposed:

Hypothesis 2: Under fiscal decentralization, the implementation of the EPL (SC-12th NPR, 2015) shows great heterogeneity in its support of the green innovation of enterprises.

METHODOLOGY

Sample and Data Source

Based on examples of heavy-polluting A-share enterprises listed in the Shanghai and Shenzhen Stock Markets in 2012-2018 as samples, the authors deleted firms which were simultaneously listed in the AH/AB share, firms with ST or *ST designations, and newly listed firms when doing this research. According to the *List of Classified Management of Environmental Protection Verification of Listed Companies* (EIA Letter [2008] 373) issued by the Ministry of Environmental Protection in 2008, thermal power and 15 other industries were designated as heavy-polluting industries. After data screening, a list of 220 effective samples of indigenous innovation was finally set, with an effective data value of 5,280. Based on the Guidelines on Industry Classification of Listed Companies (Li and Zeng, 2020), the selections were classified as follows: B06 as the coal mining and processing industry; B07 as the oil and gas exploitation and production industry; B08 as the ferrous metal mining and dressing industry; B09 as the nonferrous metal mining and separating industry; C17 as the textile industry; C19 as the leather, fur, feather and their products, and footwear industry; C22 as the paper and paper products industry; C25 as the oil processing, coking, and nuclear fuel processing industry; C26 as the chemical industry; C27 as the pharmaceutical industry; C28 as the chemical fiber industry; C29 as the rubber and plastic products industry; C30 as the non-metallic mineral products industry; C31 as the non-metallic mineral products industry; C32 as the nonferrous metal smelting and rolling processing industry; C33 the metal products industry, and D44 the production and supply of electricity and heat industry.

In the 2012 Revised Guidelines on Industry Classification of Listed Companies China Securities Regulatory Commission [China Securities Regulatory Commission (CSRC), 2012], the categories of the selected industries were regarded as the treatment group in this article. Considering the homogeneity of the industry, other listed companies in the same category were counted as the control group, adopting the simple matching principle. Under the environmental regulations, heavy-polluting enterprises have a crucial part to play in mitigating environmental pollution in a direct or indirect way. Thus, it is of highly theoretical and practical significance to study the green innovation of enterprises. Financial, operational, and R&D data of the samples can be accessed from CNINFO, an official website for information disclosure of Chinese listed companies (cninfo.com.cn, 2020), including the annals of sample enterprises and patent data from enterprise annals and Patsnap. The data on green innovation (or green patent) could be collected and measured through matching IPC codes in the WIPO GREEN list and the IPC codes of every specific enterprise. All data were searched, screened, and collated manually.

Research Method

Green innovation and other forms of innovation are always affected by many factors like region, industry, market environment, and the political public environment, so a comparison analysis was made between the treatment and control groups based on changes in enterprise performance and innovation before and after enrolling in the EPL (SC-12th NPR, 2015). Besides, the authors were also looking for evidence of a significant impact of enterprise performance and innovation on fiscal decentralization. Difference-in-difference (DID) and Difference-in-difference (DDD) analyses were used under hypothetical circumstances in this study. If assumptions about parallel trends in DID failing, DDD, a method usually applied to research policy implementation; DDD is required to find another group of variables. Variables other than policy implementation were used to analyze the difference in an effort to reduce the errors in our results. The provinces in which the sample firms resided were considered as the second treatment and control groups according to their degree of fiscal decentralization. This was done to exclude the effect of industrial and fiscal decentralization on enterprise innovation and green innovation so as to obtain a more accurate analysis of the policy effect of the EPL (SC-12th NPR, 2015).

The general econometric model of DDD is given as follows:

$$Y_{ijt} = \alpha + \beta_1 treat_j + \beta_2 period_i + \beta_3 fd_t + \beta_4 treat_j period_i + \beta_5 treat_j fd_t + \beta_6 period_i fd_t + \beta_7 treat_j period_i fd_t + \varepsilon,$$

where treat_j is the treatment and control groups that decide whether to enact the policy; $period_i$ is the year before and after implementing the policy; fd_t is the second factor group which affects the explained variable apart from the policy itself; ε is the random disturbance term; $treat_j period_i fd_t$ is the net effect of the policy and also the most important influence coefficient in DDD.

Specifically, in this paper, the values of the treatment group are marked to be 1 and those of the control group are marked to be 0; periods after the implementation of the policy are marked to be 1, and periods before the implementation of the policy are marked to be 0; enterprises with a high degree of fiscal decentralization are marked to be 1 and others are marked to be 0.

Variable Description

Explained variables: the green innovation of enterprise (*GI*). According to established research, the green innovation of enterprises could be indicated as the number of green patents (Ley et al., 2016; Van der Waal et al., 2021). Based on the WIPO GREEN list, firstly, the authors collected the IPC codes that were regarded as "green patent." Secondly, the authors matched the IPC codes to ensure the number of green patents that specific enterprises possessed. Lastly, the number of green patents/innovation was acquired manually.

Explaining variables: the implementation period of the EPL (SC-12th NPR, 2015) (*period*); whether an enterprise is heavy polluting or not (*treat*); whether or not an enterprise has a high fiscal decentralization (*fd*). Specifically, before 2015, the value of the variable *period* is defined as 0, and after 2015, the value of the variable *period* is defined as 1; if the enterprise belongs to the category of heavy-polluting enterprises, then $treat = 1$, and if not, $treat = 0$; if the enterprise is located in a province with a high degree of fiscal decentralization, then $fd = 1$, if not, $fd = 0$. The calculation of the degree of fiscal decentralization is learned from the method of financial expenditure indicators proposed by Wu et al. (2020), i.e., the mean value of the ratio of the total provincial financial expenditures after deducting transfer payments to the central government as a budget expenditure and the ratio of the provincial financial expenditures excluding the transfer payments to the central government budget expenditure. The mean value of the fiscal decentralization indicators was adopted instead of the multiple-year panel data indicator as a way to avoid endogenous problems in the model caused by the regional fiscal decentralization indicators that change with the period. At the same time, all control variables were processed logarithmically in order to reduce heteroscedasticity.

Control variables: Relevant variables established from past works are selected: characteristic variables include R&D, the scale of the enterprise, capital intensity, agency cost, asset-liability ratio, and ownership concentration, as well as industry and annual variables. The description and calculation are shown in **Table 1**.

Model Settings

Based on the general model mentioned above and the model hypothesis in this study, the following model was built:

$$GI_{ijt} = \beta_0 + \beta_1 treat_j + \beta_2 period_i + \beta_3 fd_t + \beta_4 treat_j * period_i + \beta_5 treat_j * fd_t + \beta_6 period_i * fd_t + \beta_7 treat_j * period_i * fd_t + Z + \varepsilon,$$

where GI_{ijt} are the explained variables, and Z is an umbrella term for all the control variables. The variation coefficient of green innovation is $\beta_4 + \beta_7$, among which the variation coefficient of the parallel trend assumption is β_4. The variation coefficient of the net effect of DDD, which considers the degree of fiscal decentralization of the location of different enterprises, is β_7. β_7 is also the most important interaction term in this study, as it represents the influence effect of the EPL (SC-12th NPR, 2015) on the green innovation of enterprises after excluding the impact of industrial and fiscal decentralization.

RESULTS AND DISCUSSION

Descriptive Analysis

In light of the above model settings, a descriptive analysis is shown in **Table 2**. The mean value of *GI* is 8.1766; the value of median is 3.4012; and the range is 273. These values suggest that enterprise innovation generated in the heavy-polluting industry is unstable, and the awareness and the ability of green innovation among enterprises tend to differ greatly. The mean value of the *period* is 0.5714, which manifests that the sample size before and after enacting the EPL (SC-12th NPR, 2015) is close, that is, samples in and after 2015 account for 57.14% of the total. This is enough to compare the data before and after carrying out the EPL (SC-12th NPR, 2015). The mean value of *treat* is 0.4955, meaning the sample size of the treatment group and the control group is balanced. The mean value of *fd* is 0.8364, indicating that samples with high fiscal decentralization degrees occupy a large part. It manifests that most enterprises prioritizing green innovation are located in regions with high degrees of fiscal decentralization. Basic statistics of other control variables are varied within a reasonable range. A negative value is a result of creating a logarithm in order to eliminate heteroscedasticity.

TABLE 1 | Variable description and measurement.

Variable name	Symbol	Calculation method of indicators
Green innovation	GI	Numbers of green patents calculated by WIPO GREEN
The implementation of The Law	Period	In and after 2015, period = 0; before 2015, period = 1.
Heavy-polluting enterprise	Treated	Heavy-polluting enterprise, treated = 1; not, treated = 0.
The degree of fiscal decentralization	fd	Located in a province with high fiscal decentralization degree, then fd = 1, if not, fd = 0.
Production scale	Z_1	Total assets
Asset-liability ratio	Z_2	Total liability/ending total assets
Performance	Z_3	Net profit/total assets
Capital intensity	Z_4	Fixed asset/ending total assets
Agency cost	Z_5	Overhead expenses/revenues
Ownership concentration	Z_6	Share proportion of the largest shareholder
Industry	Industry	Virtual variables
Year	Year	Virtual variables

Correlation Analysis and Analysis of Parallel Trends

The correlation between the variables is reported in **Table 3**. The explained variables show certain correlations to all independent variables and control variables, and the degree of correlation between the independent variables and the control variables is 0.5 below, indicating a small possibility of multicollinearity. A panel regression analysis of DDD is necessary for identifying the specific functional relationship between the variables.

As for the parallel trend assumption, when it is admissible, the coherence of DID or DDD estimations can be assured. In detail, the relatively consistent period trends of treatment and control groups before implementing a show of policy that changes with time is not related to the changes in explained variables. On the contrary, the trends differ after policy enactment, fully manifesting the influence of the policy implementation quasi-experiment on the observed values of samples. Grounded in the DDD model set by this study, the parallel trends occur before enacting the EPL (SC-12th NPR, 2015), and inconsistencies clearly appear after the enactment of the EPL, which is significant under the variable values of heavy-polluting enterprises (the treatment group). As revealed by **Figures 1**, **2**, the dividing point is the year 2015; the developing trends on the green innovation of enterprise between the treatment group and the control group tend to be parallel before 2015. Besides, there are significant differences in trends after 2015, with whatever degrees of fiscal decentralization. Thus, the green innovation of enterprises is

TABLE 2 | Descriptive analysis of major variables.

Variable	Mean value	Std error	Median	Max	Min
GI	8.1766	22.2640	1	273	0
Treat	0.4955	0.5001	0	1	0
Period	0.5714	0.4950	1	1	0
fd	0.8364	0.3701	1	1	0
Z_1	9.3993	1.2875	9.2447	14.2827	2.9957
Z_2	−0.8493	0.6682	−0.6878	1.4929	−6.1658
Z_3	−3.5084	1.2395	−3.3228	0.1309	−9.2103
Z_4	−3.3439	1.2695	−3.1536	0.1956	−9.2103
Z_5	−1.6328	0.9216	−1.4690	0.4900	−5.6840
Z_6	3.5308	0.5014	3.6160	4.4896	−1.2379

TABLE 3 | Correlation analysis of major variables.

	GI	Treat	Period	fd	z1	z2	z3	z4	z5	z6
GI	1									
Treat	−0.0814	1								
Period	0.0788	0	1							
Fd	−0.0029	−0.0286	0	1						
z1	0.1700	0.0888	0.141	−0.0273	1					
z2	0.0475	0.0999	−0.0456	−0.0976	0.224	1				
z3	−0.0342	0.0282	−0.0298	0.0953	−0.054	−0.280	1			
z4	−0.0426	−0.0209	−0.0609	0.0911	−0.022	−0.227	0.894	1		
z5	−0.0404	0.402	−0.0446	−0.0299	0.0694	0.0517	−0.0880	−0.171	1	
z6	0.0250	0.0931	−0.0249	−0.0241	0.187	0.0433	0.0121	0.0187	0.0208	1

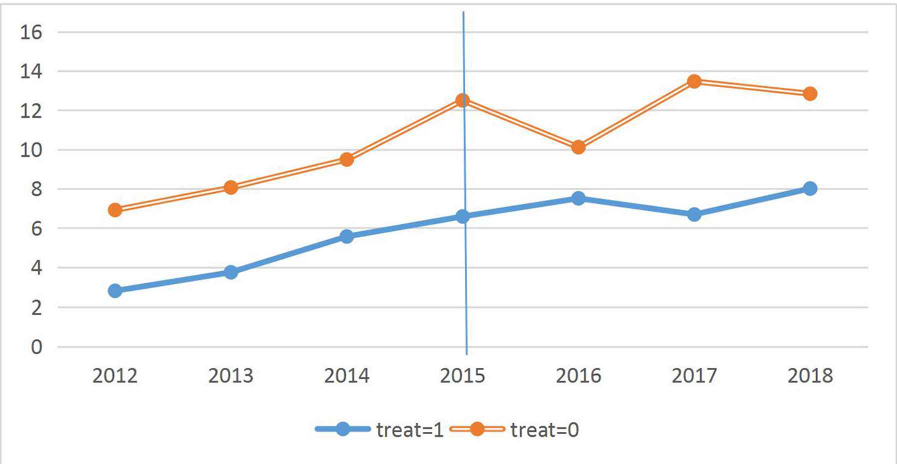


FIGURE 1 | Parallel trends of green innovation of enterprises (regions with high degrees of fiscal decentralization).

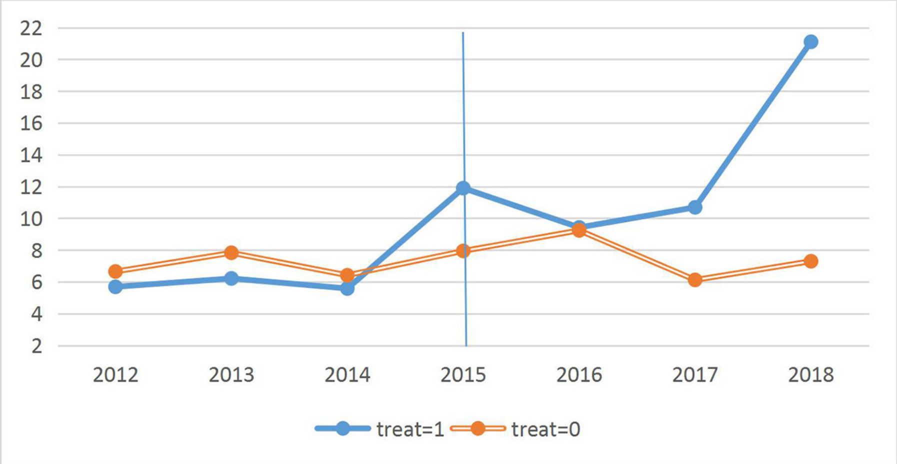


FIGURE 2 | Parallel trends of green innovation of enterprises (regions with low degrees of fiscal decentralization).

TABLE 4 | Hausman test.

GI	
chi2(10) =	$(b - B)'[(V\_b - V\_B)^{(-1)}](b - B)$
=	8.06
Prob>chi2 =	0.0274

V_b − V_B is not positive definite.

verified with parallel trend assumption, and especially, a DDD regression analysis can be done.

DDD Regression Analysis

Before carrying out the DDD regression analysis, selecting a model is the priority. The fixed effects model can be identified after the Hausman test, in which the *p*-value of the three models is smaller than 0.05 (see **Table 4**). **Table 5** reports the DDD regression results of the individual fixed effects model (Model 1) and the individual and time fixed effects model (Model 2) after adding control variables. It can be seen that the value of p, the interaction term of *treat* × *period*, is smaller than 0.01 in model 1 and smaller than 0.1 in model 2, which implies a refusal to the hypothesis. It represents that the parallel trends assumption under DID is invalid, i.e., further DDD regression is a necessity. The value of DDD is examined the hypothesis at 10% level under both models with the regression coefficient of −5.392 and −5.247, specifically. The results cannot support assumption one, because the impact of environmental regulation on green innovation is pessimistic. Consequently, the Potter hypothesis fails to be verified. Control variables exercise similar influence on two models, among which the production scale of the enterprise (*z1*) and the capital intensity (*z4*) affect the green innovation of enterprises significantly. A larger production scale or lower capital intensity will substantially increase the green innovation of an enterprise. All control variable results are stable under the individual fixed effects model and double fixed effects model.

Dynamic Effect Analysis

Based on the DDD analysis at the national level, a series of dynamic analyses delineating the effect of rolling out the EPL were conducted. In the further analysis, four new variables were added, DDD-treated*period*fd2015, treated*period*fd2016, treated*period*fd2017 and treated*period*fd2018, respectively; in order to investigate the specific dynamic effects in the four years after enacting EPL to accelerate the green innovation of enterprises. Specifically, taking the variable, *treated*period*2015, as an example, the virtual variable, 2015, is defined as 1, and the other years as 0. In **Table 6**, results from the individual fixed effects model are stated, including those of every year after the enactment of the EPL. The results show that the impacts of the control variables are similar to those in the DDD model at the national level (**Table 5**). Nevertheless, the impact of the enactment of the EPL on the green innovation of enterprises is significant in 2018, unlike in the years 2015–2017. This result may indicate that after enacting the EPL, the green innovation of enterprises has a significant impact but with a time-lag effect.

TABLE 5 | DDD regression results at the national level.

Variables	Model 1	Model 2
	GI	
Treat*Period	6.883***	5.103*
	(2.659)	(2.853)
DDD	−5.392*	−5.247*
	(2.853)	(2.858)
z1	4.029***	2.697*
	(1.329)	(1.589)
z2	0.943	1.180
	(1.612)	(1.618)
z3	1.240	1.067
	(1.320)	(1.396)
z4	−3.294**	−3.082**
	(1.298)	(1.389)
z5	0.0651	0.239
	(1.473)	(1.482)
z6	0.319	0.712
	(2.320)	(2.338)
Constants	−37.21**	−26.01
	(14.55)	(16.07)

Standard errors in parentheses.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

TABLE 6 | Dynamic effect of green innovation of enterprises in 2015.

Variables	2015	2016	2017	2018
Treat*Period	3.089	−3.348	0.0753	12.22***
	(4.786)	(3.527)	(3.641)	(3.351)
DDD	−3.516	4.922	0.522	−11.65***
	(5.072)	(3.856)	(3.933)	(3.675)
z1	5.109***	5.065***	5.014***	4.545***
	(1.238)	(1.240)	(1.261)	(1.274)
z2	0.488	0.413	0.482	0.720
	(1.607)	(1.606)	(1.606)	(1.605)
z3	1.447	1.429	1.434	1.310
	(1.321)	(1.320)	(1.321)	(1.315)
z4	−3.388***	−3.374***	−3.385***	−3.374***
	(1.303)	(1.301)	(1.302)	(1.294)
z5	0.721	0.754	0.704	0.428
	(1.462)	(1.464)	(1.464)	(1.455)
z6	0.511	0.620	0.493	0.369
	(2.327)	(2.327)	(2.327)	(2.314)
Constants	−46.31***	−46.37***	−45.47***	−41.41***
	(13.97)	(13.97)	(14.11)	(14.20)

Standard errors in parentheses.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

According to the results, authors presume that strict environmental regulation or punishment will enhance the

TABLE 7 | Placebo tests that adjust the implementation time of the EPL to 2013 and 2016.

Variables	Model 1	Model 2	Model 1	Model 2
	2013		2016	
Treat*Period	−1.094	−2.233	5.783**	5.141*
	(3.681)	(3.967)	(2.621)	(2.808)
DDD	1.702	1.914	−4.103	−3.795
	(4.013)	(4.012)	(2.817)	(2.819)
z1	5.025***	2.616	3.997***	2.711*
	(1.284)	(1.592)	(1.336)	(1.589)
z2	0.470	1.027	0.835	1.222
	(1.611)	(1.619)	(1.609)	(1.618)
z3	1.372	0.961	1.291	1.097
	(1.338)	(1.407)	(1.319)	(1.396)
z4	−3.310**	−2.942**	−3.377***	−3.169**
	(1.320)	(1.399)	(1.298)	(1.392)
z5	0.684	0.652	0.178	0.162
	(1.478)	(1.477)	(1.472)	(1.481)
z6	0.491	0.917	0.419	0.588
	(2.327)	(2.334)	(2.321)	(2.335)
Constants	−45.67***	−25.43	−37.14**	−25.94
	(14.18)	(16.10)	(14.56)	(16.07)

Standard errors in parentheses.
****p < 0.01, **p < 0.05, *p < 0.1.*

TABLE 8 | Robustness test adjusting the industry.

Variables	Model 1	Model 2
	GI	
Treat*Period	−1.751	−3.019
	(3.486)	(3.582)
DDD	7.191	7.219
	(3.889)	(3.891)
z1	2.961**	1.960
	(1.501)	(1.811)
z2	1.061	1.461
	(1.917)	(1.934)
z3	0.595	0.245
	(1.355)	(1.416)
z4	−1.958	−1.520
	(1.337)	(1.414)
z5	−0.842	−0.861
	(1.811)	(1.817)
z6	1.204	1.577
	(3.512)	(3.540)
Constants	−29.30	−22.09
	(19.92)	(21.26)

Standard errors in parentheses.
****p < 0.01, **p < 0.05, *p < 0.1.*

enterprises' costs of environment, which may occupy the enterprises' costs of green innovation, so enterprises are likely to diminish green R&D inputs. Meanwhile, the compensatory effect from green innovation is not evident, so the Potter hypothesis cannot be verified at the national level.

Robustness Test

Placebo Test

The above analysis shows that under fiscal decentralization, the enactment of the EPL (SC-12th NPR, 2015) markedly promotes the green innovation of enterprises, but such promotion could also be a result of other factors. Therefore, the time of the policy implementation was tuned, based on the practice of Topalova (2010), and it was assumed that EPL was enacted in 2013 and 2016 in order to test the possibility of empirical results. *Period,* the virtual variable, was adjusted to 1 (based on a definition of conditions in and after 2013 as well as in and after 2016), and to be 0 in other years. Detailed information is reported in **Table 7**. Results reveal that the parallel trend assumption could not reject the null hypothesis, and the regression coefficients of the DDD are not significant in the individual fixed effects model and double fixed effects model (Model 1 and Model 2, respectively), so there were no other factors affecting the green innovation of enterprises. The conclusion of this study is robust.

The Adjustment of Samples

Although 220 heavy-polluting enterprises (109 of them were samples in the treatment group) were selected as samples, problems like an insufficient number of samples and deviations in the observed values may occur; therefore, the following method was used to test the efficiency of samples. The authors first randomly chose 109 enterprises and defined them as heavy-polluting enterprises, i.e., treated = 1 and others = 0. In this way, industrial heterogeneity could be tested. The details of the above test are in **Table 8**. The results show that no matter what is found in the individual fixed effects model or the individual and time fixed effects model, the regression coefficient of DDD is not significant after the industry definition is randomly changed, and the null hypothesis is not refused. Thus, the samples have passed the robustness test.

Regional Heterogeneity Analysis

Owing to the unbalanced Chinese regional economic development, factors affecting the green innovation of enterprises are going to be different. These factors include resource endowment, economic development, scale and intensity of R&D, environmental protection awareness, and degrees of policy enforcement. Therefore, the EPL regulations and the way they have been handled in different regions are worth discussing. Enterprise locations are classified into eastern, central, and western areas according to their registration address (in light of the regional divisions set up in the China Statistical Yearbook); the results are shown in **Table 9**. This information indicates that the green innovation of enterprises in all regions shows certain positive effects because of the EPL (SC-12th NPR, 2015). The regression coefficient of the green innovation of enterprises in the eastern area group is positive, but the influence is not significant. Unlike the DDD results at the national level, it is revealed that environmental regulation had a positive effect on the green innovation of enterprises. Unlike the results

TABLE 9 | DDD regression results at the regional level.

Variables	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
	Eastern area		Central area		Western area	
Treat*Period	−2.684*	−4.410	13.36*	10.22*	5.470**	8.055**
	(5.078)	(5.149)	(6.912)	(7.758)	(2.690)	(3.193)
DDD	5.487	4.997	−16.14**	−15.54**	−2.976	−3.898
	(5.174)	(5.174)	(7.510)	(7.507)	(3.958)	(4.021)
z1	2.109	0.0425	9.197	5.850	3.458*	5.181**
	(1.480)	(1.842)	(5.676)	(6.837)	(1.821)	(2.188)
z2	0.360	1.210	7.750	6.282	−0.800	−0.479
	(1.758)	(1.802)	(6.359)	(6.547)	(2.560)	(2.587)
z3	0.703	0.402	10.34	10.43	−0.523	0.714
	(1.267)	(1.321)	(6.721)	(7.573)	(2.565)	(2.893)
z4	−2.811**	−2.330*	−12.52*	−13.14*	0.394	−0.993
	(1.290)	(1.356)	(6.441)	(7.340)	(2.386)	(2.755)
z5	1.254	1.527	−5.408	−5.473	−2.039	−2.723
	(1.533)	(1.546)	(5.794)	(5.932)	(2.708)	(2.755)
z6	−0.391	−0.0772	0.508	3.015	−3.700	−4.645
	(2.295)	(2.302)	(11.25)	(11.34)	(4.227)	(4.309)
Constants	−16.04	2.384	−84.48	−63.60	−17.55	−30.57
	(16.69)	(19.30)	(54.26)	(59.73)	(21.79)	(23.83)

Standard errors in parentheses.
****$p < 0.01$, **$p < 0.05$, *$p < 0.1$.*

in the eastern area, the impacts of environmental regulation are negative in the other two areas, especially in the central area. The results found in the central and western areas are in accordance with the DDD results at the national level. Weak economic and R&D ability alongside extensive business models may be the source of the subtle damaging effect in the central and western enterprises. Some heavy-polluting enterprises have transferred to the central and western regions due to slacker policy enforcements despite environmental regulations. The environmental protection awareness of enterprises and the financial power of the government are not enough to make a difference in areas that are not under thorough public scrutiny.

In conclusion, the Potter hypothesis cannot be verified at the regional level, but the regional heterogeneity is significant. Thus, assumption 1 is not verified, and assumption 2 is true.

The Analysis of Enterprise Performance Heterogeneity

A huge amount of R&D is necessary for the green innovation of enterprises, but R&D capital, personnel, and stock will increase the cost and operational risk of enterprises. Therefore, heavy-polluting enterprises with different performances may differ after implementing the EPL (SC-12th NPR, 2015). To verify the hypothesis, samples with higher performances than the median are regarded as high-performance groups (HROAs), and those in the lower than median groups are designated as low-performance groups (LROAs). They are put into the DDD model. Clearly, **Table 10** shows that the impacts of the enactment of the EPL on the green innovation of the enterprises are stronger in the low-performance groups than in the high-performance groups. The reason for this difference may include higher awareness of environmental protection and green innovation, advanced R&D technology, and stronger ability to cover increasing environmental costs in high-performance groups, so their green innovation projects and performances will be able to keep up, instead of incurring some kinds of voluntary production transformations or even terminations driven by environmental regulation. And of course, enterprises with low performance tend to be the other way round. Their operational cost and risk are on the up for indigenous innovation with lower competitiveness, so it would be harder for them to keep up with green innovation. Hence, the heterogeneity of enterprise performance is evident.

CONCLUSIONS AND DISCUSSION

Combined with the differences of regional fiscal decentralization with the enactment of the *EPL* as a starting point, DDD empirical research was conducted and validated on the green innovation of enterprises. The empirical results show that the EPL, as a kind of environmental regulation, makes a negative effect on the green innovation of enterprises at the national level. Specifically, the impact on green innovation is positive in the eastern areas, but it does not seem to be significant. On the other hand, the impacts in the central and western areas are negative, similar to those at the national level. Thus, the Potter hypothesis (assumption 1) cannot be verified. Furthermore, through comparisons of regions and levels of performance, the regional heterogeneity and the enterprise-performance heterogeneity are made evident. The results of heterogeneity analysis reveal that the significant effect

TABLE 10 | DDD regression results of enterprise performance.

Variables	Model 1	Model 2	Model 1	Model 2
	HROA		LROA	
Treat*Period	3.864	1.520	8.052**	8.970**
	(4.263)	(4.395)	(3.472)	(3.919)
DDD	−1.574	−1.739	−7.807**	−7.984**
	(4.420)	(4.414)	(3.907)	(3.918)
z1	3.499**	−0.105	4.903**	5.961**
	(1.722)	(2.185)	(2.183)	(2.479)
z2	−0.967	−0.267	3.567	3.674
	(2.310)	(2.325)	(2.288)	(2.308)
z3	0.594	0.252	4.170	6.259*
	(1.482)	(1.530)	(3.041)	(3.644)
z4	−2.298	−1.821	−6.238**	−8.414**
	(1.513)	(1.570)	(2.931)	(3.593)
z5	−1.433	−1.395	2.758	3.152
	(1.892)	(1.906)	(2.413)	(2.431)
z6	0.643	1.044	−0.308	−1.047
	(3.286)	(3.285)	(3.384)	(3.451)
Constants	−36.29*	−4.655	−37.34	−41.83*
	(19.08)	(22.33)	(23.85)	(25.30)

Standard errors in parentheses.
$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

of the EPL has shown the green innovation to be significantly prevalent in the eastern area and low-performance groups.

Based upon the above conclusions, the following suggestions are what the authors put forward:

(1) Under a political-institutional background, fiscal decentralization delegates power to local governments to develop local green innovation. Meanwhile, the central government shall make strategic goals and motivate the green innovation of enterprises through the evaluation systems of the local officials. This could facilitate and deepen corresponding supports from local governments.
(2) Local governments shall make good use of financial power under fiscal decentralization to supply policy supports toward the green innovation of enterprises; for example, highlighting the R&D of infrastructure in an effort to attract R&D talents from home and abroad, providing larger R&D input and more platforms for exchange, implementing preferential tax policy for green innovation, and improving the market value of green innovation may be beneficial.
(3) Based on the regional heterogeneity, local governments shall implement and adjust the EPL (SC-12th NPR, 2015) properly according to local conditions. Especially, the positive impact on the green innovation of enterprises in the eastern area is worth analyzing and learning. To transform the impacts on green innovation from negative to positive, enterprises in the central and western areas shall find out or reinforce their own priorities on green innovation and competitiveness.
(4) The green R&D awareness of enterprises shall be raised so that they can reform and adjust the environmental innovation system actively until their business models become an example of best practices for establishing clean production and sustainability.

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/s.

AUTHOR CONTRIBUTIONS

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

FUNDING

This work was supported by the National Natural Science Foundation of China, The Dynamic Mechanism and Policy Optimization of Green Technology Innovation Diffusion Based on the Theoretical and Empirical Analysis from the Perspective of Co-opetition (Grant No. 71974209), from January 2020 to December 2023.

ACKNOWLEDGMENTS

The authors thank AiMi Academic Services (www.aimieditor.com) for English language editing and review services.

REFERENCES

Bernauer, T., and Koubi, V. (2013). Are bigger governments better providers of public goods? Evidence from air pollution. *Public Choice* 156, 593–609. doi: 10.1007/s11127-012-9916-1

Calel, R., and Dechezlepretre, A. (2016). Environmental policy and directed technological change: evidence from the European Carbon Market. *Rev. Econ. Stat.* 98, 173–191. doi: 10.1162/REST_a_00470

China Securities Regulatory Commission (CSRC) (2012). Guidelines for the Industry Classification of Listed Companies (2012 Revision). Available online at: http://www.csrc.gov.cn/pub/csrc_en/newsfacts/release/200708/t20070816_69104.html

cninfo.com.cn (2020). July 2020 Overview, an online information source on Chinese companies. Available online at: https://www.similarweb.com/website/cninfo.com.cn/

Cooke, P., Boekholt, P., and Todtling, F. (2000). *The Governance of Innovation in Europe[M]. Regional Perspectives on Global Competitiveness.* London: Pinter.

Darnall, N., Henriques, I., and Sadorsky, P. (2008). Do environmental management systems improve business performance in an international setting? *J. Int. Manage.* 14, 364–376. doi: 10.1016/j.intman.2007.09.006

Dietterich, A. (2020). WIPO GREEN: Supporting green innovation and technology transfer. WIPO MAGAZINE, March 2020, a quarterly online and print publication. Available online at: https://www.wipo.int/wipo_magazine/en/2020/01/article_0003.html

Fan, Z. Y., and Zhang, J. (2009). Between China's fiscal decentralization and the efficiency of China's Economic Growth. *Management World* 7, 15–25. doi: 10.19744/j.cnki.11-1235/f.2009.07.003

Halkos, G. E., and Paizanos, E. A. (2013). The effect of government expenditure on the environment: an empirical investigation. *Ecol. Econ.* 91, 48–56. doi: 10.1016/j.ecolecon.2013.04.002

Hottenrott, H., and Rexh, S. (2015). Policy-induced environmental technology and inventive efforts: is there a crowding out? *Industry Innovation* 22, 375–401. doi: 10.1080/13662716.2015.1064255

Kemp, R., and Pontoglio, S. (2011). The innovation effects of environmental policy instruments: a typical case of the blind men and the elephant. *Ecol. Econ*. 72, 28–36. doi: 10.1016/j.ecolecon.2011.09.014

Lanjouw, J. O., and Mody, A. (1996). Innovation and the international diffusion of environmentally responsive technology. *Res. Policy* 25, 549–571. doi: 10.1016/0048-7333(95)00853-5

Ley, M., Stucki, T., and Woerter, M. (2016). The impact of energy prices on green innovation. *Energy J.* 37, 41–75. doi: 10.5547/01956574.37.1.mley

Li, D., and Zeng, T. (2020). Are China's intensive pollution industries greening? An analysis based on green innovation efficiency. *J. Clean. Prod*. 259:120901. doi: 10.1016/j.jclepro.2020.120901

Lundvall, B. A., and Borras, S. (1997). The Globalising Learning Economy: Implications for Innovation Policy Report based on contributions from seven projects under the TSER programme DG XII, Commision of the European Union. Available online at: http://www.globelicsacademy.org/2011_pdf/Lundvall%20Borras%201997.pdf

Nameroff, T. J., Garant, R. J., and Albert, M. B. (2004). Adoption of green chemistry: An analysis based on US Patents. *Res. Policy* 33, 959–974. doi: 10.1016/j.respol.2004.03.001

Porter, M. (1991). America's green strategy[M]. *Sci. Am*. 264:168. doi: 10.1038/scientificamerican0491-168

Ronacchia, C., and Lambertini, L. (2021). Porter hypothesis vs pollution haven hypothesis: can there be environmental policies getting two eggs in one basket? *Environ. Res.* 78, 177–199. doi: 10.1007/s10640-020-00533-x

Song, M., and Wang, S. (2016). Can employment structure promote environment-biased technical progress? *Technol. Forecasting Soc. Change* 112, 285–292. doi: 10.1016/j.techfore.2016.02.016

Standing Committee of Twelfth National People's Congress of the People's Republic of China (2015). *Environmental Protection Law of People's Republic of China*. Standing Committee of Twelfth National People's Congress of the People's Republic of China.

Testa, F., Iraldo, F., and Frey, M. (2011). The effect of environmental regulation on firm's competitive performance: The case of the building & construction sector in some EU regions. *J. Environ. Manage*. 92, 2136–2144. doi: 10.1016/j.jenvman.2011.03.039

Topalova, P. (2010). Factor immobility and regional impact of trade liberalization: evidence on poverty from India. *Am. Econ. J.* 2, 1–41. doi: 10.1257/app.2.4.1

Van der Waal, J. W. H., Thijssens, T., and Maas, K. (2021). The innovative contribution of multinational enterprises to the sustainable goals. *J. Clean. Prod.* 285:125319. doi: 10.1016/j.jclepro.2020.125319

Wu, H., Li, Y., Hao, Y., Ren, S., and Zhang, P. (2020). Environmental decentralization, local government competition, and regional green development: evidence from China. *Sci. Total Environ.* 708:135085. doi: 10.1016/j.scitotenv.2019.135085

Xi, J. (2017). Full text of Xi Jinping's report at 19th CPC National Congress, ChinaDaily.com delivered by President Jinping. Available online at: https://www.chinadaily.com.cn/china/19thcpcnationalcongress/2017-11/04/content_3 4115212.htm (accessed October 18, 2017).

Zhang, K., Zhang, Z. Y., and Liang, Q. M. (2017). An empirical analysis of the green paradox in China: from the perspective of fiscal decentralization. *Energy Policy* 103, 203–211. doi: 10.1016/j.enpol.2017.01.023

Zhao, W. (2008). A study on the relationship between fiscal decentralization, frontier technical development and technical development and technical efficiency. *Management World* 33–44,187. doi: 10.19744/j.cnki.11-1235/f.2008.07.005

Ziesemer, T. (2013). A knowledge-based view of the porter hypothesis. *Environ. Policy Govern.* 23, 193–208. doi: 10.1002/eet.1609

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.

frontiers
in Energy Research

ORIGINAL RESEARCH
published: 13 May 2021
doi: 10.3389/fenrg.2021.685021

Assessing Embodied Carbon Emission and Its Intensities in the ICT Industry: The Global Case

Xiucheng Dong[1,2], *Qingzhe Jiang*[1,2] *and Jianda Wang*[1,2]*

[1] School of International Trade and Economics, University of International Business and Economics, Beijing, China, [2] UIBE Belt & Road Energy Trade and Development Center, University of International Business and Economics, Beijing, China

With the intensification of globalization, the information and communication technologies (ICT) sector, as one of the emerging industrial sectors, has played an important role in reducing carbon emissions in regional trade and improving the energy efficiency of traded products. This article uses a multi-regional input-output (MRIO) model to explore the flow of embodied carbon emissions and embodied carbon emission intensities in the ICT sector triggered by trade in 15 major economies around the world from 2000 to 2014. The article further discusses the emission-reduction strategies of each ICT sector. The results show that: (1) The overall embodied carbon emissions of ICT have demonstrated a significant downward trend, but the proportion of embodied carbon emissions caused by trade is increasing; (2) The embodied carbon emissions in the ICT sector of most developed countries in 2014 are significantly lower than in 2000, but in developing countries such as China and India they show an upward trend during this period; (3) The ICT sector's export embodied carbon emission intensity in Indonesia is much higher than that of other countries, and the embodied carbon emissions of ICT exported by Mexico have increased significantly; (4) The manufacture of computer, electronic and optical products (S1) is the main contributor to the ICT sector's embodied carbon emissions, while import embodied carbon emission intensities among publishing activities (S2) are increasing significantly in most countries. The conclusion of this paper has important implications for how to reduce ICT's embodied carbon emissions of major countries.

Keywords: embodied carbon emissions, embodied carbon emission intensity, MRIO, trade, ICT

OPEN ACCESS

Edited by:
Muhammad Imran Khan,
CECOS University of Information Technology and Emerging Sciences, Pakistan

Reviewed by:
Jiawei Hu,
Technical University of Berlin, Germany
Kk Kiin,
Institutes of Science and Development, Chinese Academy of Sciences, China
Jiaquan Li,
Beijing Institute of Technology, China

***Correspondence:**
Jianda Wang
wangjd1993@163.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *24 March 2021*
Accepted: *13 April 2021*
Published: *13 May 2021*

Citation:
Dong X, Jiang Q and Wang J (2021) Assessing Embodied Carbon Emission and Its Intensities in the ICT Industry: The Global Case. Front. Energy Res. 9:685021. doi: 10.3389/fenrg.2021.685021

INTRODUCTION

With global warming and frequent disasters, countries are increasingly starting to realize the severity of climate change (Sun et al., 2020; Hou et al., 2021). Studies have shown that carbon dioxide (CO_2), as the most important greenhouse gas, has always been the main influencing factor of global warming, and has caused the global temperature to rise by nearly 1°C since the pre-industrial era (Peters et al., 2019; Tiwari et al., 2021). The continuous increase in CO_2 emissions is the result of an increase in global energy demand associated with the growth in global trade (Li and Hewitt, 2008; Lu et al., 2020). Peters and Hertwich (2008) indicate that carbon emissions caused by globally traded products accounted for 21.5% of global emissions. Wu et al. (2020) also point out that the transfer of emissions embodied in interregional trade comprises around 40% of global carbon emissions.

Many scholars are also actively exploring corresponding emission reduction strategies, including the use of clean energy or renewable energy to replace fossil fuels (Dong et al., 2017, 2018, Dong K. et al., 2020), optimizing the industrial structure (Dong et al., 2019, Dong B. et al., 2020; Zhu and Zhang, 2021), and increasing energy efficiency (He et al., 2021; Xu and Tan, 2021). Some scholars have also proposed that technological innovation can help industrial sectors achieve low-carbon development while taking into account economic improvement (Zhang et al., 2016; Wang R. et al., 2020). As a new type of industry, the information and communication technologies (ICT) industry can partially replace high-energy-consuming products, and its success in this respect and its ability to reduce carbon emissions and use energy efficiently have received widespread attention from scholars. Moyer and Hughes (2012) believe ICT can improve economic productivity, reduce energy intensity, and exert downward pressure on renewable energy costs. Global Energy Statistical Yearbook (2014) also points out that ICT have an important role to play in reducing the energy intensity and increasing energy efficiency of the economy.

However, ICT are facing issues of uneven development among regions, and even a digital divide (Anwar, 2019; Wang et al., 2021). The process of globalization and the imbalance of regional development will cause the rapid promotion of international trade. The ICT sector will flow from regions with developed industries to regions with immature ICT technology. Vogiatzoglou (2009) points out that exports of ICT products have persistently accounted for 15% of global commodity exports in the past decade. Meanwhile, trade products have also triggered the flow of carbon emissions. Since the establishment of the World Trade Organization (WTO) in 1995, policy makers have considered the impact of international trade on the economy, and have increasingly investigated its impact on the environment (Honma and Yoshida, 2020). As an important component of international trade, ICT not only promotes economic growth, but also causes a large amount of carbon emission transfer and flow (Azam et al., 2021). With the liberalization of international trade, some scholars have also highlighted an increasing transfer of CO_2 emissions from developed countries to developing countries (Schaeffer and de Sá, 1996).

Although many scholars have studied the relationship between the ICT industry and carbon emissions (Moyer and Hughes, 2012; Amri et al., 2019; Shahnazi and Dehghan Shabani, 2019; Zhou et al., 2019; Nguyen et al., 2020), few scholars have conducted in-depth research on carbon emissions caused by the flow of products in the ICT sector caused by global trade. As the ICT industry is one of the important global development sectors in the future (Li et al., 2019), it is necessary to measure its embodied carbon emissions flow and embodied carbon emission intensities, and provide corresponding cross-regional emission reduction strategies. Therefore, this paper uses a multi-regional input-output (MRIO) model to explore the flow and network relationships of embodied carbon emissions and intensities by trade in the ICT sector of the world's major economies, and proposes emission reduction strategies for each country.

Above all, three main features distinguish this study from previous studies and contribute to filling the gap in the literature. First, we explore the embodied carbon emissions of the global ICT industry and the embodied carbon emissions of imports and exports of major economies, which is necessary to understand the developing trend and emission reduction direction of the global ICT industry; Second, we measure the mutual flow and intensities of embodied carbon emissions among major economies in the world, which can better evaluate the embodied carbon emissions in export and import, and conducive to the policy formulation and negotiation of cross-regional carbon emission reduction; Third, the embodied carbon emissions and intensities of various ICT industries have also been calculated by this study, which shows heterogeneity in the ICT sector's carbon emissions and provides a good reference for government to formulate emission-reduction strategies for enterprises.

This paper is structured as follows: Section "Literature review" organizes the literature on the relationship between embodied carbon emissions, intensities and ICT sectors. Section "Methodology and data" presents the methodology and data. Section "Results and discussion" analyzes the global carbon emissions and intensities in 15 major economies. Section "Further discussion" provides further analysis of the emissions and intensities of each ICT sector. Section "Conclusions and policy implications" addresses the policy implications and concludes the paper.

LITERATURE REVIEW

Due to the rise of the ICT sector in recent years and the intensification of digital activities on a global scale, scholars have increasingly started to pay attention to research on the relationship between the ICT sectors and global embodied carbon emissions. This study intends to discuss the extant literature under two strands of research: (1) Studying the relationship between carbon emissions and ICT sectors; and (2) studying the relationship between carbon emission intensity and ICT sectors.

Carbon Emissions and ICT Sectors

Information and communication technologies contributes substantially to global greenhouse gas (GHG) pollutant emissions, but scant research has quantified the impact of ICT products on carbon emissions. From the perspective of the products themselves, the types of ICT products included are very complex, and traditional industries also include many ICT sector products, making quantification difficult (Teehan and Kandlikar, 2013). However, with the development of digital industries and the intensification of the global greenhouse effect, more and more scholars have started to pay attention to the impact of the ICT industry on carbon emissions.

Some scholars analyze the embodied carbon emissions of the ICT sector of specific countries. Zhou et al. (2019) summarize China's embodied carbon emissions of ICT and point out that the ICT sector is far from being environment friendly while considering its embodied carbon impacts, which are dozens of times greater than the direct impacts.

Shahnazi and Dehghan Shabani (2019) analyze the correlation between the development of the ICT industry and carbon emissions in Iran's provinces, and their results show that an increase in ICT in a province first leads to an increase and then a decrease in CO_2 emissions in other provinces. Due to the prominence of the ICT sectors of some developed countries and the associated advantages of ICT for economic development, these countries have become a good target for many scholars to study ICT and embodied carbon emissions growth (Malmodin et al., 2014; Malmodin and Lundén, 2016). For example, Malmodin and Lundén (2016) conduct a detailed study of embodied carbon emissions of the ICT sector in Sweden from 1990 to 2015. They point out that although the embodied carbon emissions of the ICT sectors in that country have decreased since their peak in 2010, embodied carbon emissions from their manufacturing processes abroad are the largest source of ICT-related carbon emissions in Sweden.

Some scholars have expanded their research to the global region and analyze the relationship between the development of the global ICT industry and the impact of carbon emissions, and quantified the potential reduction of emissions in ICT (Moyer and Hughes, 2012; Bastida et al., 2019). Malmodin and Bergmark (2015) explore possible reductions globally within a 2030 timeframe, and predict a potential reduction of total GHG emissions by 2030 of about 8 Gtonnes CO_2 or 12% of global GHG emissions due to ICT solutions. Asongu (2018) investigates how ICT counteracts the negative influence of globalization on CO_2 emissions in his study of 44 Sub-Saharan African countries over the period 2000–2012. The author finds that ICT can be employed to dampen the potentially negative effect of globalization on environmental degradation through CO_2 emissions. Malmodin and Lundén (2018) analyze carbon emissions of the global ICT sectors for 2010-2015, and point out that the ICT sectors have turned their previously growing carbon footprints into shrinking ones.

However, related research on the embodied carbon emissions of the ICT sector caused by global trade is relatively insufficient. With the rapid development of globalization and the systematic construction of global industrial chains and value chains, this will be a very important component.

Carbon Emission Intensities and ICT Sectors

Energy intensity and carbon emission intensity are two important indicators for studying the environmental impact of industries. Some scholars are concerned about the interaction between the ICT industry and energy intensity. And the Global Energy Statistical Yearbook (2014) points out that the ICT industry plays an important role in reducing energy intensity and improving industrial efficiency, but few scholars pay attention to the energy intensity of the ICT industry itself. Wang and Han (2016) study the impact of ICT on energy intensity in China, and point out that the impact of ICT investment in energy intensity is significantly negative in western and central regions in China.

However, relatively speaking, the intensity of carbon emissions caused by energy is more representative and has been widely studied by scholars (Pan et al., 2019; Liu et al., 2021a). However, research on carbon emission intensity and ICT-related research is relatively rare, and we can only find some relevant evidence in some research on the industrial framework or emerging technology industry. For example, Liu et al. (2021b) have shed light on the effect of Artificial Intelligence (AI) on carbon emission intensity. Their results show that AI tends to have a greater effect in reducing carbon emission intensity in the labor-intensive and tech-intensive industries. Chen et al. (2019) investigate the impact of ICT on CO_2 emission intensity by using Internet penetration and mobile phone penetration as proxies in China, and point out that the reduction effect of Internet penetration on CO_2 emission intensity in China's eastern and central provinces is more obvious. In contrast with the reduction effect of Internet penetration on CO_2 emission intensity in China's eastern provinces, it is greater in China's central provinces.

Few scholars have demonstrated concern about the intensive impact of global embodied carbon emissions. Although Jiang and Liu (2015) quantify the flow of embodied carbon emissions from the global ICT industry and trade, they do not highlight the impact of trade intensity under the global value chain system, and the research period is relatively lagging. This article will build a research framework on embodied carbon emissions and carbon emission intensities of global ICT trade in the context of global value chains. The paper will also analyze the volume and technical advantages and disadvantages of major economies' embodied carbon emissions, and recommend cross-regional emission-reduction strategies.

Furthermore, we will absorb the research experience of the above-mentioned scholars, based on previous studies on carbon emissions and carbon emission intensities in the ICT industry, and expand the analysis of embodied carbon emissions and the measurement of embodied carbon emission intensities from the perspective of global value chains in major economies around the world. Furthermore, this study will explore in detail the dynamic changes of the embodied carbon emissions and intensities of each ICT sector.

METHODOLOGY AND DATA

Multiregional Input–Output Model

The basic methodology used in this study is the multi-regional input-output (MRIO) model from the perspective of both the environment and the global value chain. This model put forward by Moses (1955), can depict economic links among regions. The row equivalent of the MRIO can be expressed as:

$$x_i^r = \sum_{s=1}^{R}\sum_{j=1}^{N} a_{ij}^{rs} x_j^s + \sum_{s=1}^{R} y_i^{rs} \tag{1}$$

Where x_i^r is denoted as the total output of sector i in region r. a_{ij}^{rs} is the direct requirement coefficient of sector i in region r for sector j in region s, which can be calculated by $a_{ij}^{rs} = t_{ij}^{rs}/x_j^s$, and t_{ij}^{rs} is the intermediate use of sector i in region r for sector j in region s; y_i^{rs} is the final demand of region s by sector i in region r. And the basic model of MRIO can be expressed in matrix form:

$$X = (I - A)^{-1} Y \tag{2}$$

where $X = \left[x_i^r\right]_{RN\times 1}$, $A = \left[a_{ij}^{rs}\right]_{RN\times RN}$, $Y = \left[\sum_s y_j^{rs}\right]_{RN\times\ 1}$.

And we define $F = \left[f_i^r\right]_{1\times RN}$ as the carbon emission intensity generated by the unitary output of sector i in region r. Embodied carbon emissions of an economy can be expressed as:

$$EC = F(I - A)^{-1} Y \tag{3}$$

where $B = (I - A)^{-1} = \left[b_{ij}^{rs}\right]_{RN\times RN}$, the embodied carbon emissions from sector i in region r to sector j in region s can be calculated as:

$$EC_{ij}^{rs} = \sum_{k=1}^{R} f_i^r b_{ij}^{rk} y_j^{ks} \tag{4}$$

Therefore, the element of domestic embodied carbon emissions diagonal matrix $DEC = \left[DEC_i^r\right]_{RN\times RN}$ can be calculated as:

$$DEC_i^r = \sum_{k=1}^{R} f_i^r b_{ii}^{rk} y_i^{kr} \tag{5}$$

The element of export embodied carbon emissions from sector i in region r to sector j to region s can make up the export embodied carbon emissions matrix $EEC = \left[EEC_{ij}^{rs}\right]_{RN\times RN}$, which can be represented as:

$$EEC_{ij}^{rs} = \sum_{k=1}^{R} f_i^r b_{ij}^{rk} y_j^{ks} \left(r \neq s, i \neq j\right) \tag{6}$$

The element of import embodied carbon emissions from sector i in region r to sector j to region s can make up the import embodied carbon emissions matrix $IEC = \left[IEC_{ij}^{rs}\right]_{RN\times RN}$, which can be represented as:

$$IEC_{ij}^{rs} = \sum_{k=1}^{R} f_j^s b_{ji}^{sk} y_i^{kr}, \left(r \neq s, i \neq j\right) \tag{7}$$

Next, we define $V = \left[v_i^r\right]_{1\times RN}$ as the value-added coefficients generated by the unitary output of sector i in region r, which can be calculated by $v_i^r = va_i^r / x_i^r$, where va_i^r denotes the value added of sector i in region r. According to the global value flow analysis method (Fan et al., 2021), the element of embodied value-added cross countries matrix $EVA = \left[EVA_{ij}^{rs}\right]_{RN\times RN}$ can be calculated as:

$$EVA_{ij}^{rs} = \sum_{k=1}^{R} v_i^r b_{ij}^{rk} y_j^{ks} \tag{8}$$

And the element of embodied carbon emission intensity of sector i in region r flowing into sector j in region s can make up the matrix $ECI = \left[ECI_{ij}^{rs}\right]_{RN\times RN}$, which can be calculated as:

$$ECI_{ij}^{rs} = EC_{ij}^{rs} / EVA_{ij}^{rs} \tag{9}$$

Similarly, the domestic embodied carbon emission intensity of sector i in region r can make up the diagonal matrix $DECI = \left[DECI_i^r\right]_{RN\times RN}$, which can be calculated as:

$$DECI_i^r = DEC_i^r / \sum_{k=1}^{R} v_i^r b_{ii}^{rk} y_i^{kr} \tag{10}$$

The export embodied carbon emission intensity of sector i in region r can make up the diagonal matrix $EECI = \left[EECI_i^r\right]_{RN\times RN}$, which can be calculated as:

$$EECI_i^r = \sum_{s=1}^{R}\sum_{j=1}^{N} EEC_{ij}^{rs} / \sum_{k=1}^{R} v_i^r b_{ij}^{rk} y_j^{ks}, \left(r \neq s, i \neq j\right) \tag{11}$$

And the export carbon emission intensity from region r to region s can be calculated as:

$$EECI^{rs} = \sum_{i=1}^{N}\sum_{j=1}^{N} EEC_{ij}^{rs} / \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{R} v_i^r b_{ij}^{rk} y_j^{ks}, \left(r \neq s, i \neq j\right) \tag{12}$$

The import embodied carbon emission intensity of sector i in region r can make up the diagonal matrix $IECI = \left[IECI_i^r\right]_{RN\times RN}$, which can be calculated as:

$$IECI_i^r = \sum_{s=1}^{R}\sum_{j=1}^{N} IEC_{ij}^{rs} / \sum_{k=1}^{R} v_j^s b_{ji}^{sk} y_i^{kr}, \left(r \neq s, i \neq j\right) \tag{13}$$

And the import carbon emission intensity from region r to region s can be calculated as:

$$IECI^{rs} = \sum_{i=1}^{N}\sum_{j=1}^{N} IEC_{ij}^{rs} / \sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{R} v_j^s b_{ji}^{sk} y_i^{kr}, \left(r \neq s, i \neq j\right) \tag{14}$$

Data

Here we will use the MRIO model to measure the embodied carbon emissions of global ICT sectors. The World Input–output tables coming from the World Input–output database (WIOD) are released in 2016. The 2016 version covers 43 countries for the period 2000–2014 (Timmer et al., 2015). We have selected 15 major countries as the research objects of this study, and other countries are classified as other countries (ROW)[1], the country names and abbreviations are shown in **Table 1**. In order to make comparative prices, the multiregional input–output tables are processed at constant 2010 prices, and use a double-shrink method to select the price indexes for each sector's products (Miller and Peter, 2009). The price indexes are selected as the consumer price index of countries from the World Bank (2020). And the data of the 56 sectors are classified according to the International Standard Industrial Classification Revision 4 (ISIC Rev.4). We select five sectors as ICT departments, including one ICT manufacturing sector and four ICT service sectors, which are shown in **Table 2**.

The direct carbon emissions come from Corsatea et al. (2019), and the data fit perfectly with WIOD and are applied to this study.

[1]The ROW is different from ROW of WIOD, it includes 28 countries and ROW countries in WIOD.

TABLE 1 | Major countries and their abbreviations.

Abbreviation	Countries
AUS	Australia
BRA	Brazil
CAN	Canada
CHN	China
DEU	Germany
ESP	Spain
FRA	France
GBR	United Kingdom
IDN	Indonesia
IND	India
JPN	Japan
KOR	Korea
MEX	Mexico
RUS	Russia
USA	United States

TABLE 2 | Information and communication technologies sectors in WIOD.

Codes	Sector names	ISIC Rev.4
S1	Manufacture of computer, electronic and optical products	C26
S2	Publishing activities	J58
S3	Motion picture, video and television program production, sound recording and music publishing activities; programming	J59–J60
S4	Telecommunications	J61
S5	Computer programming, consultancy and related activities; information service activities	J62–J63

RESULTS AND DISCUSSION

Global ICT Embodied Carbon Emissions

Calculated based on Eq. (3), the embodied carbon emissions of global ICT sectors and their proportion of global embodied carbon emissions have been shown in **Table 3**. In 2001, the embodied carbon emissions of the ICT sectors reach their highest point – 118.16 Mt. Since then, carbon emissions have been reduced year by year. In 2009, affected by the financial crisis, the embodied carbon emissions of ICT reach a historical low of 89.86 Mt. After 2009, there is a slight increase in ICT's carbon emissions. From the perspective of the percentage of ICT's embodied carbon emissions, there is a decreasing trend year by year after 2001, from 0.53% in 2001 to 0.30% in 2014.

From the perspective of the composition of embodied carbon emissions, domestic embodied carbon emissions accounted for the main part of ICT's embodied carbon emissions, reaching 58.89 Mt in 2014, and accounting for 61.63%. Although trade-embodied carbon emissions are not a major component, their share has been slowly increasing, from 34.99% in 2000 to 38.37% in 2014. With the gradual expansion of the ICT sectors, the carbon emissions caused by their trade will gradually occupy the main part.

Domestic, Export, and Import Embodied Carbon Emissions and Intensities of Major Countries

Embodied Carbon Emissions

Figure 1 shows the ICT's embodied carbon emissions [calculated by Eqs. (5–7)] and embodied carbon emission [calculated by Eqs. (10–11) and Eq. (13)] intensities of 15 major countries in 2000 and 2014. From the perspective of ICT's embodied carbon emissions, the amount of ICT emissions in most developed countries reduces significantly in 2014. For example, domestic, export, and import embodied carbon emissions of ICT in France decreased from 4.56, 1.70, and 1.44 Mt in 2000 to 0.82, 0.41, and 1.30 Mt in 2014, respectively. The ICT's domestic, export and import embodied carbon emissions of the United States decreased from 30.34, 6.40, and 9.41 Mt in 2000 to 20.09, 3.08, and 6.31 Mt in 2014. Even so, the United States has the highest embodied carbon emissions of ICT in the world, which reflects its leading role and considerable investment in internal communications technology on a global scale (Adedoyin et al., 2020). However, some developing countries, such as China, India, Brazil, etc., have shown an increase trend in embodied carbon emissions. For example, China's domestic and export embodied carbon emissions of ICT increase from 3.12 and 2.39 Mt in 2000 to 6.37 and 7.24 Mt in 2014. India's export and import embodied carbon emissions of ICT increase from 0.31 and 0.43 Mt in 2000 to 1.22 and 0.52 Mt in 2014, respectively. Brazil's domestic and import embodied carbon emissions of ICT also increase from 1.19 and 0.57 Mt in 2000 to 1.65 and 0.78 Mt in 2014, respectively. This reflects that these countries are at an important stage of economic development, and are in the process of rapid expansion, although their new technologies and digital industry technologies are not fully mature (Wang H. et al., 2020; Sahoo et al., 2021). Nevertheless, the growth of these countries' ICT industries is reflected in their domestic and export products, which have increased embodied carbon emissions. The China Academy of Information and Communications Technology

TABLE 3 | Information and communication technologies domestic and trade carbon emissions and its proportion.

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Domestic EC (Mt)	73.37	78.69	74.05	73.46	71.96	68.33	66.43	63.92	57.83	56.55	57.69	57.18	57.45	57.98	58.89
Trade EC (Mt)	39.49	39.47	37.22	37.22	39.58	40.24	42.48	40.56	38.15	33.31	36.97	37.79	36.87	36.79	36.67
ICT proportion (%)	0.51	0.53	0.49	0.46	0.44	0.41	0.40	0.37	0.34	0.32	0.32	0.31	0.30	0.30	0.30
Proportion of domestic emissions (%)	34.99	33.40	33.45	33.63	35.49	37.07	39.00	38.82	39.75	37.07	39.05	39.79	39.09	38.82	38.37
Proportion of trade emissions (%)	65.01	66.60	66.55	66.37	64.51	62.93	61.00	61.18	60.25	62.93	60.95	60.21	60.91	61.18	61.63

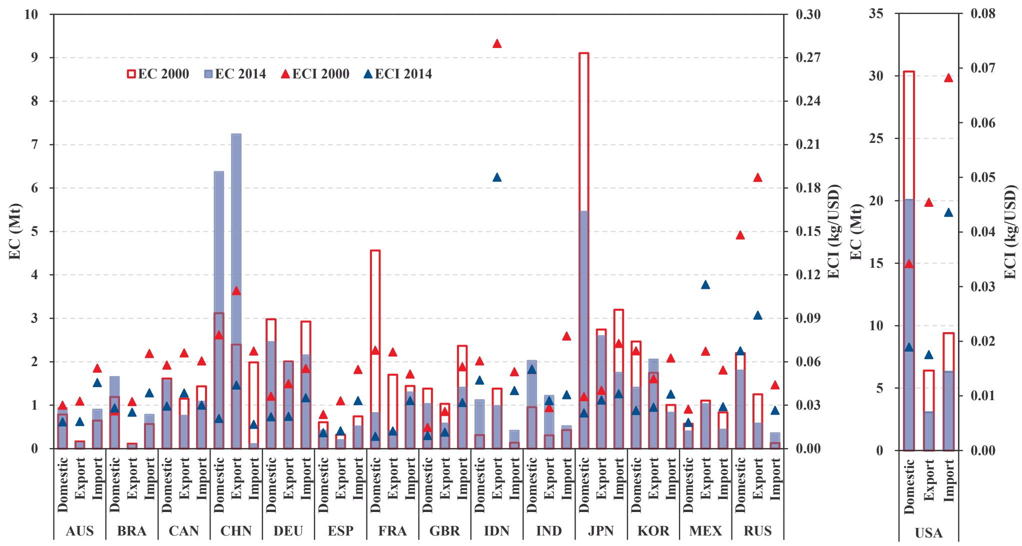


FIGURE 1 | The ICT's embodied carbon emissions and intensities of major countries in 2000 and 2014. Note: EC represents the embodied carbon emissions, ECI represents the embodied carbon emission intensities.

(CAICT) reports that China's digital economy accounted for 34.8% of GDP in 2018, and 36.2% in 2019 (CAICT, 2020). And according to a report by McKinsey in 2017, China has been one of the world's largest investors and adopters of digital technologies. For example, there are 731 million Internet users in 2016 in China, which is 1.7 times as many users as there are in India and the European Union, and 2.5 times as many users as there are in the United States that year (McKinsey, 2017). China's export embodied carbon emissions of ICT in 2014 surpass the domestic embodied carbon emissions, and become the main growth force of its ICT embodied carbon emissions. In the future, as China's technology continues to improve, export embodied carbon emissions will become China's main source of carbon emissions growth.

Embodied Carbon Emission Intensities

The carbon emission intensities of trade reflect to a certain extent the technological differences in a country's trade products and can provide intuitive emission reduction strategies. From the perspective of embodied carbon emission intensities (**Figure 1**), the amount of such emission intensities in most countries in 2014 show a downward trend compared with that in 2000. For example, the ICT's export embodied carbon emission intensities of France decrease from 0.07 kg/USD in 2000 to 0.01 kg/USD in 2014. Export and import embodied carbon emission intensities of ICT in China decrease from 0.11 kg/USD and 0.07 kg/USD in 2000 to 0.04 kg/USD and 0.02 kg/USD in 2014. The United States decreases its export and import embodied carbon emission intensities from 0.05 kg/USD and 0.07 kg/USD in 2000 to 0.02 kg/USD and 0/04 kg/USD in 2014. This reflects to a certain extent that the progress of production technology has promoted the process of carbon emission reduction in the ICT sector. However, it must be noted that India's domestic embodied carbon emission intensity and export embodied carbon emission intensity of ICT have both increased slightly, which requires the attention of local government departments. From the selected countries, Indonesia's export embodied carbon emission intensity of ICT is much higher than that of other countries. Even though there is a significant decrease in 2014 compared to 2000, the export embodied carbon emission intensities of 0.19 kg/USD should still receive the attention of the authorities. For example, key considerations for Indonesia will be to find ways of optimizing the energy structure of products in the export sector and the industrial energy consumption intensity of its ICT sector. The country will also need to improve its energy poverty environment (Setyowati, 2021). In 2000, Russia's domestic and export embodied carbon emission intensities of ICT are relatively high, reaching 0.15 kg/USD and 0.19 kg/USD respectively, but in 2014 the export embodied carbon emission intensities decrease to 0.07 kg/USD and 0.09 kg/USD, respectively.

Embodied Carbon Emission and Intensity Flows Among Major Countries

Embodied Carbon Emission Flows

Calculated based on Eq. (6–7), the embodied carbon emission flows of the ICT industry in 2000 and 2014 within the world's 15 major countries and other countries (ROW) are shown in **Figure 2**. On the whole, ICT's embodied carbon emissions have shown a downward trend, especially in European countries and the United States. For example, the ICT's embodied carbon emissions of France's exports to Germany decrease from 0.208 Mt in 2000 to 0.034 Mt in 2014, and the ICT's embodied carbon emissions of United States exports to Germany decrease from 0.472 Mt in 2000 to 0.173 Mt in 2014. Relatively speaking, embodied carbon emissions in the Asia-Pacific region have shown an increasing trend. The embodied carbon emissions of China's exports to other countries are more obvious. For example,

EC flow in 2000

	AUS	BRA	CAN	CHN	DEU	ESP	FRA	GBR	IDN	IND	JPN	KOR	MEX	RUS	USA	ROW
AUS	-	0.002	0.003	0.009	0.006	0.001	0.003	0.012	0.003	0.002	0.018	0.005	0.001	0.000	0.026	0.072
BRA	0.001	-	0.001	0.002	0.003	0.001	0.002	0.002	0.000	0.003	0.005	0.001	0.005	0.000	0.036	0.051
CAN	0.009	0.007	-	0.013	0.023	0.006	0.014	0.047	0.003	0.003	0.033	0.009	0.017	0.001	0.777	0.187
CHN	0.038	0.020	0.038	-	0.152	0.022	0.078	0.108	0.011	0.013	0.267	0.069	0.022	0.006	0.727	0.823
DEU	0.019	0.019	0.017	0.053	-	0.092	0.166	0.184	0.004	0.010	0.063	0.021	0.018	0.015	0.262	1.064
ESP	0.002	0.003	0.002	0.004	0.037	-	0.034	0.019	0.001	0.001	0.005	0.002	0.005	0.001	0.023	0.178
FRA	0.013	0.015	0.016	0.039	0.208	0.109	-	0.176	0.002	0.012	0.045	0.018	0.014	0.009	0.212	0.809
GBR	0.019	0.006	0.018	0.024	0.123	0.035	0.088	-	0.002	0.005	0.036	0.010	0.008	0.003	0.146	0.507
IDN	0.032	0.009	0.020	0.059	0.080	0.026	0.049	0.087	-	0.011	0.175	0.024	0.019	0.002	0.424	0.364
IND	0.004	0.003	0.003	0.007	0.014	0.003	0.005	0.011	0.001	-	0.015	0.003	0.008	0.003	0.050	0.176
JPN	0.052	0.025	0.053	0.187	0.195	0.026	0.079	0.125	0.018	0.016	-	0.147	0.036	0.005	0.942	0.835
KOR	0.034	0.030	0.035	0.125	0.089	0.019	0.040	0.090	0.009	0.012	0.203	-	0.030	0.005	0.591	0.434
MEX	0.004	0.006	0.050	0.009	0.011	0.003	0.006	0.014	0.001	0.003	0.015	0.004	-	0.000	0.903	0.076
RUS	0.006	0.008	0.009	0.063	0.090	0.014	0.029	0.032	0.003	0.033	0.040	0.016	0.005	-	0.121	0.783
USA	0.157	0.178	0.786	0.272	0.472	0.078	0.237	0.443	0.014	0.052	0.656	0.280	0.468	0.020	-	2.285
ROW	0.258	0.239	0.384	1.118	1.422	0.305	0.614	1.017	0.062	0.253	1.624	0.397	0.177	0.053	4.168	-

EC flow in 2014

	AUS	BRA	CAN	CHN	DEU	ESP	FRA	GBR	IDN	IND	JPN	KOR	MEX	RUS	USA	ROW
AUS	-	0.002	0.002	0.026	0.002	0.001	0.002	0.004	0.003	0.003	0.011	0.003	0.001	0.001	0.012	0.069
BRA	0.001	-	0.001	0.010	0.002	0.001	0.002	0.002	0.001	0.003	0.002	0.001	0.002	0.001	0.011	0.044
CAN	0.009	0.008	-	0.033	0.016	0.003	0.014	0.025	0.003	0.006	0.017	0.007	0.012	0.004	0.334	0.269
CHN	0.174	0.141	0.175	-	0.315	0.068	0.147	0.217	0.094	0.137	0.644	0.228	0.101	0.078	1.573	3.144
DEU	0.020	0.024	0.022	0.148	-	0.054	0.129	0.119	0.007	0.016	0.043	0.024	0.011	0.036	0.178	1.164
ESP	0.001	0.003	0.001	0.006	0.010	-	0.011	0.006	0.001	0.001	0.002	0.001	0.001	0.002	0.009	0.144
FRA	0.004	0.006	0.005	0.023	0.034	0.021	-	0.033	0.002	0.004	0.008	0.004	0.002	0.006	0.033	0.221
GBR	0.009	0.006	0.009	0.026	0.039	0.010	0.035	-	0.002	0.005	0.012	0.007	0.003	0.011	0.078	0.329
IDN	0.041	0.011	0.017	0.077	0.058	0.005	0.028	0.023	-	0.020	0.109	0.029	0.008	0.005	0.183	0.365
IND	0.008	0.009	0.006	0.042	0.023	0.005	0.021	0.020	0.007	-	0.013	0.007	0.005	0.006	0.114	0.934
JPN	0.040	0.035	0.047	0.646	0.112	0.016	0.037	0.052	0.040	0.030	-	0.105	0.031	0.029	0.456	0.914
KOR	0.023	0.070	0.029	0.642	0.050	0.012	0.027	0.034	0.022	0.028	0.107	-	0.032	0.021	0.289	0.670
MEX	0.009	0.014	0.089	0.022	0.017	0.003	0.012	0.011	0.001	0.004	0.016	0.004	-	0.001	0.706	0.116
RUS	0.003	0.005	0.005	0.044	0.027	0.005	0.011	0.015	0.004	0.018	0.017	0.007	0.002	-	0.032	0.389
USA	0.064	0.073	0.384	0.264	0.173	0.023	0.093	0.136	0.014	0.036	0.129	0.071	0.136	0.023	-	1.465
ROW	0.493	0.379	0.289	2.193	1.270	0.290	0.731	0.708	0.214	0.209	0.621	0.331	0.092	0.134	2.305	-

0.000 – 4.200

FIGURE 2 | Information and communication technologies embodied carbon emissions flow among major countries in 2000 and 2014. Note: EC represents the embodied carbon emissions, ECI represents the embodied carbon emission intensities.

the ICT's embodied carbon emissions of China's exports to the United States increases from 0.727 Mt in 2000 to 1.573 Mt in 2014, and exports to Japan increases from 0.267 Mt in 2000 to 0.644 Mt in 2014. The ICT's embodied carbon emissions of Japan and South Korea's exports to China also show significant growth, from 0.187 and 0.125 Mt in 2000 to 0.646 and 0.642 Mt in 2014, respectively.

Embodied Carbon Intensity Flows

Calculated based on Eq. (12) and Eq. (14), the embodied carbon intensities of global ICT industry trade in 2000 and 2014 are shown in **Figure 3**. In 2000, the embodied emission intensities of Indonesia and Russia's exports to other countries are significantly higher than those of other countries. For example, the embodied emission intensities of Indonesia's exports to Germany, France, the United Kingdom, and the United States all reach 0.30 kg/USD, and the embodied carbon intensity of ICT products export from Russia to India reaches 0.28 kg/USD. In 2014, embodied carbon intensity showed a significant downward trend, but relatively speaking, the ICT's embodied carbon intensities of Indonesia's exports to other countries are still higher than those of other countries in 2014, 0.29 kg/USD from Indonesia to Germany, and 0.25 kg/USD from Indonesia to Canada, which should have aroused the attention of the relevant government departments. The embodied carbon intensities of Mexico's exports of ICT products have shown an increasing trend. For example, the embodied carbon intensity of Mexico's exports to the United States increases from 0.07 kg/USD in 2000 to 0.12 kg/USD in 2014, and exports to China also increase from 0.06 kg/USD in 2000 to 0.10 kg/USD in 2014. This shows that the export of ICT products may not reduce the carbon intensity to achieve emission reduction due to technical restrictions, which has caused the significant spillover effect[2] of export carbon emissions (Liu and Liu, 2019; Wang and Li, 2019). Relatively speaking, the embodied carbon intensities of European countries, such as Spain, France, and the United Kingdom, are at the low level. The ICT's embodied carbon intensities of their exports to other countries are all about 0.01 kg/USD, reflecting the technological advantages and emission reduction driving forces of ICT products in these European countries.

[2]The flow of embodied carbon emissions in one region affects the level of carbon emissions in other regions.

FURTHER DISCUSSION

After investigating the embodied carbon emissions and embodied carbon emission intensities of the ICT sector in various countries, we find that there is relatively little understanding of the internal ICT sector, and the internal ICT manufacturing products or services that have caused the increase in embodied carbon emissions are worthy of attention. Therefore, we continue to explore the impact of each ICT sector.

Embodied Carbon Emissions of ICT Sectors

Figure 4 shows the global embodied carbon emissions of each ICT sector from 2000 to 2014 and their proportions in 2000 and 2014. The sector that manufacture of computer, electronic and optical products (S1) produces the most embodied carbon emissions from 2000 to 2014, and the changing trend almost reveals a 'W' shape. In 2006, the sector of manufacture of computer, electronic and optical products (S1) is the top producer of embodied carbon emissions (30.39 Mt). However, the proportion of embodied carbon emissions produced by the sector decrease from 68.6% in 2000 to 62.2% in 2014. Other ICT sectors, all of which belong to ICT services, have relatively low embodied carbon emissions. For example, the embodied carbon emissions of computer programming, consultancy and related activities and information service activities (S5) are 8.00 Mt in 2014, accounting for 21.8% of global ICT embodied carbon emissions that year. By 2000, although these emissions have increased, they represented 18.2% of global ICT embodied carbon emissions. The embodied carbon emissions of publishing activities (S2) are 2.96 Mt in 2014. This represents 8.1% of global ICT embodied carbon emissions, up from 2.7% in 2000. The sector representing motion picture, video and television program production, sound recording and music publishing activities, programming (S3) and telecommunications (S4) show a decreasing proportions of

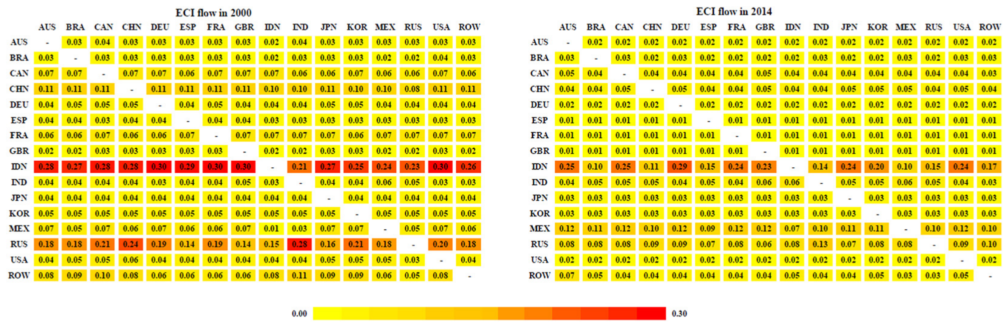


FIGURE 3 | Information and communication technologies embodied carbon intensities among major countries in 2000 and 2014. Note: EC represents the embodied carbon emissions, ECI represents the embodied carbon emission intensities.

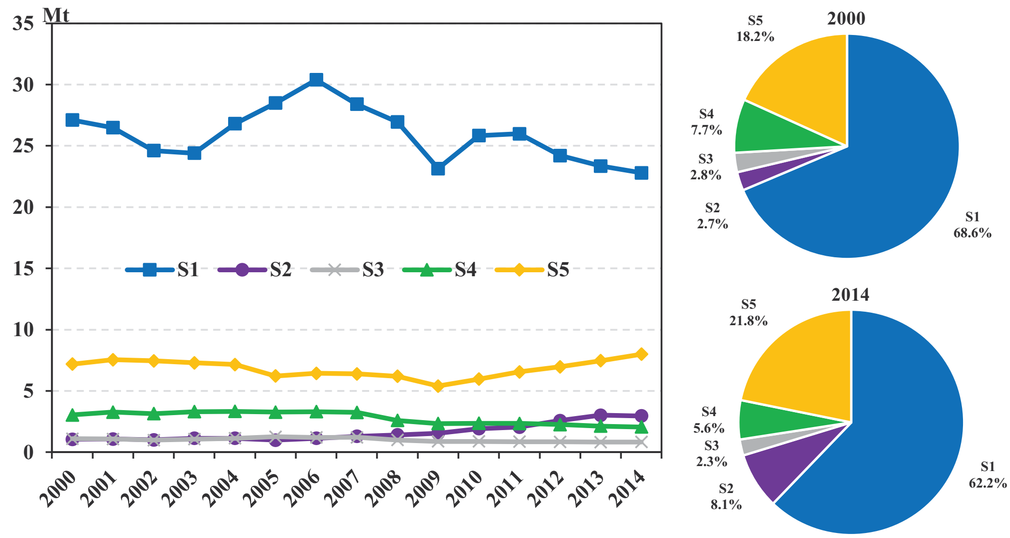


FIGURE 4 | The global embodied carbon emissions of each ICT sector and their proportions in 2000 and 2014.

embodied carbon emissions, from 7.7 and 2.8% in 2000 to 5.6 and 2.3%, respectively.

Embodied Carbon Emissions and Intensities of Each ICT Sector in Various Countries

Figure 5 shows the embodied carbon emissions and intensities of ICT sectors in each country in 2000 and 2014. From a quantitative point of view, the embodied carbon emissions of the sector of manufacture of computer, electronic and optical products (S1) in most countries are much higher than those of other sectors, and the amount in 2014 is less than that in 2000. The import and export embodied carbon emissions of manufacture of computer, electronic and optical products (S1) in China have both risen significantly, and Brazil's import embodied carbon emissions have increased. The embodied carbon emissions of manufacture of computer, electronic and optical products (S1) in other countries show a downward trend from 2000 to 2014. What is more anomalous is that in 2000, the embodied carbon emission of the telecommunications (S4) sector is the highest in India at 0.141 Mt. In 2014, the computer programming, consultancy and related activities; information service activities (S5) sector has the highest embodied carbon emissions at 0.806 Mt.

From the perspective of carbon emission intensities, the export carbon emission intensity of the publishing activities (S2) sector in many countries has increased significantly by 2014. For example, Australia increases its export carbon emission intensity of the S2 sector from 0.02 kg/USD in 2000 to 0.15 kg/USD in 2014. Germany increases from 0.03 kg/USD in 2002 to 0.08 kg/USD in 2014. The import carbon emission intensities of the other four sectors have shown varying degrees of downward trends. The export carbon emission intensities of ICT sectors in most countries have shown a significant downward trend, reflecting the rapid progress of ICT products exported by these countries. For example, the export carbon emission intensity of China's manufacture of computer, electronic and optical products (S1) sector decrease from 0.12 kg/USD to 0.05 kg/USD in 2000, and the export carbon emission intensities of the S1 sector in the United States decrease from 0.06 kg/USD to 0.02 kg/USD. India

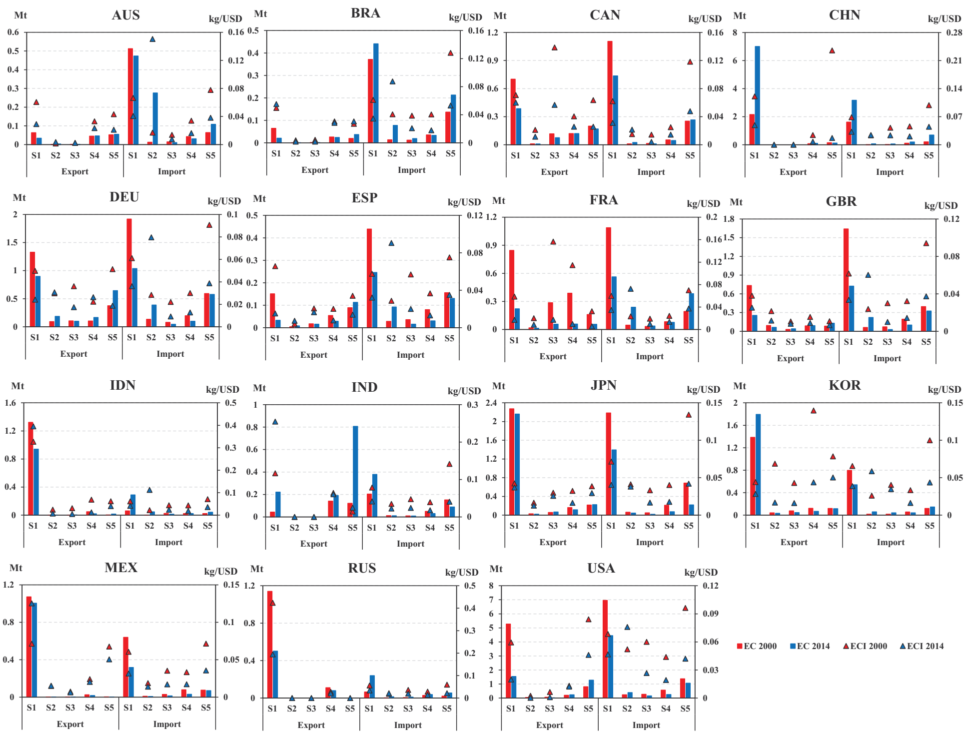


FIGURE 5 | The embodied carbon emissions and intensities of the ICT sectors in each country in 2000 and 2014. Note: EC represents the embodied carbon emissions, ECI represents the embodied carbon emission intensities.

and Indonesia are relatively special; their sector of manufacture of computer, electronic and optical products (S1) has shown an upward trend in export carbon emission intensity, indicating that the export technology of its ICT manufacturing sector has not yet shown much carbon emission reduction potential.

CONCLUSION AND POLICY IMPLICATIONS

Conclusion

This article explores the embodied carbon emissions and carbon emission intensities of 15 major countries around the world, and further discusses the changes in various industrial sectors in each country. Accordingly, the main conclusions are as follows:

(1) In 2001, global ICT carbon emissions reach the highest value in our study. Since then, in terms of quantity, the share of ICT embodied carbon in the world has slowly declined. The proportion of ICT embodied carbon emissions decrease from 0.53% in 2001 to 0.30% in 2014. The proportion of domestic carbon emissions caused by own consumption is relatively high. In 2014, this part of carbon emissions accounts for 61.63% of global ICT embodied carbon emissions. However, the ICT's embodied carbon emissions caused by trade gradually increase, from 34.99% in 2000 to 38.27% in 2014.

(2) From the perspective of the ICT's embodied carbon emissions and embodied carbon emission intensities of various countries, the embodied carbon emissions of ICT in the United States have been much higher than those of other countries. In 2000, the embodied carbon emissions of exports and imports are 6.40 and 9.41 Mt, respectively. But by 2014, there are a significant downward trend in the embodied carbon emissions of exports and imports, which reach 3.08 and 6.31 Mt, respectively. Similarly, the embodied carbon emissions of most countries in 2014 are significantly lower than in 2000. However, in some developing countries, such as India, China, and Brazil, embodied carbon emissions have shown an upward trend. China's export embodied carbon emissions in 2014 exceed domestic embodied carbon emissions, becoming the main growth force of carbon emissions in its ICT sector. From the perspective of carbon emission intensities, the embodied carbon emission intensities of most countries have decreased slightly. However, India's domestic embodied carbon emissions and export embodied carbon emissions have shown a slight increase. The embodied carbon emission intensity of Indonesia's exports is much higher than that of other countries, and should receive attention from the government.

(3) From the perspective of regional trade, the embodied carbon emissions of ICT products in the Asia-Pacific

region are increasing. The embodied carbon emissions of ICT products exported from China to other countries have increased, as have those of Japan and South Korea's ICT products exported to China. In 2000, the embodied carbon emission intensities of ICT products exported from Indonesia and Russia to other countries show a trend higher than that of other countries. However, by 2014, the embodied carbon emission intensity of the ICT sector in most countries has declined. The embodied carbon emission intensity of ICT products exported by Mexico has shown an increasing trend in contrast to the embodied carbon emission intensities of ICT product exports from European countries, which have been at a low level.

(4) From the perspective of the embodied carbon emissions and intensities of various ICT industry sectors, the sector of manufacture of computer, electronic and optical products (S1) is the main embodied carbon component of the ICT sectors, both globally and locally for each country. However, with the passage of time, the percentage of embodied carbon emissions in the ICT manufacturing industry (S1) has been decreasing year by year. In comparison, the embodied carbon emissions of the ICT service industries (S2–S5) have been increasing year by year. As far as countries are concerned, the embodied carbon emissions of India's ICT service industry are higher than those of the manufacturing industry, which is reflected in the sectors of telecommunications (S4) and computer programming, consultancy and related activities; information service activities (S5). In addition, the import embodied carbon emission intensities of the publishing activities (S2) sector in most countries have increased significantly, reflecting the technical disadvantages of imported products in this sector. The embodied carbon emission intensities of exports of various countries and ICT sectors have shown a significant downward trend.

Policy Implications

(1) Although the embodied carbon emissions of the global ICT sector are not high, the sector has already demonstrated its technological advantages and has shown a special advantage in reducing carbon emissions. However, the promotion of trade carbon emissions needs to attract the attention of local governments. It should be noted that the control of the embodied carbon emission intensities of exports can reduce the growth of embodied carbon emissions, and that the ICT sector can further reduce its carbon emissions.

(2) Developing countries such as China, India, and Brazil need to pay special attention to the significant increase in embodied carbon emissions from the ICT sector. China needs to pay attention to the embodied carbon emissions of the export sector, while India needs to pay attention to the embodied carbon emission intensity changes of exports, and realize that maintaining a downward trend is conducive to achieving emission reductions. This requires above countries to enhance the competitiveness of their enterprises in carbon reduction technologies. The Indonesian government needs to focus on the high embodied carbon emission intensity of exports, which is much higher than other countries and is the main driving force behind the embodied carbon emissions of the country's ICT sector.

(3) From the perspective of regional coordinated emission reduction, the embodied carbon emissions of the ICT sector in the Asia-Pacific region remain high, mainly in China, Japan, and South Korea. A coordinated development policy in the Asia-Pacific region could help accelerate the process of regional carbon emission reduction. The growth of embodied carbon intensity in Mexico's exports and the high level of embodied carbon intensity in Indonesia have both reminded local governments to strengthen the regulation of ICT exports, improve the energy efficiency of these products, and learn more from the experience of European countries in achieving low-carbon intensity development.

(4) Regarding the ICT sector, carbon emissions caused by trade in the manufacturing industry account for a relatively high proportion, while carbon emissions caused by trade in the service industry are on the rise. This requires countries to optimize the export carbon intensities of ICT-manufactured products and strengthen supervision of the export of ICT service industries. The Indian government should pay particular attention to the export of ICT services, mainly the embodied carbon emissions of telecommunications (S4) and computer programming, consultancy and related activities; information service activities (S5).

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

XD: conceptualization, validation, investigation, resources, data curation, and funding acquisition. QJ: conceptualization, writing – review and editing. JW: methodology, software, visualization, writing – original draft, writing – review and editing. All authors contributed to the article and approved the submitted version.

FUNDING

This manuscript was supported by the National Social Science Foundation of China (Grant No. 18VDL017), and the Innovation Methods Special Foundation of the Chinese Ministry of Science and Technology (Grant No. 2018IMO40100). Certainly, all remaining errors are our own.

REFERENCES

Adedoyin, F. F., Bekun, F. V., Driha, O. M., and Balsalobre-Lorente, D. (2020). The effects of air transportation, energy, ICT and FDI on economic growth in the industry 4.0 era: evidence from the United States. *Technol. Forecast. Soc. Chang.* 160:120297. doi: 10.1016/j.techfore.2020.120297

Amri, F., Zaied, Y. B., and Lahouel, B. B. (2019). ICT, total factor productivity, and carbon dioxide emissions in Tunisia. *Technol. Forecast. Soc. Chang.* 146, 212–217. doi: 10.1016/j.techfore.2019.05.028

Anwar, M. A. (2019). "Connecting South Africa: ICTs, uneven development and poverty debates," in *The Geography of South Africa. World Regional Geography Book Series*, eds J. Knight and C. Rogerson (Cham: Springer).

Asongu, S. A. (2018). ICT, openness and CO_2 emissions in Africa. *Environ. Sci. Pollut. Res.* 25, 9351–9359. doi: 10.1007/s11356-018-1239-4

Azam, A., Rafiq, M., Shafique, M., and Yuan, J. (2021). An empirical analysis of the non-linear effects of natural gas, nuclear energy, renewable energy and ICT-Trade in leading CO_2 emitter countries: policy towards CO_2 mitigation and economic sustainability. *J. Environ. Manag.* 286:112232. doi: 10.1016/j.jenvman.2021.112232

Bastida, L., Cohen, J. J., Kollmann, A., Moya, A., and Reichl, J. (2019). Exploring the role of ICT on household behavioural energy efficiency to mitigate global warming. *Renew. Sustain. Energy Rev.* 103, 455–462. doi: 10.1016/j.rser.2019.01.004

CAICT (2020). *White Paper of China's Digital Economy Development (2020)*. Beijing: China Academy of Information and Communications Technology.

Chen, X., Gong, X., Li, D., and Zhang, J. (2019). Can information and communication technology reduce CO_2 emission? A quantile regression analysis. *Environ. Sci. Pollut. Res.* 26, 32977–32992. doi: 10.1007/s11356-019-06380-8

Corsatea, T. D., Lindner, S., Arto, I., Román, M. V., Rueda-Cantuche, J. M., Velázquez Afonso, A., et al. (2019). *World Input-Output Database Environmental Accounts. Update 2000-2016*. Luxembourg: Publications Office of the European Union.

Dong, B., Ma, X., Zhang, Z., Zhang, H., Chen, R., Song, Y., et al. (2020). Carbon emissions, the industrial structure and economic growth: evidence from heterogeneous industries in China. *Environ. Pollut.* 262:114322. doi: 10.1016/j.envpol.2020.114322

Dong, K., Dong, X., and Jiang, Q. (2020). How renewable energy consumption lower global CO_2 emissions? Evidence from countries with different income levels. *World Econ.* 43:12898. doi: 10.1111/twec.12898

Dong, K., Dong, X., and Dong, C. (2019). Determinants of the global and regional CO_2 emissions: what causes what and where? *Appl. Econ.* 51, 5031–5044. doi: 10.1080/00036846.2019.1606410

Dong, K., Sun, R., and Hochman, G. (2017). Do natural gas and renewable energy consumption lead to less CO_2 emission? Empirical evidence from a panel of BRICS countries. *Energy* 141, 1466–1478. doi: 10.1016/j.energy.2017.11.092

Dong, K., Sun, R., Jiang, H., and Zeng, X. (2018). CO_2 emissions, economic growth, and the environmental Kuznets curve in China: what roles can nuclear energy and renewable energy play? *J. Clearn Product.* 196, 51–63. doi: 10.1016/j.jclepro.2018.05.271

Fan, J., Zhang, X., Wang, J., and Wang, Q. (2021). Measuring the impacts of international trade on carbon emissions intensity: a global value chain perspective. *Emerg. Mark. Finan. Trade* 57, 972–988. doi: 10.1080/1540496X.2019.1662783

Global Energy Statistical Yearbook (2014). *Addressing the Challenge of Energy Efficiency through Information and Communication Technologies*. Brussels: Commission of the European Communities.

He, Y., Fu, F., and Liao, N. (2021). Exploring the path of carbon emissions reduction in China's industrial sector through energy efficiency enhancement induced by R&D investment. *Energy* 225:120208. doi: 10.1016/j.energy.2021.120208

Honma, S., and Yoshida, Y. (2020). An empirical investigation of the balance of embodied emission in trade: industry structure and emission abatement. *Econ. Model.* 92, 277–294. doi: 10.1016/j.econmod.2020.01.008

Hou, H., Wang, J., Yuan, M., Liang, S., Liu, T., Wang, H., et al. (2021). Estimating the mitigation potential of the Chinese service sector using embodied carbon emissions accounting. *Environ. Impact Assess. Rev.* 86:106510. doi: 10.1016/j.eiar.2020.106510

Jiang, X., and Liu, Y. (2015). Global value chain, trade and carbon: case of information and communication technology manufacturing sector. *Energy Sustain. Dev.* 25, 1–7. doi: 10.1016/j.esd.2014.12.001

Li, Y., and Hewitt, C. N. (2008). The effect of trade between China and the UK on national and global carbon dioxide emissions. *Energy Policy* 36, 1907–1914. doi: 10.1016/j.enpol.2008.02.005

Li, Y., Lee, S. G., and Kong, M. (2019). The industrial impact and competitive advantage of China's ICT industry. *Serv. Bus.* 13, 101–127. doi: 10.1007/s11628-018-0368-7

Liu, F., and Liu, C. (2019). Regional disparity, spatial spillover effects of urbanisation and carbon emissions in China. *J. Clean. Product.* 241:1182226. doi: 10.1016/j.jclepro.2019.118226

Liu, J., Li, S., and Ji, Q. (2021a). Regional differences and driving factors analysis of carbon emission intensity from transport sector in China. *Energy* 224:120178. doi: 10.1016/j.energy.2021.120178

Liu, J., Liu, L., Qian, Y., and Song, S. (2021b). The effect of artificial intelligence on carbon intensity: evidence from China's industrial sector. *Soc. Econ. Plan. Sci.* 2021:101002. doi: 10.1016/j.seps.2020.101002

Lu, Q., Fang, K., Heijungs, R., Feng, K., Li, J., Wen, Q., et al. (2020). Imbalance and drivers of carbon emissions embodied in trade along the belt and road initiative. *Appl. Energy* 280:115934. doi: 10.1016/j.apenergy.2020.115934

Malmodin, J., and Bergmark, P. (2015). "Exploring the effect of ICT solutions on GHG emissions in 2030," in *Proceedings of the Environmental Information and ICT for Sustainability 2015*, (Paris: Atlantis Press), 37–46.

Malmodin, J., and Lundén, D. (2016). "The energy and carbon footprint of the ICT and E&M sector in Sweden 1990-2015 and beyond," in *Proceedings of the ICT for Sustainability 2016*, (Paris: Atlantis Press), 209–218.

Malmodin, J., and Lundén, D. (2018). The energy and carbon footprint of the global ICT and E&M sectors 2010–2015. *Sustainability* 10:3027. doi: 10.3390/su10093027

Malmodin, J., Lundén, D., Moberg, Å, Andersson, G., and Nilsson, M. (2014). Life cycle assessment of ICT. *J. Industr. Ecol.* 18, 829–845. doi: 10.1111/jiec.12145

McKinsey (2017). *China's Digital Economy: A Leading Global Force*. Shanghai: McKinsey and company.

Miller, R. E., and Peter, D. (2009). *Input-Output Analysis: Foundations and Extensions*. Cambridge: Cambridge university press.

Moses, L. N. (1955). The stability of interregional trading patterns and input-output analysis. *Am. Econ. Rev.* 45, 803–826.

Moyer, J. D., and Hughes, B. B. (2012). ICTs: do they contribute to increased carbon emissions? *Technol. Forecast. Soc. Chang.* 79, 919–931. doi: 10.1016/j.techfore.2011.12.005

Nguyen, T. T., Pham, T. A. T., and Tram, H. T. X. (2020). Role of information and communication technologies and innovation in driving carbon emissions and economic growth in selected G-20 countries. *J. Environ. Manag.* 261:110162. doi: 10.1016/j.jenvman.2020.110162

Pan, X., Uddin, M. K., Ai, B., Pan, X., and Saima, U. (2019). Influential factors of carbon emissions intensity in OECD countries: evidence from symbolic regression. *J. Clean. Product.* 220, 1194–1201. doi: 10.1016/j.jclepro.2019.02.195

Peters, G. P., Andrew, R. M., Canadell, J. G., Friedlingstein, P., and Peregon, A. (2019). Carbon dioxide emissions continue to grow amidst slowly emerging climate policies. *Nat. Clim. Chang.* 10, 1–4. doi: 10.1038/s41558-019-0659-6

Peters, G. P., and Hertwich, E. G. (2008). CO_2 Embodied in international trade with implications for global climate policy. *Environ. Sci. Technol.* 42, 1401–1407. doi: 10.1021/es072023k

Sahoo, M., Gupta, M., and Srivastava, P. (2021). Does information and communication technology and financial development lead to environmental sustainability in India? An empirical insight. *Telemat. Inform.* 60:101598. doi: 10.1016/j.tele.2021.101598

Schaeffer, R., and de Sá, A. (1996). The embodiment of carbon associated with Brazilian imports and exports. *Energy Convers. Manag.* 37, 955–960. doi: 10.1016/0196-8904(95)00283-9

Setyowati, A. B. (2021). Mitigating inequality with emissions? Exploring energy justice and financing transitions to low carbon energy in Indonesia. *Energy Res. Soc. Sci.* 71:101817. doi: 10.1016/j.erss.2020.101817

Shahnazi, R., and Dehghan Shabani, Z. (2019). The effects of spatial spillover information and communications technology on carbon dioxide emissions in Iran. *Environ. Sci. Pollut. Res.* 26, 24198–24212. doi: 10.1007/s11356-019-05636-7

Sun, C., Chen, L., and Zhang, F. (2020). Exploring the trading embodied CO_2 effect and low-carbon globalization from the international division perspective. *Environ. Impact Assess. Rev.* 83:106414. doi: 10.1016/j.eiar.2020.106414

Teehan, P., and Kandlikar, M. (2013). Comparing embodied greenhouse gas emissions of modern computing and electronics products. *Environ. Sci. Technol.* 47, 3997–4003. doi: 10.1021/es303012r

Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R., and de Vries, G. J. (2015). An illustrated user guide to the world input–output database: the case of global automotive production. *Rev. Intern. Econ.* 23, 575–605. doi: 10.1111/roie.12178

Tiwari, A. K., Abakah, E. J. A., Le, T. N. L., and Leyva-de la Hiz, D. I. (2021). Markov-switching dependence between artificial intelligence and carbon price: the role of policy uncertainty in the era of the 4th industrial revolution and the effect of COVID-19 pandemic. *Technol. Forecast. Soc. Chang.* 163:120434. doi: 10.1016/j.techfore.2020.120434

Vogiatzoglou, K. (2009). Determinants of Export Specialization in ICT Products: A Cross-Country Analysis. International Network for Economic Research - INFER. Available online at: https://infer-research.eu/wp-content/uploads/2020/09/yltv2bsdihkrb3rou3cyi00opy24m0fy1467292017.pdf (accessed March 15, 2021).

Wang, D., and Han, B. (2016). The impact of ICT investment on energy intensity across different regions of China. *J. Renew. Sustain. Energy* 8:055901. doi: 10.1063/1.4962873

Wang, D., Zhou, T., and Wang, M. (2021). Information and communication technology (ICT), digital divide and urbanization: evidence from Chinese cities. *Technol. Soc.* 64:101516. doi: 10.1016/j.techsoc.2020.101516

Wang, H., Ding, L., Guan, R., and Xia, Y. (2020). Effects of advancing internet technology on Chinese employment: a spatial study of inter-industry spillovers. *Technol. Forecast. Soc. Chang.* 161:120259. doi: 10.1016/j.techfore.2020.120259

Wang, R., Mirza, N., Vasbieva, D. G., Abbas, Q., and Xiong, D. (2020). The nexus of carbon emissions, financial development, renewable energy consumption, and technological innovation: what should be the priorities in light of COP 21 Agreements? *J. Environ. Manag.* 271:111027. doi: 10.1016/j.jenvman.2020.111027

Wang, Y., and Li, J. (2019). Spatial spillover effect of non-fossil fuel power generation on carbon dioxide emissions across China's provinces. *Renew. Energy* 136, 317–330. doi: 10.1016/j.renene.2019.01.012

World Bank (2020). *Consumer Price Index*. Washington, DC: World Bank.

Wu, X. D., Guo, J. L., Li, C., Chen, G. Q., and Ji, X. (2020). Carbon emissions embodied in the global supply chain: intermediate and final trade imbalances. *Sci. Total Environ.* 707:134670. doi: 10.1016/j.scitotenv.2019.134670

Xu, M., and Tan, R. (2021). Removing energy allocation distortion to increase economic output and energy efficiency in China. *Energy Policy* 150:112110. doi: 10.1016/j.enpol.2020.112110

Zhang, N., Wang, B., and Liu, Z. (2016). Carbon emissions dynamics, efficiency gains, and technological innovation in China's industrial sectors. *Energy* 99, 10–19. doi: 10.1016/j.energy.2016.01.012

Zhou, X., Zhou, D., Wang, Q., and Su, B. (2019). How information and communication technology drives carbon emissions: a sector-level analysis for China. *Energy Econ.* 81, 380–392. doi: 10.1016/j.eneco.2019.04.014

Zhu, B., and Zhang, T. (2021). The impact of cross-region industrial structure optimization on economy, carbon emissions and energy consumption: a case of the Yangtze River Delta. *Sci. Total Environ.* 778:146089. doi: 10.1016/j.scitotenv.2021.146089

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.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 04 June 2021
doi: 10.3389/fenrg.2021.696110

Financing Advantage of Green Corporate Asset-Backed Securities and its Impact Factors: Evidence in China

Yunfeng Zhao, Yiming Yue and Ping Wei *

Business school, Central South University, Changsha, China

As an innovative green financial tool, green corporate asset-backed securities can effectively solve the problems of narrow financing channels and maturity mismatches for green projects, which can help achieve green and low-carbon development, carbon peaking, and carbon neutrality goals. In this paper, we examine the financing cost advantages of green corporate asset-backed securities and the related impact factors through a combination of empirical and case studies. Empirical research based on the propensity score matching method (PSM) shows that China's green corporate asset-backed securities issuance rates are 36.97°bps lower than traditional corporate asset-backed securities on average. Credit rating, issuance scale, issuance interest rate, issuance period, and green factors have become the main impact factors of green corporate asset-backed securities financing advantages.

Keywords: green finance, asset securitization, green assets, issuance pricing, static spread method JEL classification: G21

OPEN ACCESS

Edited by:
Kangyin Dong,
University of International Business and Economics, China

Reviewed by:
Fujing Jin,
Beijing Jiaotong University, China
Jing Zhang,
Shandong University of Finance and Economics, China
Wei Bao,
Hunan University of Technology and Business Changsha Shi, China

***Correspondence:**
Ping Wei
pwei@csu.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *16 April 2021*
Accepted: *21 May 2021*
Published: *04 June 2021*

Citation:
Zhao Y, Yue Y and Wei P (2021) Financing Advantage of Green Corporate Asset-Backed Securities and its Impact Factors: Evidence in China. Front. Energy Res. 9:696110. doi: 10.3389/fenrg.2021.696110

INTRODUCTION

Industrialization has spurred long-term and rapid economic growth in China. However, the high levels of inputs and consumption have also increased the incidents of environmental pollution and ecological destruction. Studies have shown that the annual economic loss caused by environmental pollution in China is 0.6–1.8 trillion yuan, accounting for up to 3.05% of total GDP. The environmental carrying capacity has approached its limit, which makes the environmental problem one of the biggest practical challenges for China and all the rest of the world as well (Fang and Guo, 2018; Wang and Chen, 2018; UNEP, 2021). On September 22, 2020, the Chinese government announced at the General Assembly of the United Nations that China will strive to peak carbon dioxide emissions by 2030 and achieve "carbon neutrality" before 2060. At the Climate Ambition Summit (the commemorative meeting for the signing of the Paris Agreement) held on December 12 of the same year, Chinese President Xi Jinping made this same commitment in his statement. In this context, the development of green industry with the purpose of environmental protection has become an important part of accelerating China's economic transformation. The latest evidence shows that investment in green projects in China can reduce China's short- and long-term carbon emissions levels (Li et al., 2021). However, when a company develops a green project, it often requires a long period of time to pay back loans taken out to fund the project; thus, for the lending bank, the risks and benefits often do not meet the bank's typical standards. Banks have become less willing to provide long-term loans for green projects, so it is difficult for companies to obtain the required funds at low cost, which greatly affects the development speed and quality of green projects.

As a new instrument of financial innovation, green asset backed securitization is regarded as one of the most important parts of a green financial system. Since only the credit rating of corporate green assets is performed, the rating is less affected by the financial status of corporate entities. Green asset securitization allows companies to issue green products with lower financing thresholds and financing costs. Before China's green asset securitization was supported and promoted by government agency, green credit was the main channel of green financing. The implementation of China's green credit policy reduces the risks for non-state-owned banks, while state-owned banks provide green credit at the expense of profits. This institutional design makes the Chinese government a global pioneer in the greening of the financial markets (Yin et al., 2021).

China's asset securitization market has developed rapidly over the past decade, evolving from approximately US $2.14 billion at the end of 2005 to approximately US $405 billion at the end of 2018, and it has become the largest securitization market in Asia (Yang et al., 2020). As the Chinese government is committed to building the green financial system and promoting the rapid development of asset securitization, its pilot asset securitization program has been continuously expanded and has become a pivotal component of the world's securitization market. At the same time, Seven Ministries such as the People's Bank of China vigorously promote the securitization business with green credit and PPP projects serving as the basic assets. In September 2015, the State Council of China published the "General Plans for the Reform of the Ecological Civilization System", which places more emphasis on the green economy, significantly boosting green asset securitization. With the development of green asset securitization in China, the issuance of green corporate asset-backed securities has experienced a high rate of growth year by year. However, the pricing of green corporate asset-backed securities issued can vary greatly by institution.

In this paper, we use a combination of empirical research and case analysis to examine the issuance and pricing of green corporate asset-backed securities and their pricing factors, which will promote the development of green finance in China. First, we use Propensity Score Matching (PSM) to examine whether green corporate asset-backed securities have certain issuance cost advantages. Second, we analyze the impact factors of the financing costs of China's first "Labelled" green corporate asset-backed securities ("Goldwind 2016-1") through the Static Spread method, and we put forward corresponding development suggestions.

Our study contributes to the literature in the following three aspects. First, the project "Goldwind 2016-1" issued by the Shanghai Stock Exchange in August 2016 is the first green asset securitization project in China to be double certified by an internationally renowned green certification agency, which makes the project highly representative. We use this representative project to conduct case studies to provide strong evidence for the advantages and pricing of green securities. Second, the study of the impact factors of green corporate asset-backed securities provides the most intuitive evidence for the current issue pricing of green corporate asset-backed securities in China, and it provides a reference for other green enterprises as they seek to issue green corporate asset-backed securities. Third, our research expands the literature on green asset securitization, and helps companies and governments pay more attention to green asset securitization to promote carbon neutrality

The remainder of the paper proceeds as follows. In *Literature Review*, we provide the literature review. In *Methodology and Data*, we describe the methodology and data. *Empirical Analysis* presents the analysis results and discussion. In *Factors Affecting the Issuance Pricing of Green Corporate Asset-Backed Securities*, we present the pricing factors of green corporate asset-backed securities. In *Conclusion and Recommendations*, we conclude the paper and provide some recommendations.

LITERATURE REVIEW

China's financial industry has been in the situation of "Supervision Segregation" for a long time. The asset securitization market is divided into three markets: the inter-bank market, the securities exchange market, and the insurance fund market. The green asset securitization business can also be divided into three types according to the different regulatory agencies: green credit asset securitization, green asset-backed notes, and green corporate asset-backed securities. These differences are shown in **Table 1**.

The existing research on China's green asset-backed securities mostly focuses on the theoretical and policy levels; however, the discussion of the advantages of financing costs and impact factors is relatively limited.

The Development Path of China's Asset Securitization

The development of China's asset securitization has gone through a stage of theory first and then practice. As early as 1992, scholars conducted theoretical discussions, but it was not until 2005 that the pilot work of asset securitization began. However, the emergence of the global economic crisis caused Chinese regulators to adopt a cautious attitude until 2014. Since then, China's asset securitization market has begun to grow rapidly. By the end of 2018, it reached approximately US $405 billion, making it the largest asset securitization market in Asia. With the gradual integration of the Chinese financial market and the global financial market, more international investors will give the Chinese asset securitization market the potential to become an indispensable part of the world securitization market (Yang et al., 2021).

China adopts stricter divisional supervision in financial supervision, and the supervision coordination mechanism plays a relatively limited role. Therefore, supervision of asset securitization is facing greater problems (Wang and Li, 2016). As far as asset securitization itself is concerned, stricter regulatory constraints are required for the following reasons: First, there are

TABLE 1 | Comparison of three modes of green asset securitization.

Business model	Green credit asset securitization	Green enterprise asset backed securities	Green asset backed notes
Initiator	Banking financial institutions	Non financial enterprises and some financial enterprises	Non financial enterprises
Administration	the People's Bank of China, China Banking Regulatory Commission	China Securities Regulatory Commission	National Association of Financial Market Institutional Investors
Audit method	Filing system	Record system	Filing system
Registered Trustee	China Government Securities Depository Trust and Clearing Co. Ltd. (CDC)	China Securities Depository and Clearing Company Limited(CSDCC)	ShangHai ClearingHouse
Trading Places	National Interbank Bond Market	Stock Exchange, Inter agency quotation and service system	National Interbank Bond Market
Basic Assets	Bank credit assets	Earning rights or creditor's rights for built projects, which can be a collection of rights, which clearly include infrastructure income rights	Beneficial rights or creditor's rights of the built project, which can be a collection of rights
Special Purpose Carrier	Special purpose trust	asset-backed securities of securities companies/ fund companies	It is not mandatory to establish an independent special purpose carrier
Rules and Regulations	"the Notice on Reporting and Registration Procedures of Credit Assets Securitization", "Measures for the Supervision and Administration of Pilot Credit Asset Securitization Business of Financial Institutions"	"Provisions on Administration of the Asset Securitization Business of Securities Companies and Fund Management Subsidiaries"	"the Business Guidelines for Non-Financial Enterprise Project Revenue Notes on the Interbank Bond Market"

more entities participating in asset securitization, and the risk characteristics are complex; second, asset securitization makes the relationship between traditional financing intermediaries and the capital market closer; third, the basic function of asset securitization will increase the instability of the financial system.

From the existing literature, many scholars have focused on the research of regulatory policies on the asset securitization of the banking industry. (Acharya et al., 2013) conducted an empirical analysis based on the data of US commercial banks and pointed out that the tightening of regulatory constraints, the banking industry will have stronger incentives to carry out asset securitization business. This is because the bank implements asset securitization to reduce the proportion of its own risk assets to meet the minimum capital regulatory requirements (Ambrose et al., 2005). (Song and Zhang 2016) based on the perspective of international comparison, discussed the issue of self-retention supervision of China's asset securitization risk, put forward the shortcomings of current China's risk self-retention supervision rules and put forward corresponding suggestions. (Li et al., 2019) empirically tested the two methods of regulatory arbitrage for bank asset securitization in my country based on the data from 2012 to 2018. The study found that the possibility of arbitrage between banks using regulatory differences is very small.

Regarding the research on asset securitization, most scholars have focused on the theoretical level, such as the definition of asset securitization, issuance pricing, impact factors analysis, and policy recommendations.

A common view is that asset securitization is a collection of assets that are insufficiently liquid but expected to have a certain return in the future, and a structural reorganization and package sale are required to obtain cash flow in advance (Rosenthal and Ocampo, 1988). In terms of issuance pricing, there are two commonly used pricing methods. One is the absolute pricing method, which refers to the calculation of the sum of the discounted value of the product's underlying assets in the future as pricing. The other is the relative pricing method, which refers to the yields of comparable asset-backed securities with the same rating in the same period and floats a certain spread based on the benchmark interest rate for pricing calculations. Regarding the factors affecting issuance pricing, the research on China's asset-backed securities has mainly focused on the credit rating (Kou et al., 2015), and some scholars have also conducted research using investor sentiment and credit enhancement methods (Shao et al., 2015). In general, the impact factors of issuance pricing show heterogeneity according to the characteristics of the bond and the issuer or the issuance market.

China's Green Asset Securitization

China is a country with a large population and large scale of industry, which makes its carbon emissions play a decisive role in achieving the global carbon neutral goal. As of 2015, China's carbon emissions accounted for 30% of global emissions (Shan et al., 2018). Existing studies have discussed the influencing factors of carbon emission reduction. For example, technological innovation is generally recognized as promoting the reduction of carbon emissions (Yu and Du, 2019; Chen and Lee, 2020; Jiang et al., 2020; Shahbaz et al., 2020; Cheng et al., 2021).In the research on China, the development of natural gas infrastructure construction and the actual urbanization rate are pointed out as influencing factors that can significantly reduce carbon emissions (Shuai et al., 2018; Dong et al., 2020a), and the industrial distribution leads to significant reductions in carbon emissions (Shuai et al., 2018; Dong et al., 2020b). In addition, appropriate environmental regulations have been proven to have a positive impact on carbon emissions reduction (Zhao et al., 2020). There are also some studies focusing on the influencing factors of carbon prices, such as energy prices, oil supply and demand shocks, etc., which have been pointed out to have asymmetrical negative effects on carbon prices (Duan et al., 2021; Zheng et al., 2021).

The Chinese government has been committed to promoting the achievement of environmental protection goals from the policy level. In 2016, China has achieved outstanding achievements in green financial products, tools, methods, and policies. Under the green corporate asset-backed securities mechanism, companies can package the cash flow generated by the green projects they own in a specific time in the future. Also, they can use the packaged cash flow as the basic asset to issue tradable securities. Green corporate asset-backed securities provide a new financing method for green enterprises. As China attaches importance to the concept of green development and the development of asset securitization, green asset securitization has received extensive attention from issuers and investors. However, China's research on green asset securitization has focused more on theoretical aspects, such as exploring its development advantages and making path optimization suggestions. The analysis of the issuance costs, micro-price impact mechanisms, and financing benefits generated in the financing process is still in the exploratory stage.

The core of China's green asset securitization development lies in its unique financing advantages. These include lowering the financing threshold, thereby facilitating the financing efficiency of green industries. At the same time, green project standards, information disclosure systems, and policy incentives can effectively promote the development of green asset-backed securities, but in the end, we need to rely on a complete green financial market system. There are also some problems in the development of China's green asset securitization. For example, some scholars have pointed out that China's green asset-backed securities at the emergence stage have problems such as mismatches in the financing scale, high financing costs, and uncertain cash flow for green projects, and the financing model needs to be further optimized.

Issuance Pricing and Impact Factors of Green Asset-Backed Securities

Since the 2007 financial crisis, many academic research have focused on asset-backed securities and institutions involved in issuing these products. Foreign scholars have explored the pricing factors of structured products. In terms of credit rating, (Moreira and Zhao 2018) pointed out that there is a big connection between ABS ratings and their yield spread at issuance in the US market, Credit ratings may affect investors' investment decisions during the issuance stage. Fabozzi and Vink (2012) explored the influencing factors of asset-backed securitization in the European market, indicating that investors will consider other credit factors such as credit enhancement and underlying assets in addition to credit ratings. In terms of sponsor characteristics, (Faltin-Traeger et al., 2010) pointed out that the quality of sponsors will have an important impact on ABS pricing. (He et al., 2012) also confirmed that issuers with a larger market share in the US market are more likely to receive an inflated rating. Regarding China's asset-backed securities market, (Tang et al., 2017) based on the Chinese securitization market and found that China's asset securitization market is policy-driven, and the underlying assets are composed of corporate loans and assets, unlike the US or European markets, which is composed of secured or consumer loans. (Yang et al., 2020) explored the pricing factors of asset-backed securities in China's leasing industry in an empirical and comprehensive way. The study found that when the promoter is closely related to the underlying assets sold to special purpose vehicles (SPVs) investors will pay special attention to the credit quality of the promoter.

In general, the research on asset securitization in foreign countries is relatively complete, and great progress has been made in terms of the regulatory issues and influencing factors of asset-backed securities. Compared with China, asset-backed securities started late and focused more on the theoretical level, with fewer actual case discussions.

China's green asset-backed securities market belongs to the emerging development field of green bonds. Many studies have posited that there is indeed a spread between green bonds and ordinary bonds, which affirms the positive significance of the development of green bonds (Mathews et al., 2010; Yao, 2017; MacAskill et al., 2021). In terms of the research on the factors affecting the issuance interest rate, the mainstream view is that green bonds are similar to traditional bonds. That is, the support of macro and micro factors such as market interest rates, bonds, and the characteristics of the issuer can affect the green bond issuance rate. Environmental benefits and government support are also considered important factors affecting the pricing of green asset-backed securities.

In summary, the research on green asset-backed securities in China has thus far conducted only a limited discussion of the financing cost advantages and impact factors. In this paper, we use a combination of empirical research and case analysis to explore the issuance and pricing of green corporate asset-backed securities and their impact factors. This work has a certain role in promoting China's green finance development and green enterprise asset securitization pricing theory.

METHODOLOGY AND DATA

Sample Selection and Data Sources

To compare and analyze the difference in the issuance pricing of green corporate asset-backed securities and traditional corporate asset-backed securities, we select all enterprise asset securitization products that were traded on exchanges (Shanghai Stock Exchange and Shenzhen Stock Exchange) from January 2012 to May 2019, and we screen them according to the following criteria: (Acharya et al., 2013) remove the delisted bond samples; (Ambrose et al., 2005) remove the progressive interest rate and floating interest rate samples; (Chen and Lee, 2020) remove the samples with incomplete data; and (Cheng et al., 2021) remove the mezzanine and sub-product samples. The final bond sample is 5,092, consisting of 167 green corporate asset-backed securities products and 4,925 traditional asset-backed

TABLE 2 | Variable definition.

Variable	Indicator name	Symbol	Index Description
Explained variable	Issuance rate	Rate	Coupon interest rate at the time of corporate asset-backed securities product issuance
Explanatory variables	Green factor	Green	Dummy variable, if the sample is a green corporate asset-backed securities product, assign a value of 1, otherwise assign a value of 0
Covariate	Credit Rating	Credit_Rate	Dummy variable, assign value to credit rating. AAA=9, AA+=8, AA=7, AA-=6, A+=5, A=4, A-=3, BBB+=2, BBB-=1
	Issuance period	LnMaturity	The logarithm of the issuance period, which measures the length of time between the issuance date and the expiration date
	Issuance scale	LnSize	The logarithm of the total issuance, which measures the scale of the sample issuance
	Market interest rate	Shibor	Select the 1°year Shanghai Interbank Offered Rate (SHIBOR) as the market interest rate

securities products. The variables used in this paper are shown in **Table 2**. The data comes from the WIND database, the China Bond Information Network, the China Asset Securitization Analysis Network, and the China Financial Information Network Green Bond Database.

Models

Propensity Score Matching Method

To accurately identify the impact of green factors, it is necessary to ensure that in the two sets of samples, except for the green attributes, there are no systematic differences in other variables related to the issuance rate. Therefore, we adopt the Propensity Score Matching method (PSM) for empirical research. The specific steps are as follows. First, the samples are divided into a test group and a control group according to whether they are green corporate asset-backed securities products. The sample of the test group is a green corporate asset-backed securities product; that is, the value of the "Green" variable is 1. The samples of the control group are traditional corporate asset-backed securities products; that is, the value of the "Green" variable is 0.

Second, a Logit model of factors affecting enterprise asset securitization product issuance pricing is established to estimate the conditional probability of each sample entering the test group. The impact factors in the model include the credit rating, bond maturity, issuance scale, and market interest rate. The Logit model is shown in formula **Eq. 3.1**:

$$P(Green_i = 1|X_i) = \alpha_0 + \beta_1 Credit\_rate_i + \beta_2 \ln Maturity_i + \beta_3 \ln Size_i + \beta_4 Shibor_i \tag{3.1}$$

Among them: α_0 is the constant term, ε is the error term, and $\alpha_i(i=1,2,3,4)$ is the coefficient.

Finally, we calculate the propensity score value of each sample in the test group and the control group, and we match the control sample with the closest score for the test group sample.

Static Spread Method

The static spread method has made improvements to the discount factor. This method holds that the discount rate cannot be simply expressed by a fixed number. Combined with the theory of the term structure of interest rates, the corresponding interest rates are not consistent across different maturities. Based on this, the static spread method considers the spot interest rate (r_t) of the national debt and the fixed spread (ss) to discount the future cash flow when determining the issuance pricing of the product. The calculation method is shown in formula **Eq. 3.2**:

$$P = \frac{CF_1}{1 + r_1 + ss} + \frac{CF_2}{(1 + r_2 + ss)^2} + \ldots + \frac{CF_n}{(1 + r_n + ss)^n} = \sum_{t=1}^{n} \frac{CF_t}{(1 + r_t + ss)^t} \tag{3.2}$$

Among them, P represents the product price, CF_t represents the cash flow in the t period, r_t represents the spot interest rate in the t period, and ss represents the fixed spread. This method incorporates the term structure of interest rates and fixed spreads into the model to reflect the difference in interest rate levels at different points in time and the risk premium of different assets; this approach can more accurately measure product prices.

TABLE 3 | Descriptive statistics of the sample.

Variable	Mean	Std. Dev.	Min	Max	Observation
Green corporate asset-backed securities (Green=1)					
Rate	5.3622	1.0791	3.10	7.50	167
Credit_Rate	8.7365	0.5287	5	9	167
LnMaturity	1.1353	0.8485	−1.47	2.7	167
LnSize	0.0238	0.8613	−2.66	2.4	167
Shibor	3.7943	0.6511	3.03	4.75	167
Traditional corporate asset-backed securities (Green=0)					
Rate	5.5549	1.0573	0.5	10	4925
Credit_Rate	8.7283	0.5295	1	9	4925
LnMaturity	0.5271	0.9076	−3.82	3.77	4925
LnSize	0.7445	1.3745	−4.61	4.17	4925
Shibor	3.7324	0.6233	3.03	5.19	4925

EMPIRICAL ANALYSIS

Descriptive Statistics

The descriptive statistics of the sample are shown in **Table 3**. The explanatory variable issuance interest rate has a certain

TABLE 4 | Results of average treatment effect.

Matching methods	Mean (Test group)	Mean (Control group)	Difference value and significance level (%)
K Nearest Neighbor (K=3)	5.3622	5.7549	−0.3927[a] (−4.06)
Radius	5.3622	5.6765	−0.3143[a] (−3.68)
Kernel	5.3622	5.6997	−0.3375[a] (−3.94)
Local Linear Regression	5.3622	5.7460	−0.3838[a] (−3.53)
Mahalanobis	5.2067	5.6268	−0.4201[a] (−0.83)

The column of difference value and significance level is the difference between the mean value of the treatment group and the control group; that is, the average treatment effect (ATE). The t *statistic is in parentheses,*
[a]*where means significance at the 1% level.*

difference between green corporate asset-backed securities (the test group) and traditional corporate asset-backed securities (the control group). The average issuance interest rate of the test group is 19.27°bps lower than that of the control group. This preliminarily shows that China's green corporate asset-backed securities products are issued at low interest rates and have certain financing cost advantages. Among the covariates, the credit rating and issuance period of the test group are higher, while the issuance scale is lower. This is in line with our current understanding of the characteristics of green corporate asset-backed securities issuance. Since most of the green enterprises have undergone green certification and involve industries such as public utilities and natural resources, their company credit is relatively good. However, these industries typically have a long payback period for borrowed funds, so their financing periods are relatively high. At the same time, green enterprises are generally based on small and medium-sized enterprises with limited capital scale and capital demand, so the scale of issuance is relatively small.

Main Results

This paper uses a variety of matching methods (K Nearest Neighbor matching, radius matching, kernel matching, local linear regression matching, and Markov matching) to calculate and match the Propensity Score (PS). After the matching is completed, the average treatment effect (ATE) is calculated to examine whether the green enterprise asset securitization has an issue cost advantage. The regression results of the Logit model are shown in **Table 4**. The use of different matching methods results in a difference in the average issuance interest rate between the matched sample and the control group, but the average issuance interest rate of the test group is almost the same. The results obtained by different matching methods are similar, and the average treatment effect is between −31.43 and −42.01°bps, and is significant at the 1% level. Based on this, we can believe that green factors have significantly reduced the issuance interest rate of green corporate asset-backed securities, and the issuance interest rate of green corporate asset-backed securities is 36.97°bps lower than the absolute value of traditional enterprise asset-backed securitization.

Before using the PSM method, the hypothesis of matching balance needs to be tested to verify the reliability of the matching results. We take K-nearest neighbor matching (K = 3) as an example to illustrate the test results. The specific results are shown in **Table 5**. Comparing the results before matching, the standard deviations of all variables after matching are significantly reduced and less than 10%, which shows that the matching method and matching samples used in this paper are reliable. At the same time, according to the *t*-test results, the t-statistics of all variables are not significant after matching, indicating that there is no systematic difference between the test group and the control group, so the matching method satisfies the balance hypothesis to be verified.

Further, in order to discover whether there is a temporal trend in this green premium, we use the year grouping propensity score matching method for matching and testing (with K Nearest Neighbor). The results showed that with the exception of 2017, the other groups showed significant differences. This may be due to the emergence of a large number of innovative green bond products in 2017 and the first sale of green financial bonds to individual investors in the over-the-counter market (OTC). From the perspective of time, the issuance interest rate of green corporate asset-backed securities is lower than that of traditional securities. The results are shown in **Table 6** and **Figure 1**

Case Analysis: Goldwind 2016-1

On the basis of empirical analysis, we further adopt the method of case analysis to test the spread advantage of green asset securitization products. In this paper, the static spread method is used to measure the issuance pricing of the "Goldwind 2016-1" products. This method uses the overall yield curve to determine the price of securitized bonds, which is suitable for the pricing of securitized products with relatively uniform cash inflows. The cash flow inflows of "Goldwind 2016-1" products are more evenly distributed in each period, and more accurate results can be obtained based on the static spread method for pricing measurement. Above all, determining the spot interest rate of the Chinese national debt and the cash flow on the repayment date of the "Goldwind 2016-1" products during the same period. Then, according to the spot interest rate on the principal and interest payment date, the interest calculation period, and the cash flow on the payment date, the static spread method is used to calculate the static spread of A1 – A5 senior securities through formula **Eq. 4.1**.

TABLE 5 | Propensity score matching balance test results.

Variables		Mean (Test group)	Mean (Control group)	Std. Dev. (%)	Reduction of Std. Dev. (%)	t stat	p>|t|
Credit_Rate	Before	8.7365	8.7283	1.6	−21.7	0.20	0.844
	After	8.7365	8.7465	−1.9		−0.19	0.853
LnMaturity	Before	1.1353	0.5271	69.2	90.2	8.53	0.000
	After	1.1353	1.1946	−6.7		−0.62	0.537
LnSize	Before	0.0238	0.7447	−62.9	87.1	−6.73	0.000
	After	0.0238	0.1170	−8.1		−0.79	0.429
Shibor	Before	3.7943	3.7324	9.7	69.4	1.26	0.208
	After	3.7943	3.7753	3.0		0.27	0.789

TABLE 6 | Results of average treatment effect grouped by year.

Year	Mean (Test group)	Mean (Control group)	Difference	S.E.	T-stat
2014	5.2195	6.1992	−0.9797***	0.3200	−3.06
2015	5.3670	5.8459	−0.4790***	0.1071	−4.47
2016	5.3622	5.6781	−0.3160**	0.1277	−2.47
2017	5.4234	5.5652	−0.1418	0.1029	−1.38
2018	5.3440	6.3608	−1.0168***	0.1139	−8.93
2019	5.2481	5.9810	−0.7329***	0.1940	−3.78

**** means significant at the 1% level, ** means significant at the 5% level, * means significant at the 10% level.*

$$
\begin{aligned}
100 &= \frac{35.9240}{(1+2.1759\%+\Delta ss)^{0.5014}}+\frac{66.8992}{(1+2.2155\%+\Delta ss)^{0.9973}}100\\
&= \frac{1.8148}{(1+2.1759\%+\Delta ss)^{0.5014}}+\frac{1.7852}{(1+2.2155\%+\Delta ss)^{0.9973}}\\
&+\frac{52.9748}{(1+2.2994\%+\Delta ss)^{1.5014}}+\frac{49.7119}{(1+2.3331\%+\Delta ss)^{1.9973}}100\\
&= \frac{1.9660}{(1+2.1759\%+\Delta ss)^{0.5014}}+\ldots+\frac{44.8509}{(1+2.4343\%+\Delta ss)^{2.9973}}100\\
&= \frac{2.1173}{(1+2.1759\%+\Delta ss)^{0.5014}}+\ldots+\frac{47.5851}{(1+2.5150\%+\Delta ss)^{3.9973}}100\\
&= \frac{2.2685}{(1+2.1759\%+\Delta ss)^{0.5014}}+\ldots+\frac{46.8760}{(1+2.5793\%+\Delta ss)^{4.9973}}
\end{aligned}
\tag{4.1}
$$

Since the cash flow of subordinated securities is not stable, and the coupon rate is not fixed, it is impossible to measure the static spread. The static spread calculation results of the priority securities of the "Goldwind 2016-1" products at all levels are shown in **Table 7**:

To facilitate the assessment of the pricing of the coupon rates of the various senior securities of the "Goldwind 2016-1" green corporate asset-backed securities, we compare the spread between the yields of traditional corporate asset-backed securities issued with the same maturity and the same credit rating and the yields of treasury bonds. The specific situation is shown in **Table 8**:

Table 7 shows that the static spreads of the various senior securities of the "Goldwind 2016-1" products are lower than the spreads between the yields of comparable issued traditional corporate asset-backed securities and the yields of treasury bonds. This shows that compared with traditional corporate asset-backed securities, the coupon rate of "Goldwind 2016-1" green corporate asset-backed securities is relatively low at the time of issuance, and there is a certain "green" advantage in issuance costs.

TABLE 7 | Static spreads of assets at all levels.

Priorities	A1	A2	A3	A4	A5
Interest calculation period (years)	1	2	3	4	5
Static spread (%)	1.21	1.31	1.53	2.03	2.23

FACTORS AFFECTING THE ISSUANCE PRICING OF GREEN CORPORATE ASSET-BACKED SECURITIES

The public utility attributes of green corporate asset-backed securities usually enable them to obtain policy-oriented support. First, their lower credit risk will lead to higher credit ratings. Based on the decline in risk concerns, the higher liquidity brought about by the large issuance scale has become apparent. Secondly, policy support makes their marketization degree slightly lower than that of traditional products. Moreover, green attributes bring higher policy incentives and active information disclosure. Finally, the long-term investment tendency of investors in green corporate asset-backed securities makes them have lower requirements for liquidity compensation. These attributes enable green corporate asset-backed securities to be issued with lower interest rate pricing.

Credit Rating

The credit rating of asset-backed securities is the credit rating given to each file by a third-party rating agency when the product is issued. Different from the factors considered in traditional bond ratings, it is a comprehensive consideration of the transaction structure and credit enhancement measures of the issued products, the credit quality of the entire asset pool, and the order of securities repayment. Therefore, the higher the rating of the corporate asset-backed securities, the lower the probability of credit risk events and the lower the interest rate pricing should be (Elton et al., 2001). Green corporate

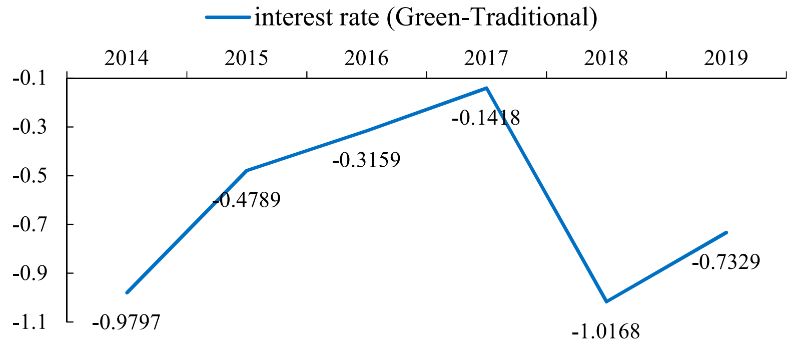


FIGURE 1 | Time trend chart of issuance interest rate difference.

TABLE 8 | The spread of corporate asset-backed securities yield (AAA) and treasury bond yield.

Term (years)	1	2	3	4	5
Treasury bond yield (%)	2.2157	2.3331	2.4343	2.5150	2.5793
Enterprise asset-backed securities yield (%)	5.1208	5.3089	5.4583	5.7937	6.2073
Spread (%)	2.9051	2.9758	3.0240	3.2787	3.6280

The data source is Wind database.

asset-backed securities mostly involve industries such as natural resources, environmental protection, and new energy. They have certain attributes of public welfare or public resources, and they have a certain degree of policy orientation, so the risk of default is low. In addition, when some green corporate asset-backed securities are issued, professional institutions will be hired to fully evaluate the company's business and financial status and carry out green certification to reduce the company's environmental risks. Therefore, green corporate asset-backed securities usually have a relatively high credit rating, which helps green enterprises reduce their financing costs. Take the "Goldwind 2016-1" priority A1 level as an example. In the same year, all products except the "Rongyin 1 Optimization 6" (code: 142017) and the "Xingxin A4" have higher issuance rates than the "Goldwind 2016-1" priority A1 level. This shows that the "Golden Wind Green 2016-1" relies on the advantages of green attributes and the dual green certification of Det Norske Veritas and the International Finance Corporation (IFC) to reduce enterprise environmental risks and enhance the credibility of the company and its pooled assets. This reduces the risk of enterprise default, thereby reducing the product's issuance interest rate.

Issuance Period

Based on the theory of the term structure of interest rates, bond coupon rates and bond maturity are correlated. Long-term interest rates are generally higher than short-term interest rates. Therefore, there is a positive correlation between maturity and bond issuance interest rates. According to the liquidity premium theory, bond maturity is positively correlated with bond price fluctuations caused by changes in interest rates.

Therefore, long-term bonds need to give a certain liquidity premium (interest rate compensation) to the interest rate risks in order to attract investors. Similar to ordinary securitization products, the longer the issuance period, the higher the issuance interest rate of the green enterprise securitization products. However, as the maturity period increases, the increase in the issuance rate of traditional corporate asset-backed securities will be greater than the increase in the issuance rate of green corporate asset-backed securities.

The reason for this is that investors' liquidity compensation requirements for green corporate asset-backed securities will be lower than for traditional corporate asset-backed securities. In practice, we find that green corporate asset-backed securities investors are more inclined to make long-term investments, and their preference for liquidity is weaker than that of traditional corporate asset-backed securities investors.

This is reflected in the fact that, according to the Wind database, China's green enterprise securitization products are mainly mid- to long-term, and products with an issuance maturity of more than 3°years account for 48.31% of total products, and the average maturity is about 4°years.

Again taking the "Goldwind 2016-1" as an example, we compare it with the "Zhongmin 2016-1", which has a similar issuance time and a credit rating of AAA, which is a traditional corporate asset-backed securities product. With the increase in bond maturity, the increase in the issuance interest rate of the "Zhongmin 2016-1" (total increase of 1.70%) has significantly exceeded the increase of the issuance interest rate of the "Goldwind 2016-1" (total increase of 1.10%). For the level of the same issuance period, the issuance interest rate of the "Goldwind 2016-1" is still lower than the issuance interest rate of the corresponding product of "Zhongmin 2016-1". Moreover, for the same issuance maturity level, the issuance interest rate of the "Goldwind 2016-1" is still lower than the issuance interest rate of the corresponding "Zhongmin 2016-1" product.

This shows that investors in China's green asset securitization market are more inclined to make long-term investments. This makes green corporate asset-backed securities less sensitive to the issuance period and has certain green advantages. The issuance interest rate is significantly lower than that of traditional corporate asset-backed securities of a similar nature.

Issuance Scale

On the one hand, the larger scale of bond issuance means higher market recognition and better asset quality, as well as better liquidity. According to the liquidity premium theory, asset liquidity will affect the pricing level, and liquidity is negatively correlated with issuance interest rates. On the other hand, higher issuance usually means higher risk, and investors will worry about whether the company has sufficient repayment ability. Therefore, there will be higher interest rate expectations, which may mean that the larger the issuance scale, the higher the issuance interest rate. For green corporate asset-backed securities, the issuance scale of the product depends on the financing needs of the green enterprise. The larger the scale of the issuance, the greater the need for funds for green projects that the issuer invests in, and the more difficult it is to complete the project. The more investors demand compensation for this part of the risk, the higher the issuance rate of the green corporate asset-backed securities. We again take the "Goldwind 2016-1" priority A1 product as an example. Among all corporate asset-backed securities products with the same issuance period and credit rating in the same year, two green enterprise asset-backed products, the "G Goldwind A" (code: 131995) and the "G Gezhouba 1" (code: 142526) are with the highest issuance scale in the sample. However, as far as the issuance rate is concerned, the "G Goldwind A" and the "G Gezhouba 1" are the lowest in the sample except for the "Rongyin 1 Optimization 6" and the "Xingxin A4". From this we can determine that due to its large financing scale and green attributes, green companies have a higher recognition of investors in the asset securitization market, making them more liquid and able to successfully issue at lower interest rates.

Market Interest Rate

The market interest rate refers to the interest rate that changes with changes in the supply and demand relationship in the capital market. When market interest rates rise, in order to maintain a competitive advantage, the coupon rate of green corporate asset-backed securities will also rise, and vice versa. For green corporate asset-backed securities, in addition to the commonality of general asset securitization products, they are also supported by stronger policies. Therefore, compared with traditional asset securitization products, the degree of marketization is slightly lower. As market interest rates increase, the rate of increase in the issuance of green corporate asset-backed securities will be smaller than that of traditional corporate asset-backed securities. Taking the "Gold wind 2016-1" as an example, and by observing the yield curve of China's treasury bonds from 2015 to 2017, we can see that as market interest rates decrease, bond prices rise. This means that market investors have increased their risk aversion in the stock market and increased their demand for products in the bond market. Therefore, the company choosing to issue green corporate asset-backed securities at this time can effectively reduce financing costs.

Green Factors

As an innovative financing tool, green enterprise asset securitization can obtain financing in a low-cost manner by internalizing green factors at the financing end, and thus guide capital to flow into green projects. The fundamental difference between green corporate asset-backed securities and traditional corporate asset-backed securities lies in the investment direction of the raised funds. Green corporate asset-backed securities are exclusively invested in the construction and operation of green projects. Therefore, there are obvious "green" impact factors in the process of determining the interest rate of green corporate asset-backed securities issuance.

Taking the "Goldwind 2016-1" as an example, we can see that the negative effect of green factors on issuance interest rates is mainly reflected in two levels of policy incentives and information disclosure. In terms of policy incentives, the total amount of policy subsidies from Goldwind Technology, the original owner of the "Goldwind 2016-1" product, increased significantly from 2013 to 2016. Driven by government policies, the cash flow of the "Goldwind 2016-1" green corporate asset-backed securities project received strong support to reduce its default risk, so the issuance rate was low. In terms of information disclosure, green enterprise asset securitization issuers took the initiative to conduct green certification. Information disclosure was carried out in a timely manner, and the information that the product met the green bond certification requirements was conveyed to investors. Green certification played a role in supervising the project, reducing the risk of default, and thereby reducing the issuance rate of the "Gold wind 2016-1" green corporate asset-backed securities.

CONCLUSION AND RECOMMENDATIONS

As an innovative green financial tool, green corporate asset-backed securities can effectively solve the problems of narrow financing channels and maturity mismatches for green projects, which can provide strong support for achieving carbon neutrality goals and green development. We examine the financing cost advantages of green corporate asset-backed securities and its impact factors through a combination of empirical and case studies.

We find that during the sample research period, the issuance interest rate of green corporate asset-backed securities is 36.97˚bp lower than that of traditional corporate asset-backed securities on average, which has certain advantages in green enterprise financing. The issuance rate of "Goldwind 2016-1" green corporate asset-backed securities is lower than that of traditional corporate asset-backed securities of the same level. It is specifically manifested in the high product credit rating, low sensitivity of Chinese green asset securitization market investors to the issuance period, and large issuance scale.

Through the combing of the development of China's green corporate asset-backed securities market, and a comparative analysis of the issuance and pricing of green corporate asset-backed securities and traditional corporate asset-backed securities. We find that China's green corporate asset-backed securities have obstacles such as non-standard green certification, insufficient basic asset profitability, low level of development of the green product market, and lack of relevant policies and regulations for green asset securitization. The development of China's green enterprise asset securitization is still in its infancy, and the government is the main force to promote its development. The policy recommendations for this article are as follows:

Firstly, cultivate and attract long-term green investors. Investors' long-term attention to the securitization of green enterprise assets is very important to its sustainable development. Specifically, we can proceed from the following perspectives: Provide tax incentives for investors to purchase green enterprise asset securitization products, including interest income tax reduction and exemption for investors; The government participates in investment in the form of industrial funds to reduce the risks faced by social capital, or to provide financial discounts for the issuance of green enterprise asset securitization; Strengthen the promotion of the concept of carbon neutrality and green development, and guide investors to join the green investment market.

Secondly, standardize the development of the green certification market. Green third-party certification can help investors screen green financial products and reduce information asymmetry. To standardize the green certification market, first of all, we should formulate a unified green industry standard, complete green industry standard documents, and enhance the authority of the certification evaluation results. Secondly, cultivate and support local certification agencies. As China's green certification evaluation system started late, the market is mainly occupied by international agencies with years of professional knowledge and service experience. Therefore, it is necessary to support third-party green certification agencies with both professional capabilities and local positioning to promote the sustainable development of the green certification market with Chinese characteristics.

Thirdly, strengthen information disclosure. Continuous and transparent information disclosure is the key to ensuring the healthy development of green enterprise asset securitization. First, increase the market's emphasis on environmental information and strengthen public disclosure of environmental information; Secondly, improve the information sharing mechanism, and establish a comprehensive inter-departmental coordination mechanism through the development of green enterprise asset securitization involving government departments, financial institutions, and other social institutions, so as to ensure the orderly development of green asset securitization.

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

YZ is responsible for text writing and data analysis; YY is responsible for mechanism analysis and data collection; PW is responsible for research direction proposal and article modification guidance

FUNDING

This research was supported by the general project of the Hunan Natural Science Foundation (2019JJ40389) and the general project of the Hunan Social Science Foundation (18YBA432).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.696110/full#supplementary-material

REFERENCES

Acharya, V. V., Schnabl, P., and Suarez, G. (2013). Securitization without Risk Transfer. *J. Financial Econ.* 107 (3), 515–536. doi:10.1016/j.jfineco.2012.09.004

Ambrose, B. W., Lacour-Little, M., and Sanders, A. B. (2005). Does Regulatory Capital Arbitrage, Reputation, or Asymmetric Information Drive Securitization? *J. Finan Serv. Res.* 28, 113–133. doi:10.1007/s10693-005-4358-2

Chen, Y., and Lee, C.-C. (2020). Does Technological Innovation Reduce CO2 emissions? Cross-Country Evidence. *J. Clean. Prod.* 263, 121550. doi:10.1016/j.jclepro.2020.121550

Cheng, C., Ren, X., Dong, K., Dong, X., and Wang, Z. (2021). How Does Technological Innovation Mitigate CO2 Emissions in OECD Countries? Heterogeneous Analysis Using Panel Auantile Regression. *J. Environ. Manage.* 280, 111818. doi:10.1016/j.jenvman.2020.111818

Dong, K., Dong, X., and Jiang, Q. (2020a). How Renewable Energy Consumption Lower Global CO 2 Emissions? Evidence from Countries with Different Income Levels. 43(6): 1665–1698. doi:10.1111/twec.12898

Dong, K., Dong, X., and Ren, X. (2020b). Can Expanding Natural Gas Infrastructure Mitigate CO2 Emissions? Analysis of Heterogeneous and Mediation Effects for China. *Energ. Econ.* 90, 104830. doi:10.1016/j.eneco.2020.104830

Duan, K., Ren, X., Shi, Y., Mishra, T., and Yan, C. (2021). The Marginal Impacts of Energy Prices on Carbon price Variations: Evidence from a Quantile-On-Quantile Approach. *Energ. Econ.* 95, 105131. doi:10.1016/j.eneco.2021.105131

Elton, E. J., Gruber, M. J., Agrawal, D., and Mann, C. (2001). Explaining the Rate Spread on Corporate Bonds[J]. *J. Finance* 56 (1). doi:10.1111/0022-1082.00324

Fabozzi, F. J., and Vink, D. (2012). Looking beyond credit ratings: Factors investors consider in pricing European asset-backed securities. *Eur. Finan. Manag.* 18, 515–542.

Faltin-Traeger, O., Johnson, K. W., and Mayer, C. (2010). Issuer Credit Quality and the Price of Asset Backed Securities. *Am. Econ. Rev.* 100 (2), 501–505. doi:10.1257/aer.100.2.501

Fang, Y., and Guo, J. (2018). Is the Environmental Violation Disclosure Policy Effective in China? —Evidence from Capital Market Reactions. *Econ. Res. J.* 53 (10), 158–174.

He, Jie., Jun, Q. Q., and Strahan, P. (2012). Are All Ratings Created Equal? the Impact of Issuer Size on the Pricing of Mortgage-Backed Securities[J]. *J. Finance* 67 (6). doi:10.1111/j.1540-6261.2012.01782.x

Jiang, H., Dong, X., Jiang, Q., and Dong, K. (2020). What Drives China's Natural Gas Consumption? Analysis of National and Regional Estimates. *Energ. Econ.* 87, 104744. doi:10.1016/j.eneco.2020.104744

Kou, Z., Pan, Y., and Liu, X. (2015). Does Credit Rating Really Affect Debt Issuance Costs in China?[J]. *J. Financial Res.* (10), 81–98.

Li, J., Yin, P., and Qiu, X. (2019). Is There Regulatory Capital Arbitrage in China's Banking Asset Securitization? *Financial Regul. Res.* (11), 36–49. doi:10.13490/j.cnki.frr.2019.11.003

Li, Z.-Z., Li, R. Y. M., Malik, M. Y., Murshed, M., Khan, Z., and Umar, M. (2021). Determinants of Carbon Emission in China: How Good Is Green Investment? *Sustainable Prod. Consumption* 27, 392–401. doi:10.1016/j.spc.2020.11.008

MacAskill, S., Roca, E., Liu, B., Stewart, R. A., and Sahin, O. (2021). Is There a green Premium in the green Bond Market? Systematic Literature Review Revealing Premium Determinants. *J. Clean. Prod.* 280 (P2), 124491. doi:10.1016/j.jclepro.2020.124491

Mathews, J. A., Kidney, S., Mallon, K., and Hughes, M. (2010). Mobilizing Private Finance to Drive an Energy Industrial Revolution. *Energy Policy* 38 (7), 3263–3265. doi:10.1016/j.enpol.2010.02.030

Moreira, F., and Zhao, S. (2018). Do credit Ratings Affect Spread and Return? A Study of Structured Finance Products. *Int. J. Fin Econ.* 23 (2), 205–217. doi:10.1002/ijfe.1612

Rosenthal, J. A., and Ocampo, J. M. (1988). *Securitization of Credit: Inside the New Technology of Finance[M]*. New York: John Wiley & Sons. 978-0-471-61368-8.

Shahbaz, M., Raghutla, C., Song, M., Zameer, H., and Jiao, Z. (2020). Public-private Partnerships Investment in Energy as New Determinant of CO2 Emissions: The Role of Technological Innovations in China. *Energ. Econ.* 86, 104664. doi:10.1016/j.eneco.2020.104664

Shan, Y., Guan, D., Zheng, H., Ou, J., Li, Y., Meng, J., et al. (2018). Data Descriptor: China CO2 Emission Accounts 1997-2015[J]. *Scientific Data*. 5, 170201. 10.1038/sdata.2017.201

Shao, X., He, M. I., and Jiang, P. (2015). The Management of Media Public Relation, Investor Sentiment and Security Offerings[J]. *J. Financial Res.* (09), 190–206.

Shuai, C., Chen, X., Wu, Y., Tan, Y., Zhang, Y., and Shen, L. (2018). Identifying the Key Impact Factors of Carbon Emission in China: Results from a Largely Expanded Pool of Potential Impact Factors. *J. Clean. Prod.* 175, 612–623. doi:10.1016/j.jclepro.2017.12.097

Song, M., and Zhang, Y. P. (2016). Research on the Problem and Optimization of Risk Retention Regulation of Credit Assets Securitization in China: Based on International Comparison[J]. *Econ. Probl.* 2016 (11), 48–52. doi:10.16011/j.cnki.jjwt.2016.11.010

Tang, Y., Chen, D., Chen, J., and Xu, J. (2017). The Rise of China's Securitization Market. *Financial Markets, Institutions Instr.* 26 (5), 279–294. doi:10.1111/fmii.12090

UNEP (2021). *Making Peace with Nature [R]*. United Nations Environment Programme. Available at: https://wedocs.unep.org/handle/20.500.11822/34807.

Wang, F. Z., and Chen, F. Y. (2018). Board Governance, Environmental Regulation and green Technology Innovation——Empirical test based on listed companies in China's heavy polluting Industry[J]. *Stud. Sci. Sci.* 36 (02), 361–369. doi:10.16192/j.cnki.1003-2053.2018.02.019

Wang, X., and Li, J. (2016). Innovation and Regulation of Asset Securitization on Functional Perspective——Against the Back Ground of the New Normal[J]. *Finance Econ.* (06), 35–46.

Yang, L., Wang, R., Chen, Z., and Luo, X. (2020). What determines the issue price of lease asset-backed securities in China? *Int. Rev. Financial Anal.* 72, 101583. doi:10.1016/j.irfa.2020.101583

Yang, X., Jia, Z., Yang, Z., and Yuan, X. (2021). The effects of technological factors on carbon emissions from various sectors in China—A spatial Perspective[J]. *J. Clean. Prod.* 301, 126949. doi:10.1016/j.jclepro.2021.126949

Yao, M. L. (2017). On the Discount Factors of Green Bond Interest Rate [J]. *Zhejiang Finance* 08, 55–59.

Yin, W., Zhu, Z., Kirkulak-Uludag, B., and Zhu, Y. (2021). The determinants of green credit and its impact on the performance of Chinese banks. *J. Clean. Prod.* 286, 124991. doi:10.1016/j.jclepro.2020.124991

Yu, Y., and Du, Y. (2019). Impact of technological innovation on CO2 emissions and emissions trend prediction on 'New Normal' economy in China. *Atmos. Pollut. Res.* 10 (1), 152–161. doi:10.1016/j.apr.2018.07.005

Zhao, J., Jiang, Q., Dong, X., and Dong, K. (2020). Would environmental regulation improve the greenhouse gas benefits of natural gas use? A Chinese case study. *Energ. Econ.* 87, 104712. doi:10.1016/j.eneco.2020.104712

Zheng, Y., Zhou, M., and Wen, F. (2021). Asymmetric effects of oil shocks on carbon allowance price: Evidence from China. *Energ. Econ.* 97, 105183. doi:10.1016/j.eneco.2021.105183

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.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 20 August 2021
doi: 10.3389/fenrg.2021.735665

Research on the Correlation Between WTI Crude Oil Futures Price and European Carbon Futures Price

*Zhengwei Ma**, *Yuxin Yan, Ruotong Wu and Feixiao Li*

School of Economics and Management, China University of Petroleum-Beijing, Beijing, China

In recent years, the rapid increase in CO_2 concentration has accelerated global warming. As a result, sea levels rise, glaciers melt, extreme weather occurs, and species become extinct. As the world's largest CO_2 emission rights trading market, EU Emissions Trading System (EU-ETS) has reached 1.855 billion tons of quotas by 2019, influencing the development of the global carbon emission market. Crude oil, as one of the major fossil energy sources in the world, its price fluctuation is bound to affect the price of carbon emission rights. Therefore, this paper aims to reveal the correlation between crude oil futures prices and carbon emission rights futures prices by studying the price fluctuation. In this paper, the linkage between West Texas Intermediate (WTI) crude oil futures prices and European carbon futures prices was investigated. In addition, this paper selects continuous data of WTI crude oil futures prices and spot prices with European carbon futures prices from January 8, 2018 to November 27, 2020, and builds a smooth transformation regression (STR) model. The relationship between crude oil futures and carbon futures prices is studied in both forward and reversal linkage through empirical analysis. The results show that crude oil futures prices and carbon futures prices have a mutual effect on each other, and both linear and nonlinear correlations between the two prices exist. Based on the results of this research, some suggestions are provided.

Keywords: carbon neutral, WTI crude oil, European carbon futures, STR model, non-linear relationship

OPEN ACCESS

Edited by:
Kangyin Dong,
University of International Business and Economics, China

Reviewed by:
James Wu,
Golden Gate University, United States
Yann Huang,
Northwestern Polytechnic University, United States
David Paul,
California State University, East Bay, United States

****Correspondence:***
Zhengwei Ma
ma_zhengwei@163.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *03 July 2021*
Accepted: *03 August 2021*
Published: *20 August 2021*

Citation:
Ma Z, Yan Y, Wu R and Li F (2021) Research on the Correlation Between WTI Crude Oil Futures Price and European Carbon Futures Price. Front. Energy Res. 9:735665. doi: 10.3389/fenrg.2021.735665

INTRODUCTION

The global economy developed rapidly after the outbreak of the Industrial Revolution, and a large amount of energy consumption coming along, including coal, oil, and natural gas. A mass of CO_2 was produced by oil burning, thus the rapid growth of CO_2 emissions caused a huge impact on the global environment. After the Industrial Revolution, global CO_2 concentrations rose from 240 to 415 ppm in May 2019, the first time in human history that the same concentration was reached more than 3 million years ago, as measured by the National Oceanic and Atmospheric Administration's (NOAA) Mauna Loa Observatory (Yiming, 2019). The rapid rise in CO_2 concentrations worsens global warming, which in turn caused environmental problems such as rising sea levels, inundation of coastal lowlands, melting glaciers, extreme weather, and species extinction.

Nowadays, implementing carbon reduction to combat climate change has become a world consensus. China is the largest emitter of carbon dioxide gas in the world. In 2019, China's annual greenhouse gas emissions accounted for 27% of the world's total, and the annual carbon dioxide emissions were 101.99 million tons. In 2020, the Chinese government proposed at the United Nations General Assembly that it would strive to achieve carbon peaking by 2030 and carbon

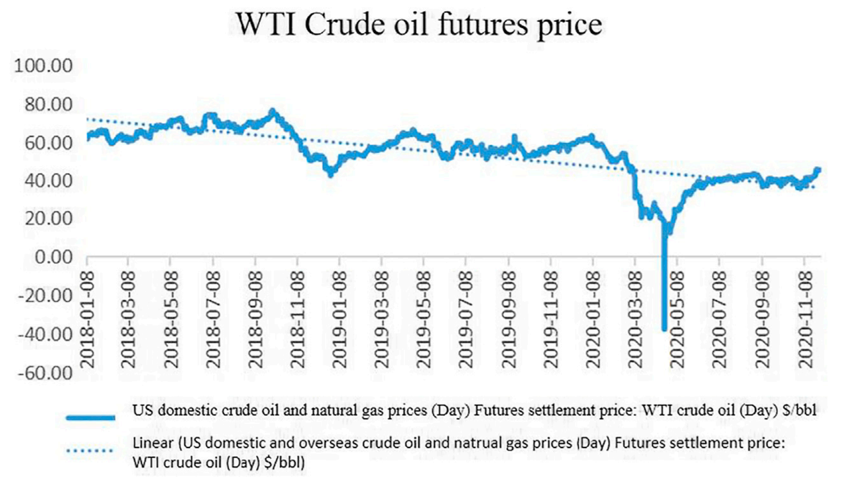


FIGURE 1 | WTI Crude oil future price (2018–2020).

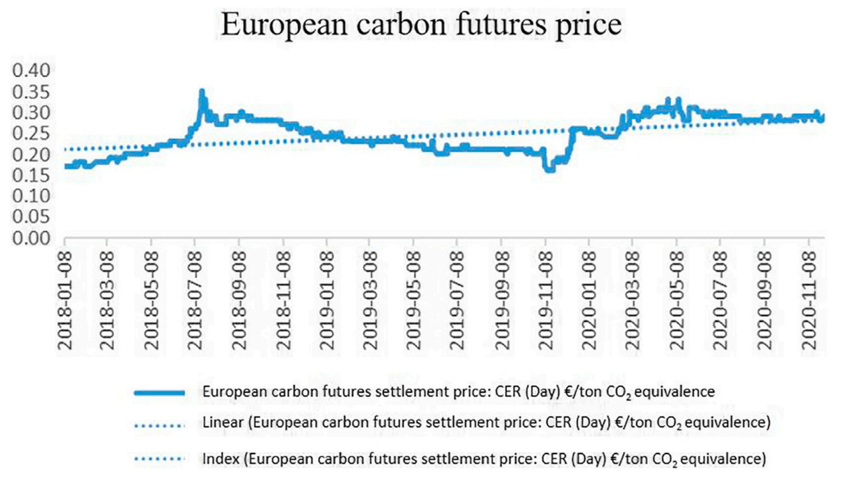


FIGURE 2 | | European carbon emissions futures price (2018–2020).

neutrality by 2060. First of all, as a country with an energy structure dominated by high-carbon fossil, China announced that the time from completing carbon peaking to carbon neutrality is much shorter than that of developed countries. This announcement with determination and execution manifests its responsibility of great power and plays a leading role for other countries in reducing carbon emissions and developing a green and low-carbon economy. Secondly, as the world's largest carbon emitter, China's carbon reduction actions can help achieve carbon neutrality earlier and dramatically improve the global climate.

The EU-ETSA is the largest carbon emissions trading market in the world. By 2019, the quota for the EU Certified Emission Reduction (CER) prices in Carbon Futures Markets (hereinafter called carbon market) has reached 1,855 million tons, affecting the global carbon market. Crude oil consumption causes an increase in carbon emissions, and crude oil futures price affects carbon futures price, then the fluctuation of carbon futures price affects carbon spot price. The chart below shows the WTI futures price and the European carbon futures price from 2018 to 2020 (See **Figure 1** and **Figure 2**). As a critical energy product, the crude oil price affects the Certified Emission Reduction prices under the EU carbon market in the following ways: first of all, crude oil price affects the natural gas price, and then the electricity price. Finally, the electricity price drives the variation of the Certified Emission Reduction prices (Kanen, 2006). It has been demonstrated in the relevant literature that crude oil futures prices correlate with Certified Emission Reduction prices. However, only a few studies are included on the specific linkage between crude oil futures and carbon futures prices. Therefore, this paper will use the STR model to conduct an in-depth research on the correlation between the two prices. The study can further clarify the relationship between carbon emission right futures and crude oil futures. At the same time, the article further analyzes the impact of carbon emission right futures trading model on reducing the use of fossil energy. This paper provides a theoretical basis for developing countries to reduce carbon emissions by means of carbon emission trading. At the same time, the conclusions reached will be helpful to provide reference experience, help solve the information asymmetry, improve the Chinese carbon trading market, and accomplish the established carbon peak and carbon-neutral goals on time, which exerts a practical significance. Meantime, the progress of the Chinese carbon market will also accelerate the global goal of carbon neutrality. Therefore, studying the price correlation between the two prices will provide references for the Chinese carbon market, and help the world achieve carbon neutrality.

LITERATURE REVIEW

European Union Allowance (EUA) means the tradable unit under the European Union Emissions Trading Scheme (EU ETS), giving the holder the right to emit one tonne of carbon dioxide (CO_2), or the equivalent amount of two more powerful greenhouse gases, nitrous oxide (N_2O) and perfluorocarbons (PFCs). And a Certified Emissions Reduction, also known as CER, is a certificate issued by the United Nations to member nations for preventing one tonne of carbon dioxide emissions. These are usually issued to member states for projects achieving greenhouse gas reductions through the use of Clean Development Mechanisms (CDM). CDMs make it possible for these projects to occur and set a baseline for future emission targets. Countries with developed or traditional economies (recognized as Annex 1 under the Kyoto Protocol) use CERs to help them reach their emission targets. Those nations are able to achieve their objectives and are able to set future goals as it makes the effort of reducing greenhouse gases more realistic many countries.

Crude oil futures, as the most traded commodity futures in the world, its price fluctuation has a pivotal role in the international financial market. Therefore, many scholars analyzed the influencing factors of crude oil futures prices. Li (2017) concluded that crude oil futures price is directly influenced by the positions of commodity index investors, and investor positions have a significant impact on crude oil futures yields by establishing the Markov-Switching Vector Autoregressions (MSVAR) model. Crude oil futures price as a financial derivative is influenced by the behaviors in financial markets. The investment strategy of commodity index investors is to dominate the direction of the crude oil futures market and then affecting the fluctuations in crude oil price. Guo (2018) concluded that crude oil futures price is influenced by various factors such as supply and demand, exchange rates, political relations, and international funding. Gao Meiling (2020) analyzed that crude oil supply and demand, financial, political, and unexpected events are the key factors affecting the price. Through adopting a gray relational model, Guo (2010) concluded that the crude oil production of OPEC has a negative influence on oil price; the world economic growth rate exerts a positive influence on oil price, and there exists a long-term dynamic equilibrium relationship between crude oil futures and spot price.

With the abundance of carbon financial derivatives, there comes the risk of price volatility in carbon trading. Therefore, studying the changing pattern of carbon futures prices and the influencing factors is conducive to predicting the price trend and avoiding volatility. Fewer researches about the relationship between EU carbon quotas (EUA) and international CER futures market price are included. (Chevallier, 2011) found the interaction effect between EUA and CER futures price through econometric methods, VAR model, Gran causality, and DCCMGARCH model test, and concluded that the two have a time-varying correlation. (Kanamura, 2016) employed the inverse Box-Cox F MAX curve to conclude that the relationship between EUA and CER futures price is related to the swap transactions and energy price. Through GARCH family model volatility fitting and VAR calculation, Wu (2013) found that CER and EUA futures price have a significant mutual relationship of mutual guidance in the short term, and EUA has a stronger motive force on CER futures price. Xu and Zhai (2020) conducted that when existing wide price variance between CER and EUA, firms will purchase lower-priced products, leading to an increase in demand, as well as in price. And eventually, EUA and CER prices tend to be the same. In addition, Xu Yue concluded that EUA has a leading role in CER. In addition, a strong linkage was showed. Huang (2020) utilized continuous data of EUA and CER futures settlement price to establish a GARCH model to investigate the price correlation, and the analysis obtained that EUA price exerts a negative effect on CER.

The Chinese carbon market is still in its infancy in international carbon trading, compared with the mature system formed by the European carbon trading market. Some scholars have conducted in-depth studies on the relationship between Chinese and European CER prices. Xiang and Zhong (2020) developed a VAR model to conclude that the Chinese carbon market price is primarily influenced by its price and the Euro exchange rate, and the CER price has an impact on the Chinese carbon market price than the EUA price. Through the ARCH test and GARCH-M-T model, Zhao (2016) empirically analyzed the price of carbon emission rights in Shenzhen, China, and it can be concluded that the fluctuations of CER spot yields in China are smoother than those in the international CER market, and less information lever effect appears. Wei Xue (2019) adopted principal component analysis (PCA) and stepwise regression of mediating effect model to test that a positive relationship exists between international CER price and Chinese carbon futures price. Moreover, influenced by the traditional energy price, the Chinese carbon trading price fluctuates inversely with the international CER price.

The "black gold" crude oil and carbon futures price affecting the financial market have been studied in academia, but the specific linkage between the crude oil and carbon futures price has been less studied. Some scholars have shown that a correlation existed between crude oil and carbon futures prices. Mansanet-Bataller et al. (2007) used a multiple regression model to prove that there must be a correlation between crude oil and Certified

Emission Reduction prices. Chen and Li (2017) empirically analyzed that a long-term equilibrium relationship and spillover effect exist between crude oil and the carbon futures market. Kanen concluded that the process of crude oil futures price on Certified Emission Reduction prices is that oil price affects natural gas price first, then natural gas price influences electricity price, and finally, electricity price affects Certified Emission Reduction prices. Through adopting the DCC-MGARCH model, Wang (2021) concluded that a significant mutual volatility spillover effect exists among natural gas, crude oil futures, and coking coal futures markets. Zhao (2012) employed cointegration theory, and the Granger causality test to conclude that a cointegration relationship exists between energy and carbon futures prices, and a causal relationship between natural gas price, electricity price, and carbon futures price.

Li (2018) made a conclusion by adopting the Engle-Granger cointegration test that there is a long-term equilibrium relationship and a short-term dynamic relationship between carbon futures and spot price. In addition, it can be drawn that carbon spot prices can be predicted according to futures price market. Bredin and Parsons (2016) came to a conclusion that carbon spot subsidies became cheaper relative to futures, and carbon futures price were higher than the hedge price defined by spot price with increasing interest rates. Modeling carbon spot and futures through GARCH models and conducting causality tests, Zeitlberger and Alexander (2016) concluded that lagged carbon futures yields have effects on spot yields, that is, the carbon futures market leads the way for the spot market and provides valuable information for spot yields. The fact that carbon futures trading volume is much larger than the spot market validates the conclusion.

Based on the correlation between crude oil and Certified Emission Reduction prices and the correlation between crude oil and carbon futures market, this paper will use crude oil-fossil energy (natural gas, coal)-electricity-carbon as a simulated industry chain to conduct an intensive study on the linkage between crude oil and carbon futures. In this paper, WTI crude oil price and European carbon futures are selected as subjects, and three variables, WTI futures settlement price, WTI spot settlement price (using Tapis spot settlement price data as a proxy) and European carbon futures settlement price, are substituted into a smoothed transformation regression model (STR) to analyze the price correlation between WTI crude oil futures and European carbon futures.

THEORETICAL ANALYSIS OF PRICE CORRELATION

Oil price is the primary indicator in the energy market, and almost all other energy product prices are influenced by oil prices, including natural gas and coal. Natural gas is a clean energy source for power generation, and coal is a cheap and highly carbon-emitting energy source for power generation. Studies have shown that natural gas and carbon market, coal, and carbon market are significantly correlated. The price of natural gas and coal affects the price of carbon through its impact on the price of electricity.

Based on this theory, the above relationship can be considered as an industrial chain, and the chain relationship diagram is established as follows (See **Figure 3**):

Forward Linkage: Crude Oil Price Towards Certified Emission Reduction Prices

In economic terms, crude oil and natural gas can be defined as substitutes for each other. When oil price falls, the price advantage of natural gas is weakened, resulting in lower demand and lower price for natural gas. In addition, the price of crude oil and natural gas is a mutual relationship with consistent changes. Natural gas prices can affect electricity prices and ultimately lead to price changes in carbon trading. Crude oil and coal are both disposable fossil energy sources and can substitute for each other. When oil price falls, crude oil demand rises and coal demand decreases, leading to lower coal prices. Moreover, oil price determines production costs in the coal chemical industry, which in turn affects coal price. Therefore, the forward linkage of oil-gas (coal)-electricity-carbon can be viewed as an industrial chain. Since it is known that both crude oil and carbon futures price are based on their spot price, the following theoretical relation is set:

$$PCER = \alpha_0 + \alpha_1 Pyy + \varepsilon_1 \quad (1)$$

In the relation, PCER refers to the European carbon futures price; Pyy refers to the WTI crude oil futures price; α_0 and α_1 refer to the variable coefficients, and ε_1 refers to the error term.

Reverse Linkage: Certified Emission Reduction Prices Towards Crude Oil Price

Based on the simulated chain relationship established by the *cis*-linkage, it can be inferred that carbon, as a downstream product of the chain, can affect natural gas (coal) price through electricity price, which eventually drives the crude oil price changes of the upstream product. In other words, the Certified Emission Reduction prices in the downstream products of the chain can be counteracted by crude oil prices upstream. Based on this inference, the following relationship is assumed (WTI spot price data substituted with Tapis spot price)

$$\mathrm{Pyy} = \alpha_0 + \alpha_1 \mathrm{PCER} + \alpha_2 \mathrm{xPxyy} + \varepsilon_2 \quad (2)$$

In the relation, Pyy refers to the WTI crude oil futures price; PCER refers to the European carbon futures price; Pxyy refers to the crude oil spot price; α_0, α_1, α_2 refer to the variable coefficients, and ε_2 refers to the error term.

Based on the above assumptions of the simulated industry chain and the theoretical model, this paper adopts the STR model to analyze the correlation between WTI crude oil and European carbon futures prices.

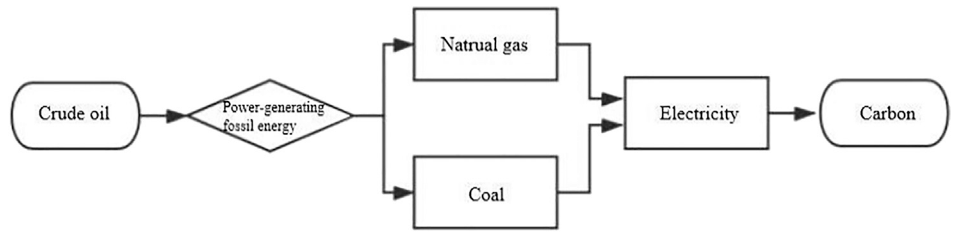


FIGURE 3 | Industrial chain relationship between crude oil and carbon emission rights.

MODEL CONSTRUCTION

Data Sources and Variable Settings

The weekly data used in the empirical analysis were collected from the WIND financial database and taken as the study interval from January 8, 2018 to May 27, 2020. The three variables include WTI futures weekly price, WTI spot weekly price (WTI spot price data substituted with Tapis spot price), and European carbon futures weekly prices. WTI crude oil and carbon futures prices are selected from the closing price of the day, and the spot price is an average level of the day. To unify the price units, the price should be converted to United States dollars. In addition, the missing values were replaced by SPSS after deleting the mismatched data to ensure that the three variables correspond to their price dates. At last, a total of 1993 groups of data were obtained after processing.

To ensure data stationery, the crude oil futures price sequence, spot price sequence, and carbon futures price sequence are taken as logarithms and denoted as lnPyy, ln Pxyy, and lnPCER respectively.

Model Construction

In this paper, crude oil futures price, crude oil spot price and carbon futures price are selected as continuous data on the time axis, and the nonlinear correlation between them is primarily studied. Therefore, a typical nonlinear time sequence model STR is adopted in model construction.

Model Form：

$$y_t = \varphi' z_t + (\theta' zt) G(s_t, \gamma, c) + \varepsilon_t \tag{3}$$

In the form, y_t refers to the explained variable; $'z_t$ refers to the vector of explained variable; φ' refers to the matrix of coefficient parameters; $G(s_t,\gamma,c)$ refers to the transformation function or switching function; s_t refers to the transformation variable or switching variable (the variable causing the nonlinear correlation), γ refers to the slope parameter or adjustment parameter (the degree of transformation of the nonlinear correlation); c refers to the position parameter (the timing of generating the nonlinear correlation), and ε_t refers to the white noise.

Steps for STR Estimation

1) Select the appropriate auto-regressive lag order to construct a dynamic linear model, and then obtain a regression residual sequence;
2) Utilize the obtained residual sequence to perform third-order Taylor expansion on the conversion function at $y = 0$ and construct an auxiliary regression model, and then perform sequential tests on the coefficients of the regression equation to determine non-linearity and the form of the conversion function;
3) Estimate the parameters;
4) Test model stationary

EMPIRICAL TEST OF PRICE CORRELATION BETWEEN WTI CRUDE OIL AND CARBON FUTURES

Data Stationary Test

The ADF test was employed to perform a unit root test for stationary of each indicator sequence, with the original hypothesis of the existence of a unit root, and a stationary sequence if the original hypothesis was rejected. After taking the logarithm of three variables, it turns to the selection of the lag order (I to IV). The ADF lag of three orders was selected for the test because the AIC and SC values were the smallest at the third order.

The test results are shown in **Table 1**. Judging the significance coefficient, it can be seen that the original sequence is not significant, while the first-order difference price sequence is very significant. The original price sequence is non-stationary and the first-order difference price sequence is stationary.

Empirical Analysis of Product Forward Linkage

Nonlinear Test

$$y_t = \beta_0 z_t + \beta_1 z_t s_t + \beta_2 z_t s_t^2 + \beta_3 z_t s_t^3 + \eta_t \tag{4}$$

$$H_{01}: \beta_1 = \beta_2 = \beta_3 = 0 \tag{5}$$

$$H_{04}: = \beta_3 = 0 \tag{6}$$

$$H_{03}: \beta_2 = 0 | \beta_3 = 0 \tag{7}$$

$$H_{03}: \beta_1 = 0 | \beta_2 = 0 \beta_3 = 0 \tag{8}$$

If H_{04} is rejected instead of H_{01}, or H_{02}, H_{03}, H_{02} are rejected in turn and the *p*-value of rejecting H_{03} is not the minimum, the LSTR1 model should be selected, otherwise the LSTR2.

TABLE 1 | Stationary test results.

	Variables	ADF-value	1% critical value	5% critical value	10% critical value	Prob
Original Sequence	lnPYY	0.697889	−3.436062	−2.863950	−2.568104	0.9921
	lnPXYY	−0.057216	−3.966351	−3.413873	−3.129017	0.9955
	lnPCER	−1.169332	−3.436035	−2.863939	−2.568098	0.6895
First order difference sequence	lnPYY	−13.98994	−3.436736	−2.864248	−2.568264	0.0000
	lnPXYY	−12.32469	−3.967289	−3.414332	−3.129289	0.0000
	lnPCER	−13.41113	−3.436696	−2.864230	−2.568255	0.0000

TABLE 2 | Nonlinear test results.

Conversion variables	*F*	F_4	F_3	F_2	Suggested model
lnpcer(t-1)	2.6185e−12	2.6341e−02	1.1486e−03	1.4225e−01	LSTR1
lnpyy(t)[a]	1.5765e−14	NaN	9.1211e−08	1.7712e−01	LSTR1
lnpyy(t-1)	1.1561e−06	2.1514e−04	4.4786−05	5.4929e−02	LSTR2
TREND	NaN	4.6540e−11	2.0461e−13	7.2846e−04	Linear

[a]*The non-linearity is most significant when lnpyy(t) is the transformation variable.*

TABLE 3 | Parameter estimation results.

Variables	Start	Value estimates	T-value	*p*-value
---- Linear ------				
CONST	−0.80445	−0.85443	−11.0805	0.0000
lnpcer(t-1)	0.3358	0.30616	5.0075	0.0000
lnpyy(t-1)	0.02304	0.02879	1.9316	0.0538
---- Nonlinear ----				
CONST	-0.94419	−0.79814	−3.4132	0.0007
lnpcer(t-1)	0.57965	0.61439	9.3787	0.0000
lnpyy(t)	0.2582	0.23918	3.9685	0.0001
lnpyy(t-1)	0.10864	0.10045	3.156	0.0017
Gamma	3.94668	3.70655	8.4678	0.0000
C	3.91559	3.90187	283.9891	0.0000

The JMulTi was used to perform the nonlinearity test, the judgment principle is that the variable with the smallest *p* value is the optimal conversion variable. And the results in **Table 2** show that the four F-statistics *p*-values are relatively minimal when the conversion variable is lypyy(t). Therefore, the optimal conversion variable suggested by JMulTi is the original order of crude oil futures (lnpyy(t)), and the optimal conversion function model is LSTR1.

Parameter estimation

After selecting the optimal transformation variable and model, the parameters of the STR model were estimated. **Table 3** shows that the smoothing parameter (gamma) is 3.70655 and the results are highly significant at a *p*-value of 0. The transformation regime is more pronounced. After removing the variable lnpyy (t-1), which has no significant linear relationship with a *p*-value of 0.65519, the three variables we got in **Table 3** are obtained with significant relationships.

Based on the results shown in **Table 3**, the form of LSTR1 is obtained as follows:

$$\begin{aligned} \mathrm{lnYt} = &- 0.85443 + 0.30616\mathrm{lnpCER}(\mathrm{t}-1) \\ &+ 0.02879\mathrm{lnpYY}(\mathrm{t}-1) - \big(0.79814 \\ &- 0.61439\mathrm{lnpCER}(\mathrm{t}-1) - 0.23918\mathrm{lnpYY}(\mathrm{t}) \\ &- 0.10045\mathrm{lnpYY}(\mathrm{t}-1)\big)\mathrm{G}(st,\gamma,c) \end{aligned} \tag{9}$$

$$G(st,\gamma,c) = \left[1+\exp\left(-3.70655\mathrm{lnpCER}(\mathrm{t}-1) - 3.90187\right)\right]\hat{}-1 \tag{10}$$

When selected transformation variable as lnpyy(t), the position parameter c can be determined as 3.90187. When the transformation variable is lethan the position parameter, the crude oil futures price has a positive linear effect on the carbon futures price; conversely, the positive relationship weakens and the non-linear part will act stronger.

Empirical Analysis of Product Reverse Linkage

Nonlinear Test

Table 4 shows the test results after JMulTi. When the transformed variables are lnpyy(t-1), lnpcer(t), lnpxyy(t-1), lnpcer(t-1), lnpxyy(t-2), and lnpcer(t-2), the results are linear models with no nonlinearities due to the insignificant *p*-values of the F-test effect. Therefore, only lnpxyy(t) can be used as a transformation variable, and the optimal functional model is LSTR1.

Parameter Estimation

LSTR1 model was selected, then the model was continued with parameter estimation using JMulTi. Parameter estimates and significance results for linear and nonlinear parts are obtained. According to **Table 5**, the form of the model can be concluded as follows:

TABLE 4 | Non-linear test results.

Conversion variables	F	F4	F3	F2	Suggested model
lnpyy(t-1)	NaN	NaN	0.016229	3.67E–07	Linear
lnpxyy(t)*	4.1E-99	NaN	5.73E–14	NaN	LSTR1
lnpcer(t)	NaN	1.97E–06	0.21218	9.87E–12	Linear
lnpxyy(t-1)	NaN	5.05E–05	7.34E–08	NaN	Linear
lnpcer(t-1)	NaN	NaN	3.78E–09	NaN	Linear
lnpxyy(t-2)	NaN	NaN	0.000144	NaN	Linear

TABLE 5 | Parameter estimation results.

Variables	Start	Value estimates	T-value	*p*-value
----- Linear ------				
CONST	3.86024	4.21205	8.8008	0.0000
lnpyy(t-1)	–0.71042	-0.59844	–12.7067	0.0000
lnpxyy(t)	0.74563	1.72708	10.6734	0.0000
lnpcer(t)	2.97395	5.4174	15.3781	0.0000
lnpxyy(t-1)	1.5605	1.66981	19.9986	0.0000
lnpcer(t-1)	3.22462	3.83871	13.6959	0.0000
lnpxyy(t-2)	0.3039	0.14718	2.8309	0.0048
---- Nonlinear----				
CONST	–3.87661	–4.17616	–8.7176	0.0000
lnpyy(t-1)	1.61629	1.47139	28.7127	0.0000
lnpxyy(t)	0.2203	–0.77608	–4.7784	0.0000
lnpcer(t)	–2.91875	–5.36097	–15.1715	0.0000
lnpxyy(t-1)	–2.3817	–2.4656	–28.246	0.0000
lnpcer(t-1)	–3.27455	–3.88247	–13.7669	0.0000
lnpxyy(t-2)	–0.352	–0.18608	–3.4457	0.0006
lnpcer(t-2)	0.00086	–0.00541	–0.1971	0.8438
Gamma	5.96602	232.0085	0.0507	0.9596
C1	3.20752	3.14106	51.4996	0.0000

4.21205–0.59844lnpyy(t-1)+1.72708lnpxyy(t)+5.41740 lnpcer(t)+1.66981lnpxyy(t-1)+3.83871lnpcer(t-1)+0.14718 lnpxyy(t-2)-(4.17616–1.47139lnpyy(t-1)+0.77608lnpxyy(t) +5.36097lnpcer(t)+2.46560lnpxyy(t-1)+3.88247lnpcer(t-1)+ 0.18608lnpxyy(t-2)+0.00541lnpcer(t-2))$G(st,\gamma,c)$

The smoothing parameter (gamma) is 232.00853, which indicates that the slope of the transition function is large, i.e., the speed of transition between different regimes of the model is fast. After selecting the transformation variable as lnpxyy(t), the unknown parameter c can be confirmed as 3.14106. At the 1% significant level, the carbon futures price has a positive linear effect on crude oil futures price; the nonlinear relationship is enhanced when the value of the transformed variable is stronger than the location parameter. The positive linear effect of carbon futures price on crude oil futures price diminishes.

CONCLUSIONS AND INSPIRATIONS

Conclusions

1) The assumed theory that crude oil price affecting Certified Emission Reduction (CER) prices in the simulated chain crude oil-natural gas (coal)-electricity-carbon holds. In this industrial chain, the correlation between the crude oil and carbon product price can be transmitted through the futures market transaction and reflected in the corresponding price in the futures bottle. The results show that the relationship between the price series of crude oil futures and carbon futures is not only linear, but also nonlinear.
2) There is a long-term linear and nonlinear bidirectional relationship between crude oil futures and carbon futures market. The linkage between crude oil and carbon futures prices is a reversible mutual relationship, and the relationship between the two prices is tested to be highly significant.
3) In the product linkage analysis, there are both positive effects and nonlinear linear effects. Without considering the nonlinear effect, crude oil futures has a positive price linkage effect on carbon futures. When considering the nonlinear effect, the nonlinear effect will weaken the positive effect of the linear relationship. But generally speaking, crude oil futures have a positive impact on carbon futures, which is consistent with the price transmission in the spot market. In the reverse linkage, carbon futures price has a positive linear effect on crude oil futures price, and there is also a nonlinear relationship.

Inspirations and Prospects

The climate problem brought by the massive emission of global carbon dioxide is becoming increasingly serious. Carbon emission reduction has attracted global attention, and carbon neutrality will be the goal for all countries. Carbon trading will form a brand new carbon financial market, which is a great challenge and opportunity. At present, China's carbon trading market is gradually developing. Through further studying on the price information of global carbon market, the disadvantages caused by the information asymmetry in China's carbon market will be improved, and the carbon market mechanism and carbon pricing will be enhanced.

1) Carbon emissions are mostly caused by energy activities, including the utilization of crude oil and coal. The above empirical evidence shows that the crude oil price has a significant impact on the Certified Emission Reduction prices. Therefore, the government can refer to the trend of crude oil price and the correlation between crude oil and carbon market when regulating carbon pricing and formulating carbon market related regulation policies, so as to avoid the risk in Certified Emission Reduction prices fluctuation.

2) Studies have shown that coal can ultimately contribute to the Certified Emission Reduction prices by influencing the electricity price. The development and utilization of new energy sources will play a crucial role in achieving carbon neutrality in the future. New energy generation methods such as photo-voltaic, wind power and nuclear power can be gradually implemented to reduce carbon emissions caused by power generation.
3) Early in 2011, China started carbon trading pilot projects in Shenzhen, Shanghai, Beijing, Guangzhou, and other areas. At present, China's carbon trading market is still less active than Europe, and the carbon trading price is lower than the EU. In the future, China should keep improving the carbon trading market system and reasonably price carbon quotas. China should invest more in the carbon market and develop carbon futures and other financial derivatives to stimulate carbon trading activity.
4) The world has entered a new phase of globalization, carbon emission control requires global participation and practical actions. As a developing country, China takes the lead in committing to the carbon neutrality goal and leads the transformation with practical actions, which can drive the global technological innovation to achieve the carbon neutrality goal and create a good atmosphere for global climate governance.

China has pledged to the world that it will reach the goal of carbon neutrality by 2060. It means that China will accomplish a tremendous carbon emission reduction task. As a major carbon emitter, China plays a leading role in the world, and the achievement of the carbon emission reduction target will vigorously promote the achievement of the world carbon neutrality target.

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/s.

AUTHOR CONTRIBUTIONS

ZM contributed to the conception of the study; YY contributed significantly to analysis and manuscript preparation; RW and FL helped perform the analysis with constructive discussions.

FUNDING

The National Social Science Foundation is the main channel for China to support basic research in the field of scientific research. It is oriented to the whole country and focuses on funding researchers in universities and scientific research institutions with good research conditions and research strength. And the project was sponsored by National Social Science Fund of China (Grant Number: 18BJY251).

ACKNOWLEDGMENTS

I would like to express my deepest appreciation to all who have helped me complete this study.

REFERENCES

Bredin, D., and Parsons, J. (2016). Why Is Spot Carbon So Cheap and Future Carbon So Dear? the Term Structure of Carbon Prices[J]. *Energ. J.* 37 (3), 83–107. doi:10.5547/01956574.37.3.dbre

Chen, Q., and Li, D. (2017). Research on the Correlation between EU Carbon Quota Market and Crude Oil Market[J]. *J. Fuqing Branch Fujian Normal Univ.* (05), 93–98. doi:10.3969/j.issn.1008-3421.2017.05.017

Chevallier, J. (2011). Anticipating Correlations between EUAs and CERs: A Dynamic Conditional Correlation GARCH Model [J]. *Econ. Bull.* 31 (1), 255–272.

Guo, Q. (2010). *The Study on Formation Mechanism and Fluctuating Factors of International Crude Oil Price[D]*. Tianjin: Tianjin University.

Guo, J. (2018). Analysis of Factors Influencing Crude Oil Futures Price[. *J].Co-Operative Econ. Sci.* (18), 66–67. doi:10.3969/j.issn.1672-190X.2018.18.024

Huang, J. (2020). Research on Price Fluctuation, Correlation and Enlightenment of Carbon Futures: Taking the EU Carbon Futures Market as an Example[J]. *Econ. Probl.* 22 (05), 63–70. doi:10.16011/j.cnki.jjwt.2020.05.012

Kanamura, T. (2016). Role of Carbon Swap Trading and Energy Prices in price Correlations and Volatilities between Carbon Markets. *Energ. Econ.* 54, 204–212. doi:10.1016/j.eneco.2015.10.016

Kanen, J. L. M. (2006). *Carbon Trading and Pricing[M]*. London: Environment Finance Publications.

Li, H. (2017). *Research on the Impact of Commodity Index Investors on Crude Oil Futures Price Volatility [D]*. Wuhan: Wuhan University.

Li, Y. (2018). Research on the Correlation between EU Carbon Quota Futures and Spot Price[J]. *China J. Commer.* (21), 48–49. doi:10.19699/j.cnki.issn2096-0298.2018.21.048

Mansanet-Bataller, M., Pardo, A., and Valor, E. (2007). CO 2 Prices, Energy and Weather[J]. *Energ. J.* 28 (3), 73–92. doi:10.5547/issn0195-6574-ej-vol28-no3-5

Meiling, G. (2020). Study on Influencing Factors of international crude oil futures price fluctuation [J]. *Economic outlook around the Bohai Sea* 2 (5), 173–174doi:10.16457/j.cnki.hbhjjlw.2020.05.114

Wang, X. (2021). The Spillover Effect between Natural Gas and Alternative Energy in Xinjiang-Research Based on DCC-MGARCH [J/OL]. 1-15. Development Finance Research (Accessed on 05 31, 2021). doi:10.16556/j.cnki.kfxjr.20200721.001

Wu, P. (2013). *Research on Risk Measuring and Interaction of Carbon Futures under EU-ETS[D]*. Kunming: Yunnan Normal University.

Xiang, W., and Zhong, C. (2020). Research on the Factors Affecting China's Carbon Market Price[J]. *J. Chongqing Univ. Technol.(Natural Sci.)* 34 (10), 259–265. doi:10.3969/j.issn.1674-8425(z).2020.10.035

Xu, Y., and Zhai, T. (2020). Interaction Effect of Carbon Markets under the Background of UN Climate Negotiations: Based on EUA and CER Markets[J]. *Ecol. Economy* 36 (06), 19–26.

Xue, W. (2019). *Traditional Energy Price, International CER Price and China's Carbon Trading Price[D]*. Xi'an: Xi'an Shiyou University.

Yi, M. (2019). Record Breaking Carbon Dioxide Concentration [J]. *Glob. Sci.* (16), 10–14. Available at https://d.wanfangdata.com.cn/periodical/ChlQZXJpb2RpY2FsQ0hJTmV3UzIwMjEwNzIzEhdRS1YyMDE5MjAxOTEwMTcwMDExMzU2ORoIbDduMW9sbWg%3D.

Zeitlberger, A. C. M., and Brauneis, A. (2016). Modeling Carbon Spot and Futures price Returns with GARCH and Markov Switching GARCH Models. *Cent. Eur. J. Oper. Res.* 24 (1), 149–176. doi:10.1007/s10100-014-0340-0

Zhao, J. (2012). Research on EU Carbon Futures Price and Energy Price [J]. *Finance Econ.* (14), 92–94. doi:10.3969/j.issn.1007-0753.2012.07.038

Zhao, S. (2016). A Comparative Analysis of Price Fluctuations in the Chinese Carbon Emission Rights Market and the European Market[J]. *China Market* (13), 86–94. doi:10.13939/j.cnki.zgsc.2016.13.086

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.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 26 October 2021
doi: 10.3389/fenrg.2021.764914

International Trade as a Double-Edged Sword: The Perspective of Carbon Emissions

*Jialin Gao[1], Fengfeng Gao[2], Bo Yin[3] and Mengwan Zhang[2]**

[1]Postdoctoral Research Station of China Banking and Insurance Regulatory Commission, School of Economics and Management, Tsinghua University, Beijing, China, [2]School of Economics and Management, Beijing University of Technology, Beijing, China, [3]Europe Office of Global Energy Interconnection Development and Cooperation Organization, Brussels, Belgium

OPEN ACCESS

Edited by:
Kangyin Dong,
University of International Business and Economics, China

Reviewed by:
Zewen Ge,
Shanghai Jiao Tong University, China
Pengfei Zhang,
Shandong University, China
Mingkun Jiang,
East China University of Science and Technology, China

****Correspondence:***
Mengwan Zhang
alicezmw@163.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies,
a section of the journal Frontiers in Energy Research

Received: *26 August 2021*
Accepted: *08 October 2021*
Published: *26 October 2021*

Citation:
Gao J, Gao F, Yin B and Zhang M (2021) International Trade as a Double-Edged Sword: The Perspective of Carbon Emissions.
Front. Energy Res. 9:764914.
doi: 10.3389/fenrg.2021.764914

Due to the rapid growth of fossil energy consumption, countries worldwide have paid considerable attention to reducing carbon emissions. Moreover, with economic globalization and trade liberalization, exploring the relationship between foreign trade and carbon emission reduction has become increasingly critical. Exploring this relationship can aid in establishing suitable recommendations for global carbon emission reductions. This paper uses a spatial econometric model and a dynamic panel threshold model to empirically test the spatial effect, nonlinear effect, and heterogeneous effect of foreign trade on global carbon emissions. All the above models are based on the construction of the economic weight matrix of different countries. The results reveal that 1) carbon emissions in various countries exhibit with significant spatial spillover in the overall spatial context; 2) foreign trade has a significant role in promoting carbon emissions in local and similar economic areas, but it has an apparent dual-threshold effect on economic development; and 3) there are significant differences in the impact of foreign trade on carbon emissions in different regions and different periods. Therefore, in the process of global economic integration, based on their development stages and comparative advantages, countries can focus on overall planning and coordination to promote the optimal allocation of resources and reduce carbon emissions.

Keywords: international trade, carbon emission reduction, space econometric, dynamic panel, heterogeneous test

INTRODUCTION

An urgent focus must be placed on reducing greenhouse gas emissions and controlling climate change. The rapid development of industrialization has dramatically improved people's living standards. However, the consumption of a large amount of fossil energy has led to a dramatic increase in CO2 emissions. According to the assessment report of the Intergovernmental Panel on Climate Change, over the past 50 years, global warming has largely been related to greenhouse gas emissions. The global average temperature is approximately 1.2°C higher than that before industrialization, and the six years between 2015 and 2020 were the warmest recorded in the history of meteorological observation. All countries, whether developed or developing, must assume responsibilities and obligations related to global climate change. At present, 126 countries and organizations around the world have promised to achieve the goal of "carbon neutrality". Twenty-two countries and regions have set the goal of carbon neutrality in the form of legislation and policies. In addition, carbon emission reduction has become a common research focus and an urgent issue in current global development (Li, et al., 2020). Moreover, in the process of industrialization, international trade has effectively promoted the growth of the world economy and enabled countries to realize comparative advantages, but it has also led to an international trade pattern with a centre-periphery structure, which has led to regionally varying carbon emissions.

There are two main problems in global carbon emissions and international trade. First, the transfer of products through trade may lead to disputes regarding carbon emission reduction responsibilities. In global supply and production chains, carbon emissions embedded in traded products are transferred through international trade. For example, developing countries usually export products associated with high energy consumption and high pollution and import low-pollution and high value-added products from developed countries. This process amplifies the carbon emission intensity through trade and leads to an imbalance in the carbon emission reduction burden between exporting and importing countries, leading to potential conflicts (Zhang, et al., 2020). Second, additional green barriers and carbon tax competition may impact the free trade system. After years of industrial development, most developed countries have achieved a carbon peak, and their carbon neutralization strategies were implemented at various points in the past. However, the application of low-carbon technology and equipment renewal have increased the production costs of enterprises. To protect domestic enterprises, developed countries may introduce carbon tariffs or raise environmental protection standards to set obstacles to international trade. For example, the European Union has introduced the "carbon border adjustment mechanism", which levies taxes on countries' goods in a slow emission reduction process, thus forming *de facto* trade barriers and increasing the costs to exporting countries (Chu, et al., 2021).

International trade and energy economics have been identified among the top-ten research topics of current economic studies (Luo, et al., 2021). With the acceleration of global carbon neutrality, developing export-oriented economies face heavy pressure to reduce emissions, and exporting countries may require importing countries to assume more carbon emission responsibilities, which may increase international carbon emission responsibility disputes and trade frictions. Moreover, the increase in green barriers may create obstacles for the international trading system. In addition, under the condition of noncooperative emission reduction, the phenomenon of free riding occasionally occurs, causing a "tragedy of the commons".

Hence, this paper focuses on clarifying the impact of international trade on carbon emissions. There are several issues that need to be addressed, such as the effect of international trade on carbon emissions, whether international trade can be an opportunity for countries to reach their carbon emission reduction goals, and whether countries with different regional economic development levels have the same carbon emission reduction level. This paper systematically investigates the carbon emission reduction effect of foreign trade from different perspectives to provide theoretical and empirical support for countries worldwide to better cope with energy development. In the next section, a literature review is conducted to analyse the existing research and identify research gaps.

LITERATURE REVIEW

Reducing carbon emissions and addressing global climate change have become unified goals worldwide (Chang, et al., 2019). However, agreement about how international trade influences carbon emissions has not been reached. Some scholars have suggested that the rapid growth of international trade has led to carbon emission issues. For example, Zhong et al. (2021) analysed the impact of international trade on carbon emission reductions based on the global value chain. With evidence from 39 major economies, they found that the development of international trade has led to a 5% increase in the interregional flow of carbon emissions, on average. Wang et al. (2021) found that China's energy consumption increased due to the expansion of the international trade scale. Shi et al. (2020) focused on countries from the Belt and Road region using a threshold model and discovered a nonlinear relation between international trade and carbon emissions. Wang W et al. (2019) discovered that the ratio of embodied carbon per unit value-added exports to embodied carbon per unit value-added imports is much lower in developed countries than in developing countries, indicating that developed countries have obtained higher trade benefits at relatively low environmental costs. This finding suggests that developed countries are in an advantageous position in relation to embodied carbon flows in global trade. Wang L et al. (2020) found that with the development of international trade, environmental quality is threatened by an increasing energy demand, which has also led to an increase in carbon emissions.

Some scholars have reported that international trade can reduce carbon emissions. For instance, Kerui et al. (2020), using approximately 116 panel datasets from 1986 to 2014, indicated that international trade could improve carbon emission reductions and increase income, and the greater the increase in income is, the higher the carbon emission reduction. Li et al. (2019) showed the positive effects of international trade on carbon emission reduction. China's high level of technological development has led to reduced carbon emissions in the context of international trade. Wang et al. (2018) found that improving the level of economic expansion and enhanced foreign trade are conducive to improving environmental effects. Khan et al. (2020) analysed international trade in G7 countries and identified the relationship among international trade, carbon emission reduction, and renewable energy, thereby discovering a sustainable environment for G7 countries. Misak et al. (2018) also studied international trade, carbon emissions and other factors, such as model choice and international transport. The results indicated that establishing international transport laws can help reduce carbon emissions within international trade. Sun et al. (2019) also considered international trade and carbon emission reduction in conjunction with green innovation and energy efficiency.

In the research on international trade and carbon emissions, several methods have been applied. For example, Wang S et al. (2020) used a stochastic regression model to determine the best path to reach a carbon emission reduction target. Carbon emissions can also be calculated through an accounting framework with investment-based methods (Zhang, et al., 2020). Moreover, intertemporal mechanisms were provided by Bednar et al. (2021) to encourage countries to take responsibility for carbon emissions in the international trade market. Adnan et al. (2021) used second- and third-panel cointegration methods, and the results indicated that cross-sectional dependency and heterogeneity confirm the correlations among panels in the study. Moreover, technological innovation can reduce carbon emissions in international trade. Baloch et al. (2018) used the autoregressive distributed lag (ARDL) model, vector error correction (VEC) model and regressive threshold model to estimate carbon emission reductions and identify financial instability within an international trade background.

RESEARCH GAPS

The literature review indicated that many scholars have examined international trade and carbon emissions, but research gaps still exist. First, few researchers have systematically investigated the impact of foreign trade on carbon emission reduction in countries worldwide from a spatial perspective based on economic geography. Second, few studies have considered the overall context of international trade and carbon emissions. Through heterogeneity analysis, this paper examines the heterogeneous effects of international trade on carbon emissions in different countries and at different times and refines the research on the impact of international trade on carbon emissions. The marginal contribution of this paper is three-fold. First, the spatial spillover effect of foreign trade and carbon emissions are studied by using dynamic spatial models, including the Durbin model and a spatial autoregression model, thus expanding upon the existing research. Second, a dynamic threshold panel model is used to discuss the dynamic relationship between foreign trade and carbon emissions and obtain scientifically valid estimation results.

METHODS

Research Hypotheses

Countries can meet their own consumption needs by importing products while avoiding the responsibility of reducing the emission of carbon dioxide and other greenhouse gases. Therefore, international trade and industrial transfer generally increase the total carbon emissions of the host country. To a certain extent, international trade forces a country to optimize and upgrade its industrial structure, which is conducive to energy efficiency improvement. However, carbon emission reduction is characterised by global externalities. Different countries have different emission reduction capabilities, historical responsibilities, environmental protection strategies, and free-riding problems, which may cause cross-border transfers of carbon emissions through international investment and trade, resulting in "carbon leakage". Therefore, we formulate research Hypothesis 1 as follows.

Research Hypothesis 1: International Trade has a Spatial Spillover Effect on the Carbon Emission

Antweiler et al. (2001) believed that technological level improvements can reduce the pollution caused by trade and that international trade is beneficial to the environment. Therefore, developing international trade is conducive to improving the environment and reducing carbon emissions. However, with regional development, the introduction of advanced technology, the optimization and upgrading of the industrial structure and the elimination of backward production capacity, the allocation of carbon resources tends to be optimized, and carbon emissions are reduced. In addition, economic improvements increase the environmental protection requirements of products, which result in the development of high-tech and low-polluting products and help reduce carbon emissions. Therefore, we formulate research Hypothesis 2 as follows.

Research Hypothesis 2: The impact of international trade on carbon emissions exhibits nonlinear changes due to different levels of economic development, with a certain threshold effect.

Model Setting

The Dynamic Spatial Model

To explore the impact of international trade on carbon emissions, we establish a dynamic spatial model as follows:

$$lnCarr_{i,t} = \alpha + \beta_1 WLNCarr_{2i,t} + \beta_2 WLNCarr_{2i,t-1} + \rho_1 open_{i,t} + \rho_1 Wopen_{i,t} + \delta X_{i,t} + \mu_i + \mu_t + \varepsilon_{i,t} \tag{1}$$

In **Eq. 1**, i stands for the country; t is time; LNCarr represents the log of carbon emission intensity; open stands for foreign trade; X is a series of control variables; $\beta_1, \beta_2, \rho_1, \rho_2$ and δ represent the estimation coefficients of the respective variables; μ_i and μ_t are spatial and temporal effects; $\varepsilon_{i,t}$ is the residual term; W is a spatial weight matrix; and α is a constant term.

The Dynamic Threshold Model

The effect of international trade on carbon emissions varies in different countries. Therefore, a dynamic threshold model is necessary and can be expressed as follows:

$$\begin{aligned} lnCarr_{2i,t} = {} & \mu_1 + lnCarr_{2i,t-1} + \beta open_{i,t} + \delta X_{i,t} + \lambda WLNCO_{2i,t} \\ & + \lambda_1 lnopen_{i,t} * I\left(LNPGDP_{i,t} \le \gamma_1\right) \\ & + \lambda_2 lnopen_{i,t} * I\left(LNPGDP_{i,t} \le \gamma_2\right) \\ & + \lambda_3 lnopen_{i,t} * I\left(LNPGDP_{i,t} \le \gamma_3\right) + \varepsilon_{i,t} \end{aligned} \tag{2}$$

In **Eq. 2**, λ_1, λ_2, and λ_3 are the coefficients of the influence of the foreign trade level on carbon emissions at different threshold intervals based on the economic development level; $LNPGDP_{i,t}$ is a threshold variable; γ is the threshold estimate; γ_1 and γ_2 represent the first threshold value and the second threshold value, respectively; $I(\cdot)$ is an indicator function; and the other variables are set as described above.

Moran's Index Model

To perform a spatial correlation test, Moran's index was used to test foreign trade and carbon emissions based on the corresponding autocorrelation. According to Moran's theory, when the Moran's index varies from 0–1, a positive relation exists. The formula for the Moran's index is as follows:

$$M = \frac{q}{T_0} \frac{\sum_{i=1}^{q} \sum_{k=1}^{q} A_{i,k} B_i B_k}{\sum_{i=1}^{q} B_i^2} \tag{3}$$

In **Eq. 3**, B_i is the deviation between the attribute value for sector i and the average value $(O_i - \bar{O})$; $A_{i,k}$ represents the spatial weights between sectors i and k; q refers to the total number of sectors; and T_o is the sum of all the spatial weights. When Moran's M > 0, a positive spatial correlation exists, and a high value indicates a high correlation. When Moran's M < 0, a negative spatial correlation exists, and a low value represents a large spatial difference. When Moran's M = 0, the spatial correlation is random.

VARIABLE DESCRIPTIONS AND DATA SOURCES

Explained Variable

This paper selects the carbon emission intensity ($LNcarr_{2i,t}$) as the explained variable; it is calculated based on the CO_2 emissions per unit Gross Domestic Product (GDP).

Core Explanatory Variable

This paper selects foreign trade (Open) as the core explanatory variable. This variable is equal to the ratio of import and export trade to the GDP and is used to express the foreign trade level of a country or region.

Control Variables

There are six control variables in this paper: PGDP, Urban, Industry, People, Foreign Direct Investment (FDI) and GDPdeflator.

PGDP refers to the per capita GDP, which is the GDP divided by the population of the country. Urban refers to the proportion of the urban population to the total population of the country. Industry refers to the ratio of the added value of secondary industry to GDP. People refers to the number of people per unit area. FDI refers to the ratio of FDI stock to the GDP of a country. The GDPdeflator measures inflation based on the GDP in the current year divided by the GDP in the previous year.

Data Sources

To investigate the effect of international trade on carbon emissions, this paper empirically examines the corresponding trade-emissions relationship using a spatial measurement model and a dynamic threshold model. In total, 17 of the G20 countries were selected as the sample in this paper based on the availability of data (Refer to **Appendix Table A1**). The explained variable "LNCarr" is the log of the carbon emission intensity, with a unit of million tons, and the corresponding data source is the BP database. The core explanatory variable "Open" refers to the ratio of import and export trade to the GDP, with a unit of United States dollars, and the corresponding data source is the World Integrated Trade Solution (WITS) database. The control variable "PGDP" is from the World Bank database, with a unit of United States dollars. "Urban", with a unit of people per square kilometre, is derived from the World Bank. "Industry" refers to the proportion of industrial output value in the GDP, with a unit of United States dollars, and the corresponding data source is the World Bank. "People" refers to the population density, with a unit of people per square kilometre, and the data source is the World Bank. "FDI" refers to the proportion of foreign direct investment stock in the GDP, with a unit of %, and the corresponding data source is the United Nations Conference on Trade and Development (UNCTAD) database. "GDPdeflator", in %, is derived from the World Bank. The above data were obtained from 1996 to 2018, and the corresponding descriptive statistics (e.g., mean, SD, minimum value and maximum value) are shown in **Table 1**.

EMPIRICAL RESULTS

Results of Moran's Index Calculations

The Moran's index calculation results are listed in **Table 2**. The results show that Moran's M > 0 in all years except 2015. The results also indicate that the Moran's index for carbon emissions and foreign trade fluctuated between approximately 0.22 and 0.559 from 1996 to 2018, exhibiting significant positive spatial

TABLE 1 | Descriptive statistics for the considered variables.

	Variables	Obs	Mean	SD	Min	Max
Explained	LNCarr	391	6.251494	0.8504613	4.660,028	8.90654
Core explanatory	Open	391	0.396318	0.143,606	0.1186059	0.8613456
	PGDP	391	21,533.68	17,588.19	399.95	68,150.11
	Urban	391	70.63276	15.84259	26.82	91.62
Control	Industry	391	28.54	7.40	17.07	48.06
	People	391	151.75	146.99	2.38	529.19
	FDI	391	34.51	56.51	0.61	425.37
	GDPdeflator	391	1.058579	0.1269025	0.4424	1.5176

SD, Min and Max denote the standard deviation, minimum and maximum, respectively.

TABLE 2 | Moran's index results regarding the effect of foreign trade on carbon emissions.

Year	Moran's M	Year	Moran's M
1996	0.336	2008	0.366
1997	0.433	2009	0.33
1998	0.496	2010	0.328
1999	0.415	2011	0.325
2000	0.379	2012	0.401
2001	0.412	2013	0.559
2002	0.517	2014	0
2003	0.446	2015	0.271
2004	0.484	2016	0.22
2005	0.576	2017	0.352
2006	0.356	2018	0.362
2007	0.391		

TABLE 3 | Empirical analysis results regarding the effect of foreign trade on carbon emissions.

	LNCARR			
VARIABLES	(1)	(2)	(3)	(4)
	SAR	SDM	GMM	OLS
L.LNCarr			0.825*** (32.86)	
Open	0.351***	0.495***	0.241***	0.443***
	(5.27)	(6.47)	(6.28)	(5.92)
Urban	0.030***	0.025***	0.004***	0.032***
	(18.46)	(12.97)	(3.20)	(17.57)
FDI	0.000	0.000	0.000	0.000
	(0.22)	(0.88)	(0.93)	(0.44)
People	0.004***	0.005***	0.000*	0.004***
	(10.06)	(10.66)	(1.70)	(8.64)
PGDP	−0.690***	−0.672***	−0.097***	−0.669***
	(−43.41)	(−40.40)	(−5.03)	(−37.43)
Industry	0.017***	0.015***	0.004***	0.020***
	(7.28)	(6.66)	(3.07)	(7.53)
GDPdeflator	−0.139***	−0.117***	−0.797***	−0.133***
	(−4.17)	(−3.81)	(−28.87)	(−3.50)
Constant			2.301***	9.330***
			(9.95)	(50.91)
ρ	−0.236***	−0.288***		
	(−7.51)	(−3.72)		
sigma2_e	0.004***	0.003***		
	(13.93)	(14.06)		
Observations	391	391	391	391
R-squared	0.8134	0.6425	0.9934	0.9718
Number of IDs	17	17	17	17

*Note: z-statistics in parentheses: ***p < 0.01, **p < 0.05, and *p < 0.1.*
SAR, SDM, GMM, and OLS denote the spatial lag regression model, spatial Durbin model, Gaussian mixture model, and ordinary least squares model, respectively.

dependence. This finding indicates that from the perspective of spatial correlation, an increase in international trade leads to an increase in carbon emissions. This result verifies research Hypothesis 1.

SAR, SDM, GMM and OLS Results

The robustness of the spatial econometric results for the panel dual fixed-effect model, GMM, SAR model, and SDM was assessed. The results are shown in **Table 3**. The trend and magnitude of the core explanatory variable coefficients are consistent, and the results pass the significance test, reflecting good model robustness.

Table 3 lists the empirical analysis results regarding the effect of foreign trade on carbon emissions. The first column in **Table 3** lists the variables, the second column gives the SAR results, the third column gives the SDM results, the fourth column gives the GMM results, and the fifth column gives the OLS results. First, the regression coefficient of carbon emissions with one-stage lag (L.LNCarr) is significantly positive, which indicates that there is a significant "temporal inertia" related to carbon emissions in various countries, with a specific "snowball effect". Second, the coefficients of ρ are −0.236 and −0.288, which are significantly negative. This result indicates that an increase in carbon emissions in a region has a significant negative impact in areas with a similar per capita GDP; that is, carbon emission reductions are transferred among regions through trade. The coefficient of foreign trade (open) is significantly positively related to the core explanatory variables, indicating that an increase in foreign trade in this region is positively correlated with the intensity of carbon emissions. This finding shows that foreign trade has a positive spatial spillover effect on carbon emissions. In addition, the degree of urbanization, population density, and the proportion of industrial output value are all positively correlated with the carbon emission intensity, which is in line with expectations. The SAR, SDM, GMM and OLS results all validate research Hypothesis 1.

Analysis of the Regression Results for Threshold Effects

The single and dual thresholds in **Table 4** pass the significance test, but the triple threshold fails, which means there is a dual-threshold effect. In addition, **Table 5** shows that the threshold values in the 95% confidence interval are 8.5345 and 10.4494. To intuitively express this results, further delogarithmic processing is performed. The values after delogarithmic processing correspond to the regional per capita GDP, with threshold values of 5,087.29 United States dollars and 34,523.65 United States dollars. Therefore, the global economic development stage can be divided into three threshold intervals. The first threshold interval is GDP per capita values less than 4,337.27 United States dollars. The second threshold interval is GDP per capita values between 4,337.27 United States dollars and 34,523.65 United States dollars. The third threshold interval is GDP per capita values above 34,523.65 United States dollars. Thus, research Hypothesis 2 in this paper is validated.

Based on **Table 6**, a high level of foreign trade significantly inhibits carbon emissions. Specifically, if a region is in the first threshold range and the regional economy is underdeveloped, foreign trade positively promotes regional carbon emissions. To catch up with economically developed areas, financially underdeveloped areas consume many natural resources at the expense of the environment. This process increases carbon emissions. When the regional economic development level passes the second threshold, there is a gradual shift from a state of underdevelopment to a moderate development level.

TABLE 4 | Threshold estimation and test results.

Model	F- statistic	Prob	Bootstrap time	Critical value		
				10%	5%	1%
Single threshold	109.57	0.09	300	106.2615	122.2793	171.7156
Double threshold	166.79	0.000	300	68.8225	78.3972	119.7082
Triple threshold	61.53	0.7133	300	159.836	187.1816	272.5536

TABLE 5 | Threshold estimation and confidence intervals.

	Threshold	95%
Threshold 1	8.3193	[8.2599, 8.3227]
Threshold 2–1	8.5345	[8.4532, 8.5499]
Threshold 2–2	10.4494	[10.4245, 10.4521]

TABLE 6 | Results of the threshold effect model.

Interpreted variable	Elasticity coefficient	t-statistic	Prob
λ_1	0.3768076	6.56	0.000
λ_2	0.114,673	3.48	0.001
λ_3	0.057255	1.73	0.085

The promoting effect of foreign trade on carbon emissions disappears and gradually changes to inhibition. When the economic development level passes the third threshold, the economy becomes relatively developed, and foreign trade significantly inhibits carbon emissions. Notably, economically developed areas can introduce advanced technology and achieve a high resource utilization efficiency; therefore, increasing trade helps allocate resources to achieve a comparative advantage, reduce the consumption of ecological resources and restrain carbon emissions. Hypothesis 2 is confirmed, which suggests that the impact of foreign trade on carbon emissions nonlinearly varies according to different levels of economic development.

HETEROGENEITY TEST

To investigate the heterogeneity in the relationship between international trade and carbon emissions, this paper conducts extensive tests on regional and temporal heterogeneity.

Regional Heterogeneity Tests

The results regarding regional heterogeneity indicate that countries with high economic development levels focus on the introduction of clean technologies when developing foreign trade, which can restrain carbon emissions. The foreign trade coefficient is significantly negative in non-BRICS G20 countries but highly positive in BRICS countries. BRICS countries are characterised by relatively backward economic development. In the early period of development, rapid economic growth is achieved at the expense of environmental damage, thus increasing carbon emissions. The above results suggest that the impact of international trade on carbon emissions varies across G20 countries. Therefore, different countries will choose different strategies to reduce carbon emissions in the future.

Temporal Heterogeneity Tests

The results of temporal heterogeneity tests are analysed over two periods: from 1996 to 2000 and from 2000 to 2018. According to the results shown in **Table 7**, the coefficient of foreign trade is positive. Between 1996 and 2000, which was part of the early stage of economic development, economic growth mainly involved a large amount of energy consumption. In comparison, between 2000 and 2018, the coefficient of foreign trade was significantly negative. This trend reveals that with the rapid economic development achieved by increased foreign trade, environmental protection was enhanced, and advanced technology was introduced. Most countries have recognized the importance of reducing carbon emissions. To a certain extent, pollution prevention and control were thus improved, and carbon emission reductions were achieved. These changes are associated with certain stages, dynamics, and continuity characteristics of the impact of foreign trade on carbon emissions.

Finally, based on the results of the regional heterogeneity tests and temporal heterogeneity tests, international trade can affect carbon emissions, and this relationship exhibits periodic features and dynamic characteristics.

ROBUSTNESS TEST

The above results and tables show that international trade generally promotes carbon emissions. To assess the robustness of the above results, this section presents a robustness test, and the results are listed in **Table 8**. Specifically, a variable substitution method is used in this assessment. The logarithm of the carbon emission intensity is replaced by the logarithm of the carbon emissions of a country. As shown in **Table 8**, the OLS and GMM trends reflect the moderate effect of international trade on carbon emission reductions. For the core explanatory variable Open, the OLS, GMM, SDM and SAR results are all significant, and the core explanatory variables are highly robust. For the control variables PGDP, Urban, Industry, People, and FDI, the OLS, GMM, SDM and SAR results are all significant. Although the OLS, SDM, and

TABLE 7 | Results of the heterogeneity tests.

	LNCARR			
Variables	**(1)**	**(2)**	**(3)**	**(4)**
	Non-BRICS	**BRICS**	**Years 1996–2000**	**Years 2000–2018**
Open	−0.312***	0.766***	0.125	−0.457***
	(−3.17)	(3.30)	(1.03)	(−3.95)
Urban	0.017***	0.034***	0.020***	0.021***
	(4.70)	(10.45)	(3.08)	(5.09)
FDI	0.000	0.006*	−0.000	−0.001**
	(1.56)	(1.99)	(-0.15)	(−2.14)
People	0.003**	0.003***	0.001	0.004***
	(2.33)	(4.55)	(1.06)	(4.93)
PGDP	−0.960***	−0.697***	−0.924***	−0.904***
	(−35.56)	(−13.90)	(−26.44)	(−38.66)
Industry	0.037***	0.011	0.003	0.034***
	(9.02)	(1.60)	(0.66)	(7.06)
GDPdeflator	0.053	0.081	0.015	0.006
	(0.93)	(0.91)	(0.55)	(0.11)
Constant	12.688***	9.866***	13.231***	11.883***
	(38.43)	(20.21)	(24.12)	(38.70)
Observations	276	115	85	306
Number of IDs	12	5	17	17
R-squared	0.917	0.982	0.967	0.914

*Notice: z-statistics in parentheses: ***p < 0.01, **p < 0.05, and *p < 0.1.*

TABLE 8 | Results of the robustness test.

	LNcarbon			
Variables	**OLS**	**GMM**	**SDM**	**SAR**
L.LNCarbon		0.888***		
		(41.57)		
Open	0.272***	0.145***	0.320***	0.169**
	(3.08)	(3.96)	(3.64)	(2.07)
Urban	0.034***	0.002**	0.026***	0.032***
	(15.66)	(2.04)	(11.67)	(16.54)
FDI	0.000**	0.000**	0.001***	0.000***
	(2.20)	(1.98)	(2.80)	(2.70)
People	0.005***	0.000*	0.005***	0.004***
	(10.26)	(1.81)	(10.63)	(9.44)
PGDP	0.315***	0.060***	0.286***	0.258***
	(14.97)	(5.51)	(14.50)	(11.80)
Industry	0.025***	0.004***	0.019***	0.026***
	(7.96)	(2.90)	(7.34)	(8.94)
GDPdeflator	−0.167***	0.034*	−0.136***	−0.142***
	(−3.72)	(1.85)	(−3.88)	(−3.47)
Constant	−0.086	−0.230**		
	(−0.40)	(−2.53)		
rho			−0.296***	0.240***
			(−3.85)	(5.35)
sigma2_e			0.004***	0.006***
			(13.80)	(13.92)
Observations	391	374	391	391
Number of IDs	17	17	17	17
R-squared	0.8347	0.9723	0.6155	0.6695

*Notice: t-statistics in parentheses: ***p < 0.01, **p < 0.05, and *p < 0.1.*
OLS, GMM, SDM and SAR denote the ordinary least squares model, generalized method of moments model, spatial Durbin model, and spatial autoregression model, respectively.

SAR results for GDPdeflator are below 0, the GMM result is 1.85. The overall results are significant; therefore, they verify the previous results. Moreover, the robustness test shows that the measurement of the explained variables does not influence the core conclusions of this paper.

CONCLUSION AND POLICY IMPLICATIONS

Conclusion

Based on the above results, the conclusions of this paper are as follows: 1) The spatial correlation indicates significant positive spatial dependence between international trade and carbon emissions. 2) The spatial econometric model results indicate that foreign trade has a positive spatial spillover effect on the carbon emissions of countries with similar local development levels. The growth of foreign trade promotes carbon emissions to a certain extent. 3) The regression results for the threshold effect indicate that the impact of foreign trade on carbon emissions in various countries has a noticeable dual-threshold effect on the economic development level, with threshold values of GDP per capita of 5,087.29 United States dollars and 34,523.65 United States dollars. Thus, three threshold intervals are delineated to indicate the different stages of economic development. 4) The heterogeneity test results indicate that foreign trade impacts carbon emissions differently in different regions and different periods and that the spatial spillover effect is characterised by regional and temporal heterogeneity, with certain stages, dynamics, and continuity.

International trade is important for a country's economic development, but carbon emission reduction is also necessary. Hence, research on the relationship between international trade and economic development and the corresponding effects has significant value for long-term development. For instance, the international trade war between China and the United States has led to a reduction in current carbon emissions. China has reduced its carbon emissions by 3,621.11–4,031.52 ten thousand tons, and the United States has reduced its carbon emissions by 214.6–314.59 ten thousand tons. However, the international trade war may also lead to a carbon increase in other countries (Zhang, et al., 2021).

In current research, the relationship between international trade and carbon emissions is still mainly viewed from two perspectives. One view posits that international trade increases carbon emissions, and the other posits that international trade reduces carbon emissions. The results of studies adopting different perspectives, variables, and research methods can contradict each other. For example, international trade between China and the United States has led to emissions issues because global shipping generates 938 million tons of carbon emissions per year (Lin, et al., 2014; Liu, et al., 2019; Zhang, et al., 2017). Kazakhstan can develop green energy to reach the goal of a green economy (Wang X, et al., 2019), and China can improve agricultural technology to mitigate poor energy use (Jiang et al., 2020). Dietzenbacher et al., 2020 proposed accounting methods to encourage countries to develop an effective energy policy in relation to international trade and establish a reward and punishment system as a useful way to reach the established goals. In addition to benefiting from low-carbon industries, high-income countries develop leading low-carbon technologies and management modes based on their advantages in technology, talent, capital, and awareness of environmental protection, thus contributing to carbon reduction (Qin, 2020). According to above literatures, international trade as a double-edged sword impacts the carbon emissions. Therefore, in future research, more scholars need to study the relationship between international trade and carbon emissions.

Policy Implications

The results of this paper highlights several policy implications for further development, and they are listed below.

1) Promote the low-carbon transformation of foreign trade strategies according to the conditions in different countries. While maintaining the current development trend, countries can formulate differentiation strategies according to the threshold effect of economic development. They should also strengthen environmental supervision while expanding foreign trade. For instance, mandatory corporate social responsibility information disclosure, which is conducive to corporate green technological innovation, can be supported to finally achieve a win-win situation between the economy and environment. For instance, countries in threshold 1 should improve their particular strengths to increase the GDP rather than rely on international trade because in threshold 1, international trade increases carbon emissions. Countries with a threshold of 2–1 should balance industrial development to prevent carbon emissions. For countries with a threshold of 2–2, although international trade can reduce carbon emissions, they should identify green development methods for the future.
2) Strengthen international coordination and urge developed countries to assume more responsibilities in trade. The impact of carbon dioxide on climate is the same everywhere. Due to the gap between output and energy efficiency, the carbon emissions of the same products produced in different countries vary. The international trade mode of production in low-income countries and consumption in high-income countries is associated with high carbon emissions. Therefore, developed countries should provide financial and technical support to developing countries to help them improve their overall energy efficiency and reduce emissions.
3) Monitor the different relationships between international trade and carbon emission reductions and adjust the relationships considering the associated dynamics. This approach requires relevant departments to understand the development trends of international trade and carbon emissions. Moreover, different countries can adopt certain methods to reduce carbon emissions without restricting international trade. For example, to reduce carbon emissions, China has focused on establishing new transitional policies.

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

JG: Thesis Writing; FG and BY: Data processing; MZ: Data analysis, thesis writing and correction. All authors contributed to the paper and approved the submitted version.

FUNDING

This article supported by Beijing Postdoctoral Research Foundation (Q6011019202101), the Key Projects of the National Social Science Foundation (19AZD004).

ACKNOWLEDGMENTS

Thankful for the comments and suggestions that given by the reviewers. They have improved the content of this paper and pointed out research directions of particular interest.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2021.764914/full#supplementary-material

REFERENCES

Antweiler, W., Copeland, B. R., and Taylor, M. S. (2001). Is Free Trade Good for the Environment. *Am. Econ. Rev.* 91 (4), 877–908. doi:10.1257/aer.91.4.877

Avetisyan, M. (2018). Impacts of Global Carbon Pricing on International Trade, Modal Choice and Emissions from International Transport. *Energ. Econ.* 76, 532–548. doi:10.1016/j.eneco.2018.10.020

Baloch, M. A., DanishMeng, F., Zhang, J., and Xu, Z. (2018). Financial Instability and CO2 Emissions: the Case of Saudi Arabia. *Environ. Sci. Pollut. Res.* 25 (26), 26030–26045. doi:10.1007/s11356-018-2654-2

Bednar, J., Obersteiner, M., Baklanov, A., Thomson, M., Wagner, F., Geden, O., et al. (2021). Operationalizing the Net-Negative Carbon Economy. *Nature* 596, 377–383. doi:10.1038/s41586-021-03723-9

Chang, C.-P., Dong, M., Sui, B., and Chu, Y. (2019). Driving Forces of Global Carbon Emissions: From Time- and Spatial-Dynamic Perspectives. *Econ. Model.* 77, 70–80. doi:10.1016/j.econmod.2019.01.021

Chu, J., Shao, C., Emrouznejad, A., Wu, J., and Yuan, Z. (2021) Performance Evaluation of Organizations Considering Economic Incentives for Emission Reduction: A Carbon Emission Permit Trading Approach, *Energ. Econ.*, 101, 105398, doi:10.1016/j.eneco.2021.105398

Dietzenbacher, E., Cazcarro, I., and Arto, I. (2020). Towards a more effective climate policy on international trade. *Nat Commun* 11, 1130. doi:10.1016/j.eneco.2021.105398

Du, K., Yu, Y., and Li, J. (2020). Does International Trade Promote CO2 Emission Performance? an Empirical Analysis Based on a Partially Linear Functional-Coefficient Panel Data Model. *Energ. Econ.* 92, 104983. doi:10.1016/j.eneco.2020.104983

Jiang, S. J., Deng, X. Z., Xiao-xue, Z., and Guo-feng, W. (2020). Quantitative Predictions of Impacts of Trade Friction between China and the US on Wheat Trade and its Embodied Carbon Emissions[J]. *J. Agro-Environment Sci.* 39 (4), 762–773.

Khan, Z., Ali, S., Umar, M., Kirikkaleli, D., and Jiao, Z. (2020). Consumption-based Carbon Emissions and International Trade in G7 Countries: The Role of Environmental Innovation and Renewable Energy. *Sci. Total Environ.* 730, 138945. doi:10.1016/j.scitotenv.2020.138945

Li, S., and Wang, S. (2019). Examining the Effects of Socioeconomic Development on China's Carbon Productivity: A Panel Data Analysis. *Sci. Total Environ.* 659, 681–690. doi:10.1016/j.scitotenv.2018.12.409

Lin, J., Pan, D., Davis, S. J., Zhang, Q., He, K., Wang, C., et al. (2014). China's International Trade and Air Pollution in the United States. *Proc. Natl. Acad. Sci. USA* 111, 1736–1741. doi:10.1073/pnas.1312860111

Liu, H., Meng, Z.-H., Lv, Z.-F., Wang, X.-T., Deng, F.-Y., Liu, Y., et al. (2019). Emissions and Health Impacts from Global Shipping Embodied in US-China Bilateral Trade. *Nat. Sustain.* 2, 1027–1033. doi:10.1038/s41893-019-0414-z

Lu, Q., Fang, K., Heijungs, R., Feng, K., Li, J., Wen, Q., et al. (2020). Imbalance and Drivers of Carbon Emissions Embodied in Trade along the Belt and Road Initiative. *Appl. Energ.* 280, 115934. doi:10.1016/j.apenergy.2020.115934

Luo, R., Li, Q., and Xie, X. (2021) Analysis of Hot Spots of Chinese Economics Research in 2020. *Econ. Dyn.*., 38–57.

Safi, A., Chen, Y., Wahab, S., Ali, S., Yi, X., and Imran, M. (2021). Financial Instability and Consumption-Based Carbon Emission in E-7 Countries: The Role of Trade and Economic Growth. *Sustainable Prod. Consumption* 27, 383–391. doi:10.1016/j.spc.2020.10.034

Shi, Z., and Trigkas, V. (2020). Reconstructing Geography, Power and Politics in the Belt and Road Initiative. *Investment Res.* (06), 67–92. doi:10.1007/978-3-030-53153-9_4

Sun, H., Edziah, B. K., Sun, C., and Kporsu, A. K., and (2019). Institutional Quality, green Innovation and Energy Efficiency. *Energy Policy* 135, 111002. doi:10.1016/j.enpol.2019.111002

Wang, Di., Liu, X., Yang, X., Zhang, Z., Wen, X., and Zhao, Y. (2021). China's Energy Transition Policy Expectation and its CO2 Emission Reduction Effect Assessment. *Front. Energ. Res.* 8, P410. doi:10.3389/fenrg.2020.627096

Wang, L., Chang, H. L., Sari, A., Rizvi, S. K. A., and Sari, A. (2020). Are Eco-Innovation and export Diversification Mutually Exclusive to Control Carbon Emissions in G-7 Countries. *J. Environ. Manage.* 270, 110829. doi:10.1016/j.jenvman.2020.110829

Wang, p., Du, G., and Jiang, X.(2018). Study on the Structural Decomposition of Implied Carbon Emissions in China's export Trade — Based on the Comparative Analysis of Industrial Trade Carbon Emissions Data between China and its Trading Partners [J]. *Price Theor. Pract.*,

Wang, S., Yun, T., Zehua, D., and Malin, S. (2020). Export Trade, Embodied Carbon Emissions, and Environmental Pollution: An Empirical Analysis of China's High- and New-Technology Industries. *J. Environ. Manage.* 276, 111371. doi:10.1016/j.jenvman.2020.111371

Wang, W., Yang, S., and Wang, Y. (2019). Shared Responsibility for Embodied Carbon in Global Trade and its Cross-Regional Compensation[J]. *Environ. Econ. Res.*, (3): 30–47.

Wang, X., Heran, Z., Zhenyu, W., Yuli, S., Jing, M., Xi, L., et al. (2019). Kazakhstan's CO2 Emissions in the post-Kyoto Protocol Era: Production- and Consumption-Based Analysis, *J. Environ. Manage.*, 249, 109393, 2019, ISSN 0301-4797, doi:10.1016/j.jenvman.2019.109393

Xiang, L., Theodoros, D., Stadler, Z., Stefano, M., Meier, B., Markus, F., et al. (2020). Decarbonization in Complex Energy Systems: A Study on the Feasibility of Carbon Neutrality for Switzerland in 2050. *Front. Energ. Res.* 8, 274. doi:10.3389/fenrg.2020.549615

Zhang, Q., Jiang, X., Tong, D., Davis, S. J., Zhao, H., Geng, G., et al. (2017). Transboundary Health Impacts of Transported Global Air Pollution and International Trade. *Nature* 543, 705–709. doi:10.1038/nature21712

Zhang, Z., Guan, D., Wang, R., Meng, J., Zheng, H., Zhu, K., et al. (2020). Embodied Carbon Emissions in the Supply Chains of Multinational Enterprises. *Nat. Clim. Chang.* 10, 1096–1101. doi:10.1038/s41558-020-0895-9

Zhong, Z., Zhifang, G., and Jianwu, Z. (2021). Does Participation in Global Value Chains Promote Interregional Carbon Emissions Transferring via Trade? Evidence from 39 Major Economies. *Technol. Forecast. Soc. Change* 169, 120806. doi:10.1016/j.techfore.2021.120806

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: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

APPENDIX

TABLE A1 | The 17 countries of this paper.

17 Countries	Australia, Brazil, Germany, Russia, France, South Korea, Canada, United States, Mexico, South Africa, Japan, Turkey, Italy, India, Indonesia, United Kingdom, China

frontiers in Energy Research

ORIGINAL RESEARCH
published: 14 December 2021
doi: 10.3389/fenrg.2021.789871

Check for updates

Research on Time-Varying Two-Way Spillover Effects Between Carbon and Energy Markets: Empirical Evidence From China

Sen Qiao[1], Chen Xi Zhao[1], Kai Quan Zhang[2,3] and Zheng Yu Ren[4]*

[1]School of Business, Zhengzhou University, Zhengzhou, China, [2]School of Economics, Xiamen University, Xiamen, China, [3]School of Economics and Management, Longyan University, Longyan, China, [4]School of Business, Macau University of Science and Technology, Macau, China

OPEN ACCESS

Edited by:
Kangyin Dong,
University of International Business and Economics, China

Reviewed by:
Vidya C. T.,
Centre for Economic and Social Studies (CESS), India
Chi Lau,
Teesside University, United Kingdom

***Correspondence:**
Kai Quan Zhang
zhangkaiquan_ly@sina.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: 05 October 2021
Accepted: 15 November 2021
Published: 14 December 2021

Citation:
Qiao S, Zhao CX, Zhang KQ and Ren ZY (2021) Research on Time-Varying Two-Way Spillover Effects Between Carbon and Energy Markets: Empirical Evidence From China. Front. Energy Res. 9:789871. doi: 10.3389/fenrg.2021.789871

With the improvement of China's carbon emission trading system, the spillover effect between carbon and energy markets is becoming more and more prominent. This paper selects four representative pilot carbon markets, including Beijing (BEA), Guangdong (GDEA), Hubei (HBEA) and Shanghai (SHEA). And three representative energy markets, including Crude Oil Futures (SC), power index (L11655) and China Securities new energy index (NEI). Combining the rolling window technology with DY spillover index, set a 50-weeks rolling window to measure the spillover index, and deeply analyze the time-varying two-way spillover effect between China's carbon and energy markets. The results show that the spillover effect between China's carbon and energy markets has significant time variability and two-way asymmetry. The time-varying spillover effect of different carbon pilot markets on the energy market has regional heterogeneity. The volatility spillover effect of Beijing and Shanghai carbon markets mainly comes from the crude oil futures market, Guangdong carbon market mainly comes from the new energy market, and Hubei carbon market mainly comes from crude oil and electricity market. The above research results contribute to the prevention of potential risk spillover between carbon and energy markets, which can promote the establishment of China's unified carbon market and the prevention of systemic financial risks in energy market.

Keywords: carbon market, energy market, time-varying spillover, spillover index model, regional heterogeneity

INTRODUCTION

Climate change brought about by the increase of carbon emissions poses a serious threat to the ecosystem. As the world's largest energy consumer and carbon emitter, China attaches great importance to the energy and environmental problems caused by carbon emissions and actively participates in the construction of the global climate governance system (Mansanet-Bataller., 2007; Liu and Chen, 2013). The proposal of "double carbon" goal and the establishment of carbon market are broad and profound changes in the energy system (Sandra and Jūratė, 2018; Wang et al., 2021). Carbon market is widely regarded as an effective policy means to control global carbon emissions (Liu et al., 2021; Chen and Lin, 2021), which has a far-reaching impact on high emission industries, especially the thermal power industry (Todd et al., 2019; Qi et al., 2021). Generally, raising the carbon price can reduce the carbon emission of the thermal power industry (Jonathan et al., 2013; Zhu et al., 2017). China is dominated by thermal power, and more than 80% of carbon emissions come from the use of fossil energy (Gallego-Alvarez et al., 2015; Zhao et al., 2019). While limiting carbon emissions, the construction of carbon market also provides opportunities for the development of renewable energy (Zou et al., 2021; He et al., 2021). Therefore, developing low-carbon economy is a new way to seize the commanding height of a new round of world economic development and competition (Joanna, 2010; Li et al., 2021).

There is a close relationship between carbon market and energy market. When the carbon price fluctuates sharply, industrial enterprises may change the energy structure and affect the energy market. In turn, the adjustment of the energy market structure will also affect the carbon market (Guo and Farouk, 2021; Zhang et al., 2021). The carbon market and energy market have significant time-varying characteristics in the direction and intensity of volatility spillover (Chevallier, 2012), especially when impacted by emergencies, the spillover effect is significantly higher than that in other periods, which indicates that there is a structural break (Li et al., 2015; Lin and Chen, 2019). Therefore, this paper discusses the time-varying two-way spillover effect between carbon and energy markets, so as to prevent the sharp fluctuation of carbon price, stabilize the carbon trading price, and promote the formation of a reasonable price transmission mechanism between China's carbon market and energy market. At the same time, it is also conducive to the prevention of systemic financial risks in the energy market and ensure the safe supply of energy.

The linkage effect theory showed that if there is a certain correlation mechanism between markets, the change of one market parameter will cause the change of one or more other related market parameters, thus forming the interaction linkage between markets (Hirschman, 1958). With the mutual penetration and integration of carbon market and energy market. Energy commodities such as crude oil, natural gas, ethanol, heating oil, coal, and gasoline will improve the diversification of carbon assets (Gazi and Jose., 2018), and then promote the mutual penetration and integration of carbon and energy markets. There is a significant two-way causal relationship between carbon and energy markets, which is mainly reflected in the dynamic spillover effect between crude oil, natural gas and carbon market (Chevallier, 2012). Specifically, there are strong two-way linear and nonlinear spillover effects between carbon and crude oil markets (Yu et al., 2015), especially the volatility spillover effect between carbon and coal markets is the strongest (Wu et al., 2020).

Our study makes three major contributions to the empirical literature on modeling carbon and energy markets. On one hand, we provide new evidence for the existing literature to prove that the volatility spillover between carbon and energy markets has two-way time-varying characteristics. On the other hand, dynamic model is a contribution, previous literature dealt mostly with static models, whereas this paper applied dynamic and its advantage is that it better reflects the dynamic spillover effect over time. In addition, the spillover index model is also a contribution, previous literature dealt mostly with the Copula and GARCH models, whereas this paper applied the spillover index model combined with rolling window technology, and its advantage is that it can more accurately measure the time-varying spillover effect between carbon and energy markets.

LITERATURE REVIEW

The spillover effect between markets is that the emergencies will usually cause severe fluctuations in related market prices. According to the linkage effect transmission mechanism, it can be considered that there is a certain linkage behavior between energy and carbon markets, and there is a time-varying price fluctuation transmission mechanism between the two markets. Lin and Jia (2019) used a dynamic recursive computable general equilibrium model to analyze the impact of different emission trading scheme (ETS) price level, they found the output of energy industry is more sensitive to ETS price than that of other industries. Low ETS prices will weaken the ability of the carbon market to reduce emissions, and higher ETS prices will lead to higher carbon dioxide emission reduction. There is a nonlinear structure between the carbon and energy markets, and there is a relatively significant correlation between the carbon and energy futures markets on different time scales (Cao and Xu, 2016). Xu et al. (2020) constructed a time-delay multilayer recursive network, and introduced the time-delay information correlation coefficient to measure the interaction between systems. They found that the linkage relationship between oil, coal, natural gas, and carbon prices showed a U-shaped trend of the EU carbon market, while the linkage trend between gasoline and carbon prices continued to rise. Balcilar et al. (2016) indicated that the dominant relationship between energy and carbon price changes in different stages, and carbon price plays a leading role at this stage. There is a significant spillover effect between carbon and energy markets, changes in energy prices often affect carbon emission rights prices.

Risk spillover is a particular concern in the connection between carbon and energy markets. Balcilar et al.(2016) examined the risk spillover between energy futures prices and European carbon futures contracts, and pointed out that there is significant volatility and time-varying risk transmission from energy to carbon market, then the spot and futures parts of emission market show time-varying correlation and volatility hedging effectiveness. In the renewable energy market system, the volatility spillover relationship involving multiple markets is more complex than that between two markets. Fuel cell and solar energy markets play an important role in the risk diffusion path, which needs to be prevented. Zhou et al. (2021) comprehensively analyzed the risk diffusion relationship between renewable energy markets. They found that the volatility spillover of renewable energy market tends to exist in high dimensions. Khamis et al. (2019) analyzed the dynamic returns and risk spillovers between commodity futures (energy and precious metals) and the Gulf Cooperation Council (GCC) stock market. It showed that there is a significant income and risk spillover between commodities and GCC stock market, especially during the outbreak of the global financial crisis in 2008–2009. In addition, the systemic risk brought by volatility spillover may threaten the stability of financial markets. Hedi and Imed. (2020) studied the spillover mechanism of permanent and temporary shocks in the Islamic stock market and a series of global risk factors by using the Diebold and Yilmaz (DY) methods, and pointed out that the intensity of earnings and volatility spillover increased during the financial turmoil, which supported the evidence of contagion. Chen and Jin (2020) studied the risk spillover of China's stock market by using the method of spatial econometrics. It showed that both real contact channel and information channel are effective communication channels to drive spillover effect. The spillover effects of specific determinants persist, and the communication channels and spillover effects in different regions are asymmetric.

The spillover relationship between carbon and energy markets is not invariable, and there is a time-varying spillover effect (Ji et al., 2018). There is dynamic dependence between the international carbon and energy markets (Chen et al., 2021). Ma et al. (2020) used the copula GARCH model and the overall fitting effect method to study the dynamic dependence between the international carbon emission rights market, and found that there is an obvious dynamic dependence between EUA and CER futures and spot. Balcilar et al. (2016) used MS-DCC-GARCH model to analyze the risk spillover effect and linkage relationship between the European energy and carbon markets, indicating that the energy market has significant dynamic characteristics of risk spillover to the carbon market. Zhang and Sun (2016) employed the threshold dynamic conditional correlation generalized autoregressive conditional heteroscedasticity (GARCH) model to explore the dynamic volatility spillover between European carbon trading market and fossil energy market. Dutta et al. (2018) studied the daily return and volatility relationship between EU subsidy (EUA) price and clean energy stock return, and used the bivariate VAR-GARCH method to record the positive impact of the change of EUA price on the return of renewable energy stock. The results showed that there is a significant volatility relationship between emissions and European clean energy price index. Compared with foreign countries, China's carbon market started relatively late. Gong et al. (2021) showed that there is an obvious spillover effect between carbon and fossil energy markets, and its intensity and direction are time-varying and asymmetric. The coal market has the greatest impact on the carbon market. The time-varying spillover effect between carbon and fossil energy markets lasts about 3 weeks, and the spillover effect gradually weakens with time. Especially in the case of 1 week lag, the time-varying spillover effect is the most significant. Chang et al. (2019) used dynamic conditional correlation (DCC) generalized autoregressive conditional heteroscedasticity (GARCH) model to study the fluctuation spillover effect and dynamic correlation between China's emission quota and fossil energy market. The dynamic correlation between fossil energy and regional emission quota market shows a slight time-varying trend, and its dynamic correlation is at a low level in the considered period. The prohibition of cross regional emission quota flows, inefficient dynamic links between the two markets and low-price transmission may lead to the reduction of volatility spillover effect and dynamic correlation.

The spillover effect between carbon and energy markets still has some bidirectional and regional heterogeneity. Xu (2021) combined copula and conditional VaR methods to reveal the asymmetric risk spillover of international and China's domestic energy market uncertainty, such as Hubei and Shenzhen carbon pilot. Although the uncertainty of international and China's domestic energy market has a significant risk spillover effect on China's carbon pilot, there are differences between carbon pilot projects. Liu et al. (2017) examined the level of oil market risk measured by value at risk (VaR) and conditional var (CoVaR), as well as the dynamic and asymmetric dependence between West Texas Intermediate (WTI) yield and crude oil volatility index (OVX). The results showed that WTI returns are negatively correlated with OVX in most cases, OVX has a significant risk spillover effect on WTI returns, and CoVaR also has an asymmetric effect on the extreme fluctuations of different OVX. Wang and Guo (2018) revealed the asymmetric spillover effects of the two types of markets on the return and volatility series. Among the three major energy markets of WTI oil, Brent oil and natural gas, WTI oil market has the strongest spillover effect on the system, and natural gas has the most significant spillover effect on the carbon market. There is feedback from carbon to other energy markets, and electricity price has proved to be the largest information receiver in the system. And the connectivity level of volatility system is significantly higher than that of income system. The extreme risk Spillovers of energy companies vary greatly in business and regions, which deserves more attention in energy risk management (Zhu et al., 2020). Chang et al. (2018) showed that coal, oil and natural gas prices are the main determinants of regional emission quota prices in the long run, except for the second phase of Beijing ETS pilot. The long-term cointegration relationship in Beijing and Shanghai is not completely consistent with that in Guangdong and Hubei. In the short term, the oil and gas price changes in the second stage of Beijing ETS pilot, the natural gas price changes in Shanghai ETS pilot and the coal price changes in Hubei ETS pilot have a significant impact on China's regional emission quota price.

In summary, the existing literature on the spillover effects of carbon and energy markets mostly discusses the relationship between carbon market and single energy market, such as the spillover effects of carbon market and traditional energy market, carbon market and new energy market, ignoring the connection and risk transmission between the whole energy market. In addition, the existing literature mainly measures the spillover effect between carbon and energy markets by analyzing the GARCH model, and can't accurately analyze the directional characteristics of spillover effect. Finally, most of the existing literatures use static models to study the volatility spillover effect, but there is still a lack of investigation on the dynamic spillover effect.

MODEL

DY spillover index model was proposed by Diebold and Yilmaz (2009) to analyze the volatility spillover effect between stock markets in different countries, which has certain limitations. It can only simply quantify the dynamic total spillover index, but can't measure the directional spillover index, and is too dependent on the order of variables. This paper adopts the method improved by Diebold and Yilmaz (2012, 2014), and uses the DY spillover index model based on generalized VaR to measure the time-varying two-way spillover effect between China's carbon and energy markets. On the one hand, it eliminates the possible dependence of the results on the lag order of variables, on the other hand, it can quantify the directional spillover between different markets. The method is established as follows. The VaR (P) model as:

$$X_t = \sum_{i=1}^{p} \Phi_i X_{t-i} + \varepsilon_t \tag{1}$$

Where represents the random disturbance term vector of independent and identically distributed. The moving average is expressed as:

$$X_t = \sum_{i=0}^{\infty} A_i \varepsilon_{t-i} \tag{2}$$

Where A_i is a coefficient matrix subject to recursive sequence:

$$A_i = \Phi_1 A_{i-1} + \Phi_2 A_{i-2} + \ldots \Phi_p A_{i-p} \tag{3}$$

When $i < 0$, $A_i = 0$, when $I = 0$, it is an N-dimensional identity matrix.

Under the framework of the above vector autoregressive model, the improved DY spillover index model in 2012 adopts the generalized variance decomposition method to predict the impact of the residual term in order to eliminate the possible dependence of the calculation results on the lag order of the variables. The results obtained based on this method not only do not depend on the lag order of the variable, but also do not require the orthogonalization of the equation error. In this model, the estimated value of variable X_j to variable X_i becomes the h-Step prediction error variance of variable X_i, which is the part $\theta_{ij}^{g}(H)$ from X_j. For the value of H, the formula can be expressed as follows.

$$\theta_{ij}^{g}(H) = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} \left(e'_i A_h \sum e_j\right)^2}{\sum_{h=0}^{H-1} \left(e'_i A_h \sum A'_h e_i\right)} \tag{4}$$

Where, $\theta_{ij}^{g}(H)$ A is the element in row i and column j of the matrix, expressed as the proportion from the j variable in the total prediction variance of the i variable, σ_{jj} A represents the variance of the j-th perturbation term, and e_i and e_j represent the i-th and j column vectors of the identity matrix, respectively.

In order to make the error variance decomposition matrix satisfy that the sum of row vectors is equal to 1, the matrix needs to be standardized in rows, and the matrix element calculation formula is expressed as follows.

$$\tilde{\theta}_{ij}^{g}(H) = \frac{\theta_{ij}^{g}(H)}{\sum_{j=1}^{N} \theta_{ij}^{g}(H)} \tag{5}$$

Based on the transformed matrix $\tilde{\theta}$, various overflow indexes can be calculated. Using the volatility power supply line of generalized variance decomposition, the total volatility spillover index is constructed:

$$S^{g}(H) = \frac{\sum_{\substack{i,j=1\\ i \neq j}}^{N} \tilde{\theta}_{ij}^{g}(H)}{\sum_{i,j=1}^{N} \tilde{\theta}_{ij}^{g}(H)} \times 100 = \frac{\sum_{\substack{i,j=1\\ i \neq j}}^{N} \tilde{\theta}_{ij}^{g}(H)}{N} \times 100 \tag{6}$$

Since the generalized impulse response and variance decomposition do not depend on the ranking of the variables to be measured, the generalized variance decomposition matrix can be used to calculate the directional overflow index. Among them, the spillover index, that is, the spillover effect of the market on all other markets, is calculated as follows:

$$S_{\cdot i}^{g}(H) = \frac{\sum_{\substack{j=1\\ j \neq i}}^{N} \tilde{\theta}_{ji}^{g}(H)}{\sum_{i,j=1}^{N} \tilde{\theta}_{ji}^{g}(H)} \times 100 = \frac{\sum_{\substack{j=1\\ j \neq i}}^{N} \tilde{\theta}_{ji}^{g}(H)}{N} \times 100 \tag{7}$$

Similarly, the spillover index is that the market is subject to the directional spillover effect of all other markets, and the calculation formula is:

$$S_{i\cdot}^{g}(H) = \frac{\sum_{\substack{j=1\\ j \neq i}}^{N} \tilde{\theta}_{ij}^{g}(H)}{\sum_{i,j=1}^{N} \tilde{\theta}_{ij}^{g}(H)} \times 100 = \frac{\sum_{\substack{j=1\\ j \neq i}}^{N} \tilde{\theta}_{ij}^{g}(H)}{N} \times 100 \tag{8}$$

Thus, the net spillover effect index can be obtained, that is, the net spillover effect of the market on all other markets:

$$S_{i}^{g}(H) = S_{\cdot i}^{g}(H) - S_{i\cdot}^{g}(H) \tag{9}$$

Finally, the net volatility spillover index between markets can also be obtained:

$$\begin{aligned} S_{\cdot i}^{g}(H) &= \left(\frac{\tilde{\theta}_{ji}^{g}(H)}{\sum_{i,k=1}^{N} \tilde{\theta}_{ik}^{g}(H)} - \frac{\tilde{\theta}_{ij}^{g}(H)}{\sum_{j,k=1}^{N} \tilde{\theta}_{jk}^{g}(H)} \right) \times 100 \\ &= \left(\frac{\tilde{\theta}_{ji}^{g}(H) - \tilde{\theta}_{ij}^{g}(H)}{N} \right) \times 100 \end{aligned} \tag{10}$$

RESULTS AND DISCUSSION

Sample Selection and Data Description

China currently has nine carbon emission pilot markets, among which there is no quota trading in Sichuan carbon pilot trading market before 2018. China has established pilot carbon emission

TABLE 1 | Descriptive statistical results of the markets.

Variables	Mean value	Standard deviation	Skewness	kurtosis	ADF test	*p*-value
BEA	–0.0030	0.0890	–0.8877	4.8138	–20.70142	0.0000
GDEA	0.0008	0.0377	–4.3065	80.0111	–22.09143	0.0000
HBEA	0.0008	0.0339	–0.2424	5.3233	–27.79976	0.0000
SHEA	–0.0013	0.0575	–0.4150	3.3461	–14.39893	0.0000
SC	–0.0008	0.0399	–3.9568	49.1691	–24.99839	0.0000
L11655	–0.0001	0.0110	–0.4967	6.1308	–26.66923	0.0000
NEI	0.0012	0.0227	0.1421	7.6363	–27.47754	0.0000

TABLE 2 | Spillover index of pilot carbon markets to energy markets.

Overflow index type	BEA	GDEA	HBEA	SHEA
H = 10				
SC	1.11	0.51	0.92	1.86
L11655	2.43	0.83	0.69	0.79
NEI	0.46	1.11	0.98	1.23
Directional TO Others	4.00	2.45	2.59	3.89
Directional Including Own	101.36	100.94	99.40	98.63
NET Directional Connectedness	1.36	0.94	-0.60	-1.37

trading markets in various regions. Each pilot carbon market is established at different times and the economic conditions of the cities are different, so the degree of market activity is also different. According to the historical transaction data of each carbon market, this paper selects four relatively representative pilot carbon markets: Beijing (BEA), Guangdong (GDEA), Hubei (HBEA), and Shanghai (SHEA) as the research object. These four pilot carbon markets not only opened early, but also ranked among the top in market activity. In energy market, this paper selects crude oil futures (SC), power index (L11655) and CSI new energy index (NEI) to represent China's traditional energy market, power market and new energy market respectively. Finally, each pilot carbon market and energy market are analyzed respectively.

The transaction hours of the four carbon markets are different from those of the three energy markets. In order to ensure the consistency of time series, this paper selects the trading period of each group of data, and finally selects the common trading date of each market. The start dates and end dates of the samples are March 26, 2018 and May 31, 2021, respectively. In order to ensure the stability of the time series data, the daily log yield of each market is calculated. The descriptive statistics and ADF test results of the daily yield of each market are shown in **Table 1**.

From **Table 1**, first, the ADF test and its *p*-value can confirm that the log return data of each market are smooth. Second, from the standard deviation, among the four carbon markets, the daily yield fluctuation of Beijing pilot carbon market is the largest, that of Hubei pilot carbon market is the smallest. The standard deviation of crude oil futures market is the largest, and standard deviation of power industry index is the smallest. Third, the skewness of the time series in the table is not equal to 0, and the kurtosis is greater than 3, that is, the sample data do not belong to normal distribution, showing the characteristics of peak and thick tail.

Static Fluctuation Spillover Effect

The static volatility spillover index model between China's pilot carbon market and energy market is constructed. The static volatility spillover effect between markets is shown in **Table 2**. The spillover index describes the extent to which the market is affected by the spillover effects of other markets. The net spillover index represents the difference between the spillover effect of the market on other markets and the spillover effect by other markets. The total spillover index is the total spillover effect included in the market.

From **Table 2**, the spillover index between the pilot carbon market and the energy market is greater than 0, indicating that there is a fluctuation spillover effect between the carbon market and each energy market. In addition, the static directional spillover index shows that the spillover and spillover indexes of the pilot carbon market are not equal, and both are greater than 0, indicating that there may be two-way asymmetry in the spillover effect between the carbon market and the energy market. In addition, in the static net spillover effect, the net spillover index of the pilot carbon markets in Beijing (BEA) and Guangdong (GDEA) is greater than 0, indicating that the spillover effect of the carbon market on the energy market is stronger on the whole. On the contrary, the net spillover index of carbon market in Hubei (HBEA) and Shanghai (SHEA) is less than 0, indicating that the spillover effect of energy market on carbon market is stronger.

Estimation Effect of Time-Varying Volatility Spillover

Due to the static estimation of volatility spillover effect cannot reflect the dynamic spillover effect changing with time, this paper further combines the rolling window technology with DY spillover index. Firstly, a 50-weeks rolling window is set to measure the time-varying spillover effect between China's pilot carbon market and energy market. Then, the total volatility spillover index, directional spillover index, net spillover index and net paired spillover index between China's pilot carbon market and energy market are drawn. Finally, the spillover index charts obtained from different angles can help us comprehensively identify the characteristics of time-varying spillover effects between China's pilot carbon market and energy market.

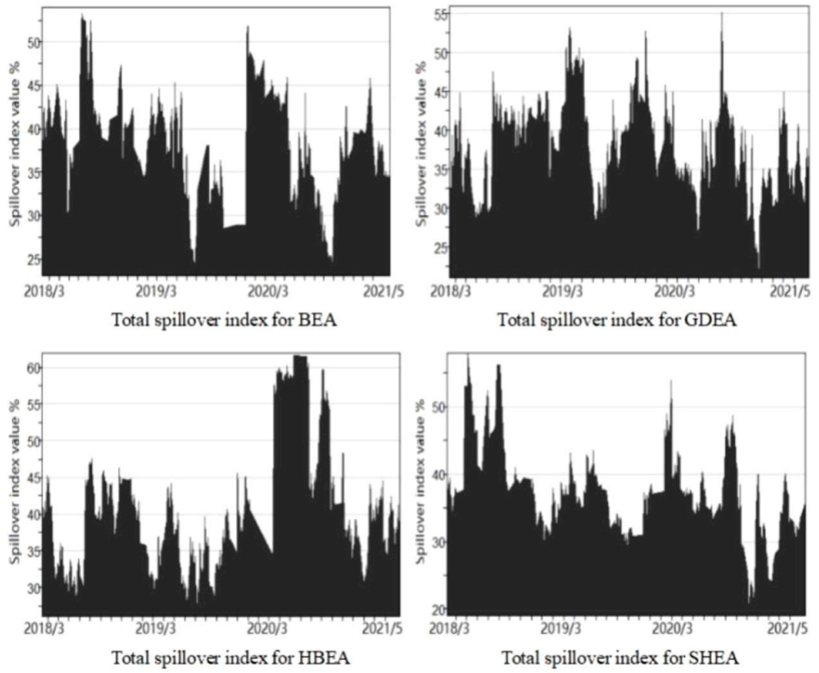


FIGURE 1 | Total spillover index of carbon and energy markets. Notes: This group of figures shows the total time-varying spillovers indexes generated between carbon and energy markets in four sample groups, each containing different carbon markets (BEA, GDEA, HBEA, SHEA) and energy markets (SC, L11655, NIE).

Spillover Effect of Carbon Market on Total Fluctuation of Energy Market

Figure 1 shows the total spillover index of four pilot carbon markets and energy market in Beijing (BEA), Guangdong (GDEA), Hubei (HBEA), and Shanghai (SHEA). Observing the total volatility spillover index between the pilot carbon market and energy market, it can be found that the total spillover index of the four carbon markets and energy markets has generally fluctuated greatly since the beginning of 2018. Among them, the total spillover index of Beijing pilot carbon market and energy market changes between 20 and 54%. The total spillover index of the pilot carbon market group in Guangdong varies from 20 to 56%. The total spillover index of Hubei pilot carbon market group changes between 25 and 65%. The total spillover index of Shanghai pilot carbon market group changes between 20 and 60%. The four groups of total spillover indexes of carbon market and energy market show significant time-varying characteristics within the sample measurement range.

In addition, the total spillover index chart shows some significant fluctuation cycles of the total spillover effect. The first cycle is from 2018 to early 2019. In the early stage of this cycle (before 2019), the total spillover index of carbon market and energy market directly fluctuated and decreased by different ranges. On the one hand, China's crude oil futures market has just been officially established in 2018, and the market trading is in its infancy, which has little impact on other relevant markets. On the other hand, due to the continuous international trade differences between China and the United States in 2018, the policy impact of the Sino US trade war led to more fluctuations in the energy market due to real-time policies, and the spillover effect between markets was relatively reduced. In the later period (from the end of 2018 to the beginning of 2019), due to the increasing Sino US trade friction and the import and export of energy and energy equipment involved in international trade, the energy market price is greatly uncertain affected by policies, resulting in a sharp rise in the total spillover index between markets. After the first significant fluctuation cycle, the total spillover index between carbon market and energy market experienced relatively small and frequent fluctuations. From the beginning of 2019 to the end of 2019, the total spillover index of each group did not show significant periodicity. The second significant cycle is from the beginning of 2020 to the end of 2020. This cycle also experienced a significant rise and fall of the total spillover index. During this period, it should be mainly due to the impact of price fluctuations in the crude oil futures market on the total spillover index among various markets. At the beginning of 2020, the COVID-19 epidemic swept the world. In March of the same year, the U.S. WTI crude oil futures price fell to a negative number. During this period, the huge price fluctuation in the energy market dominated by the crude oil market caused the sharp rise of the total spillover index between markets. According to the above analysis of some significant fluctuation cycles of the total spillover index, it can be seen that the total spillover effect between China's pilot carbon market and energy market will have a significant upward trend mainly in the period of major social time and significant fluctuation of energy market.

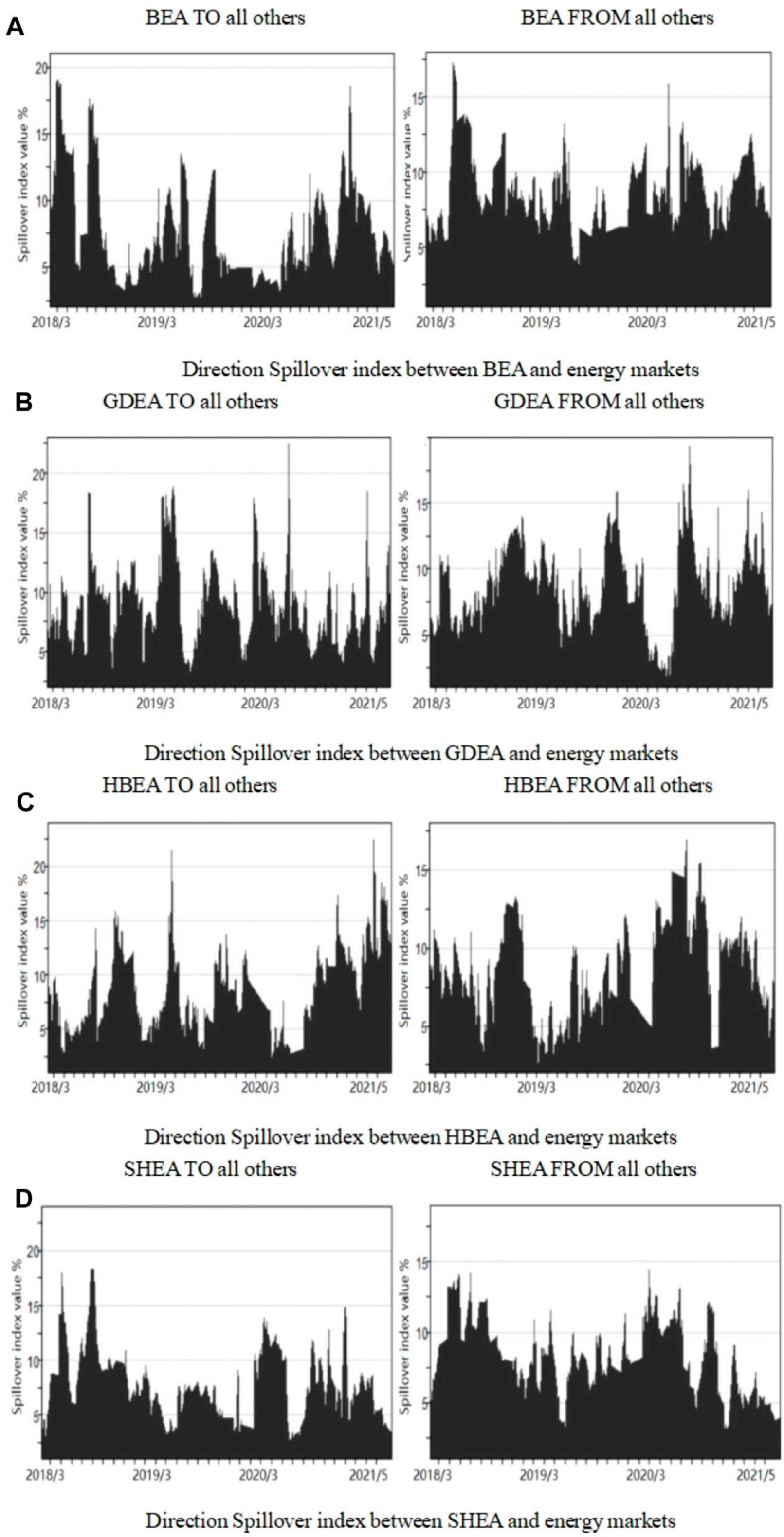


FIGURE 2 | (A) Direction spillover index between BEA and energy markets. **(B)** Direction spillover index between GDEA and energy markets. **(C)** Direction spillover index between HBEA and energy markets. **(D)** Direction spillover index between SHEA and energy markets.

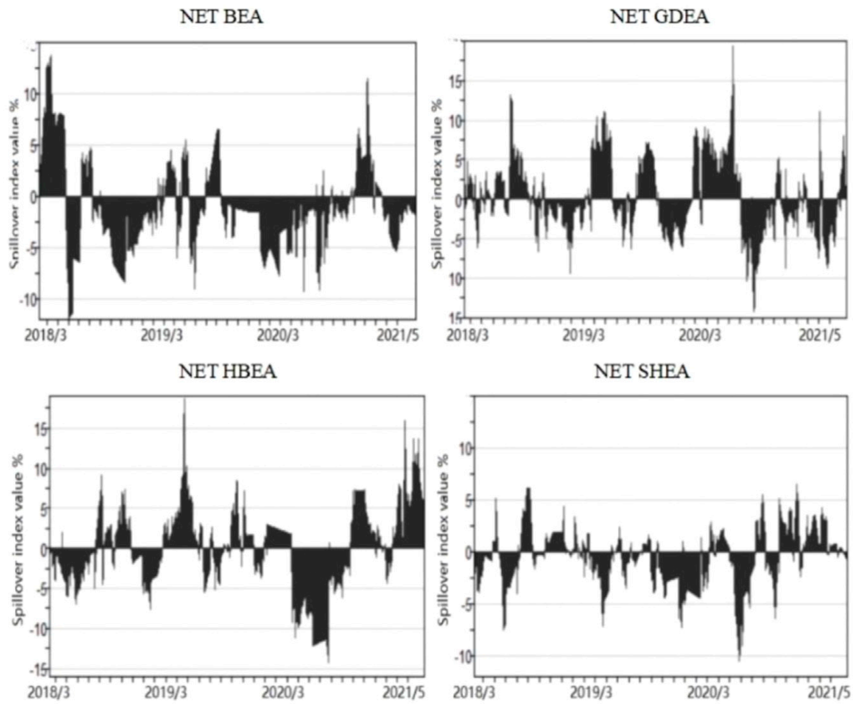


FIGURE 3 | Net spillover index between carbon and energy markets. Notes: This group of figures shows net spillover index for each carbon market. The net spillover index is calculated from the spillover index from the carbon to energy markets minus the spillover index from the energy to carbon markets.

Analysis on Directional Spillover Effect of Carbon and Energy Markets

Since the total spillover index can only measure the time-varying characteristics of the overall volatility spillover effect between the pilot carbon market and the energy market, this paper also needs to further measure the time-varying directional spillover effect between the pilot carbon market and the energy market.

From **Figure 2**, both the spillover effect of carbon market on energy market and the spillover effect of energy market on carbon market have significant time variability. In addition, from the spillover indexes in different directions, it can be seen intuitively that the spillover effects between the four pilot carbon markets and energy markets are bidirectional and asymmetric. From the value of the spillover index, the peak value of the directional spillover index of the pilot carbon market to the energy market can reach 20% or even higher, while the peak value of the carbon market affected by the spillover effect index of the energy market is mostly below 15%. On the other hand, the overall continuity of the directional spillover effect of the pilot carbon market on the energy market is not as good as that of the carbon market. It is because the carbon market is largely affected by policy regulation. When new policies or new regulatory mechanisms are introduced, the spillover effect index of the pilot carbon market on the energy market will increase, but the fluctuation of the pilot carbon market caused by policy adjustment will soon stabilize, and the spillover effect index of the carbon market on the energy market will also decline rapidly. The energy market is more subject to market independent regulation, which itself has high volatility, so the spillover effect index on the carbon market is also high. Overall, when there are major social events or market policy adjustments, the spillover effect of the carbon market on the energy market is significant. The spillover effect of the energy market on the carbon market is stronger in the case of daily market fluctuations.

Analysis of Net Spillover Effect and Net Pairing Spillover Effect Between Carbon and Energy Markets

Figure 3 shows the net spillover index between the pilot carbon market and the energy market in each group. In order to facilitate the analysis of the characteristics of the time-varying spillover effect between the pilot carbon market and the energy market, this paper also measures the net paired spillover effect of the pilot carbon market on the energy market (**Figure 4**). Based on the net spillover index in **Figure 3**, we can intuitively see that, unlike the static spillover index, the time-varying net spillover effect between China's pilot carbon market and energy market is not always positive or negative. When the net spillover index is positive, it shows that the forward spillover effect of China's pilot carbon market on the energy market is greater than the backward spillover effect. On the contrary, when the net spillover index is negative, it shows that the output of China's pilot carbon market on the energy market is less than the input. Overall, there are net spillovers in different directions between China's pilot carbon market and energy market.

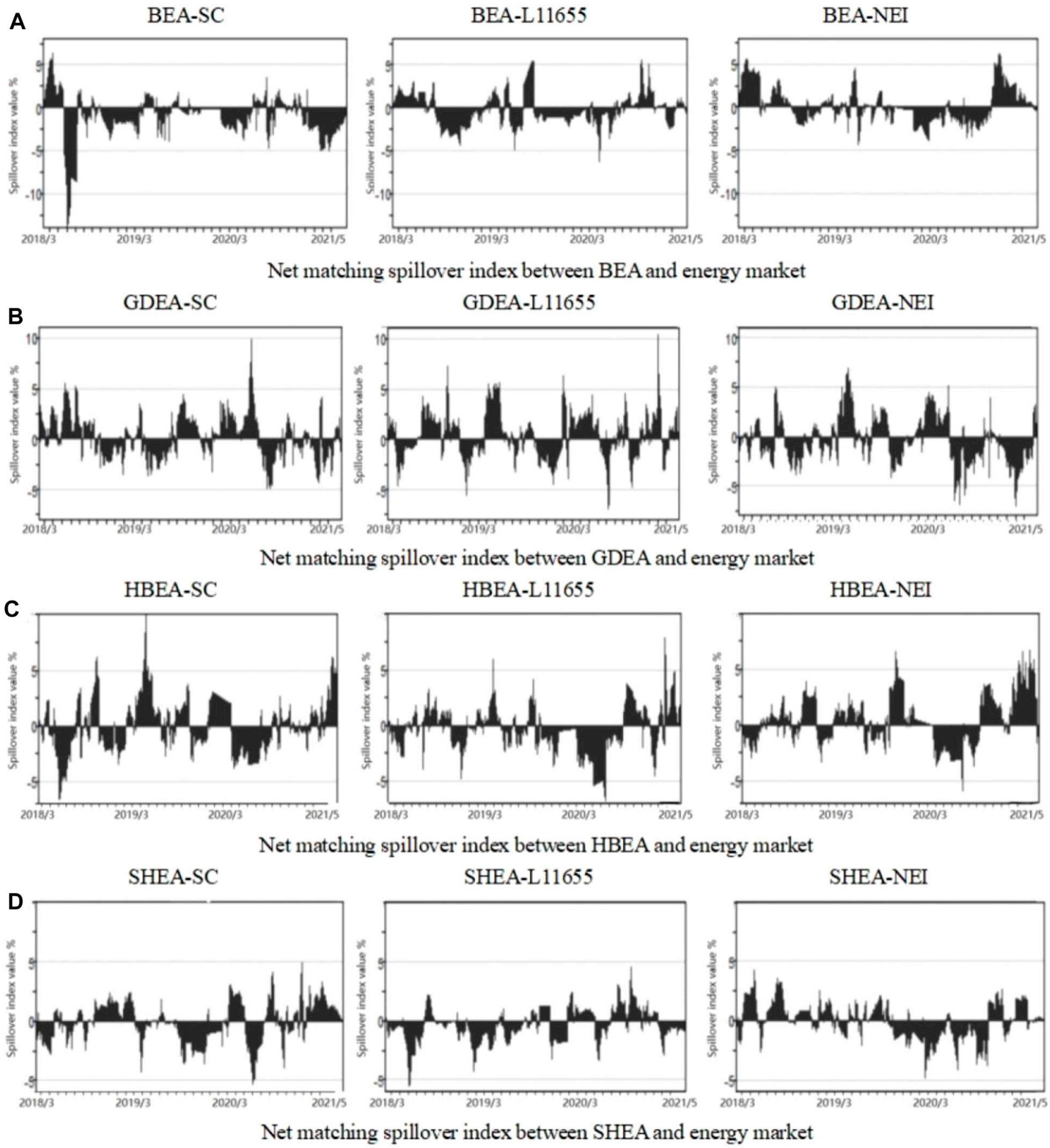


FIGURE 4 | (A) Net matching spillover index between BEA and energy market. **(B)** Net matching spillover index between GDEA and energy market. **(C)** Net matching spillover index between HBEA and energy market. **(D)** Net matching spillover index between SHEA and energy market.

From the directional spillover index between the pilot carbon market and the energy market, we can find that during the period of energy market shock, the spillover index of the energy market to the pilot carbon market increased significantly. Combined with **Figure 3**, we found that the net spillover index showed a negative net spillover index in the corresponding period, this can better explain that the spillover effect of the energy market on China's pilot carbon market mainly increases significantly during the shock period of the energy market. When sudden political events happen, major social events and market environmental factors will cause energy market shocks, due to the existence of inter market linkage mechanism, the

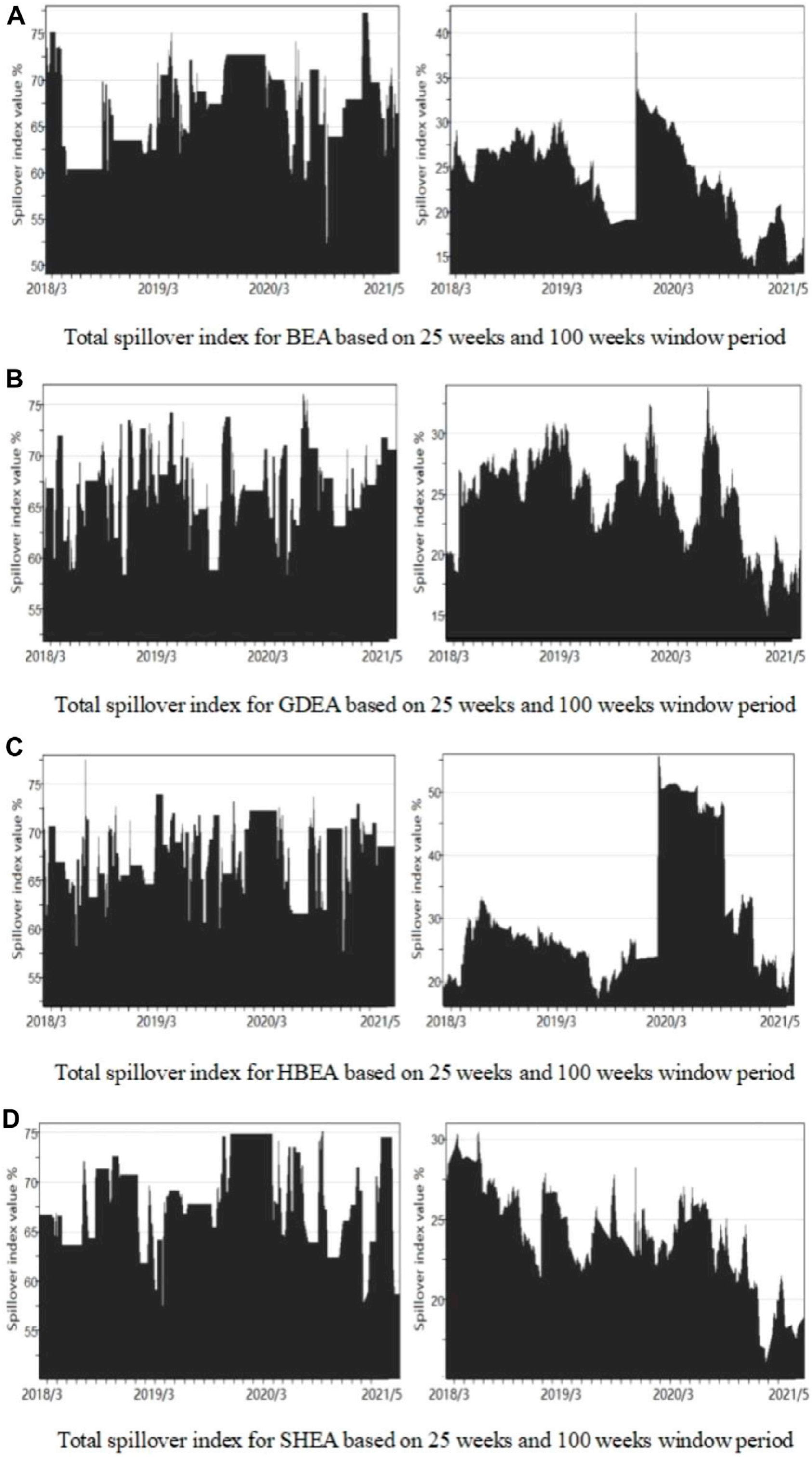


FIGURE 5 | (A) Total spillover index for BEA based on 25 weeks and 100 weeks window period. **(B)** Total spillover index for GDEA based on 25 weeks and 100 weeks window period. **(C)** Total spillover index for HBEA based on 25 weeks and 100 weeks window period. **(D)** Total spillover index for SHEA based on 25 weeks and 100 weeks window period.

fluctuation of energy price will also affect the pilot carbon market. At this time, it is reflected in the significant enhancement of the spillover effect of energy market on carbon market in the corresponding period.

Further analysis of the net paired spillover index between the pilot carbon market and the energy market shows that there are some differences in the time-varying spillover effects between different carbon markets and different energy markets. The volatility spillover effect of Beijing (BEA) and Shanghai (SHEA) pilot carbon markets mainly comes from the crude oil futures market, especially the volatility spillover effect of Beijing Pilot carbon market from 2018 to 2019 is negative and reaches the minimum. In addition, from 2020 to 2021, Shanghai's carbon market was also affected by the significant fluctuation spillover effect of the new energy index. For Guangdong pilot carbon market (GDEA), its net spillover index changed significantly negatively during the shock period of new energy index. The volatility spillover effect of Hubei pilot carbon market (HBEA) mainly comes from crude oil and power industry indexes. Overall, in the period of energy market price shock, the spillover effect of energy market on China's carbon market is significantly higher than that in other periods, but there are certain regional differences in the degree of impact of different pilot carbon markets in China by the fluctuations of the energy market in the corresponding period. This phenomenon may be caused by the significant differences in local economic development level, energy consumption structure and government market policies.

Robustness Test

This paper changes the window period of the rolling window to test the robustness of the time-varying overflow index. The rolling window period is adjusted from 50 to 25 weeks and 100 weeks respectively, and then the total spillover index is measured respectively. It can be seen from the total spillover index diagram of each group in **Figure 5** that although the increase of the window period will cause the total spillover index to lose more sample values than the small window period, on the whole, each total spillover index will rise significantly in early 2020, indicating that the time-varying total spillover index can still reflect the conclusion that the total spillover index will rise during the period of severe fluctuations in the energy market. Thus, the robustness test is passed.

CONCLUSION AND POLICY IMPLICATIONS

Conclusion

Combined with rolling window technology and DY spillover index model, this paper studies the time-varying two-way spillover effect between China's carbon and energy markets, and draws the following conclusions: 1) The spillover index between carbon and energy markets measured by the static volatility spillover index model is greater than 0, indicating that there is volatility spillover effect between China's carbon and traditional energy markets, power and new energy markets. 2) The total spillover index shows that there is a time-varying spillover effect between China's carbon and energy markets. 3) The directional spillover index reflects that the spillover effect between China's carbon and energy markets is bidirectional and asymmetric. 4) The net spillover index and net paired spillover index show that the time-varying spillover effect between China's carbon and energy markets has significant regional heterogeneity.

Policy Implications

Based on the above conclusions, the policy implications are as follows:

1) Form an inherently stable price mechanism between China's carbon market and energy market. The fluctuation transmission mechanism between China's carbon market and energy market has great uncertainty. In order to effectively prevent the intrusion of energy price fluctuations on China's carbon market, it is necessary to integrate the carbon emission right trading price into China's energy price system for comprehensive consideration, so as to form an internal stable price mechanism between China's carbon market and energy market.
2) Improve the risk monitoring and early warning mechanism of China's carbon market. The spillover effect of carbon market during the period of energy market price shock is significantly higher than that in other periods, so it is necessary to improve the risk monitoring and early warning mechanism of China's carbon market to effectively deal with the possible fluctuation impact during the period of energy market shock. On the one hand, carbon market regulators need to be vigilant about the possible risk impact when the energy market price fluctuates violently. On the other hand, when building a national unified carbon market, it is necessary to fully consider the adverse impact that external shocks such as energy price fluctuations may have on regional emission reduction costs, and formulate reasonable and effective risk monitoring, risk early warning and crisis management schemes.
3) Comprehensively consider and effectively coordinate regional differences. The impact of energy market price shocks on carbon markets in different regions of China shows certain differences. Therefore, on the premise of ensuring the design of national unified carbon market system, comprehensively consider the characteristics of regional carbon market and choose diversified trading systems to effectively reduce the adverse effects caused by different shocks. In addition, in the process of carbon market system design and rule management, it is necessary to comprehensively analyze the reasons for the differences in the impact of external shocks such as energy price fluctuations on different regional carbon markets, so as to effectively reduce regional heterogeneity and ensure fair competition in carbon prices.
4) Give play to the guiding role of the government in the construction of carbon market. The development of the carbon market is inseparable from the top-level design of the government. It should be carried out from the aspects of the establishment of the institutional system, regulatory

legislation and macro-control of the carbon market, improve the legal system and supporting management system of the carbon market, and effectively play its role in resource allocation. At the same time, it is necessary to learn from the experience of EU carbon market construction, combined with the actual situation of China's development, improve the regulatory mechanism, reduce the carbon market risk, take the impact of energy market risk spillover into account, and establish an effective risk monitoring and early warning mechanism to prevent the occurrence of systemic risks.

In the future research, this study will add time-varying factors when analyzing the asymmetry of volatility connectivity between markets, and the connectedness network is also introduced to visualize the direction and intensity of volatility spillover effect between carbon and energy markets. In addition, with the establishment of China's unified carbon market and the continuous development of crude oil futures market, we can further research the long-term time-varying two-way spillover effect of the national unified carbon market on the energy market.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: http://cndata1.csmar.com/.

AUTHOR CONTRIBUTIONS

The research is designed and performed by SQ, CZ, and KZ. The data was collected by SQ, CZ, and KZ. Analysis of data was performed by SQ, KZ, and ZR. Finally, the paper is written by SQ, CZ, and KZ.

FUNDING

This work was supported by Youth Project of Humanities and Social Sciences of Ministry of Education in China (grant number: 19YJC790103), Social Science Foundation of Fujian Province (grant number: FJ2021C023), Youth talent innovation team support program of Zhengzhou University (grant number: 32320293).

REFERENCES

Balcilar, M., Demirier, R., Hammoudeh, S., and Khuong Nguyen, D. (2016). Risk Spillovers across the Energy and Carbon Markets and Hedging Strategies for Carbon Risk. *Energ. Econ.* 54, 159–172. doi:10.1016/j.eneco.2015.11.003

Cao, G., and Xu, W. (2016). Nonlinear Structure Analysis of Carbon and Energy Markets with MFDCCA Based on Maximum Overlap Wavelet Transform. *Physica A: Stat. Mech. its Appl.* 444, 505–523. doi:10.1016/j.physa.2015.10.070

Chang, K., Ge, F., Zhang, C., and Wang, W. (2018). The Dynamic Linkage Effect between Energy and Emissions Allowances price for Regional Emissions Trading Scheme Pilots in China. *Renew. Sustain. Energ. Rev.* 98, 415–425. doi:10.1016/j.rser.2018.09.023

Chang, K., Ye, Z., and Wang, W. (2019). Volatility Spillover Effect and Dynamic Correlation between Regional Emissions Allowances and Fossil Energy Markets: New Evidence from China's Emissions Trading Scheme Pilots. *Energy* 185, 1314–1324. doi:10.1016/j.energy.2019.07.132

Chen, N., and Jin, X. (2020). Industry Risk Transmission Channels and the Spillover Effects of Specific Determinants in China's Stock Market: A Spatial Econometrics Approach. *North Am. J. Econ. Finance* 52, 101137. doi:10.1016/j.najef.2019.101137

Chen, W. D., Xiong, S., and Chen, Q. Y. (2021). Characterizing the Dynamic Evolutionary Behavior of Multivariate price Movement Fluctuation in the Carbon-Fuel Energy Markets System from Complex Network Perspective. *Energy* 239, 121896. doi:10.1016/j.energy.2021.121896

Chen, X., and Lin, B. (2021). Towards Carbon Neutrality by Implementing Carbon Emissions Trading Scheme: Policy Evaluation in China. *Energy Policy* 157, 112510. doi:10.1016/j.enpol.2021.112510

Chevallier, J. (2012). Time-varying Correlations in Oil, Gas and CO2prices: an Application Using BEKK, CCC and DCC-MGARCH Models. *Appl. Econ.* 44 (32), 4257–4274. doi:10.1080/00036846.2011.589809

Diebold, F. X., and Yilmaz, K. (2012). Better to Give Than to Receive: Predictive Directional Measurement of Volatility Spillovers. *Int. J. Forecast.* 28 (1), 57–66. doi:10.1016/j.ijforecast.2011.02.006

Diebold, F. X., and Yilmaz, K. (2009). Measuring Financial Asset Return and Volatility Spillovers, with Application to Global Equity Markets. *Econ. J. (London)* 119 (534), 158–171. doi:10.1111/j.1468-0297.2008.02208.x

Diebold, F. X., and Yılmaz, K. (2014). On the Network Topology of Variance Decompositions: Measuring the Connectedness of Financial Firms. *J. Econom.* 182 (1), 119–134. doi:10.1016/j.jeconom.2014.04.012

Dutta, A., Bouri, E., and Noor, M. H. (2018). Return and Volatility Linkages between CO2 Emission and Clean Energy Stock Prices. *Energy* 164, 803–810. doi:10.1016/j.energy.2018.09.055

Gallego-Álvarez, I., Segura, L., and Martínez-Ferrero, J. (2015). Carbon Emission Reduction: the Impact on the Financial and Operational Performance of International Companies. *J. Clean. Prod.* 103, 149–159. doi:10.1016/j.jclepro.2014.08.047

Gazi, S. U., Jose, A. H., Shahzad, S. J. H., and Hedström, A. (2018). Multivariate Dependence and Spillover Effects across Energy Commodities and Diversification Potentials of Carbon Assets. *Energ. Econ.* 71, 35–46. doi:10.1016/j.eneco.2018.01.035

Gong, X., Shi, R., Xu, J., and Lin, B. (2021). Analyzing Spillover Effects between Carbon and Fossil Energy Markets from a Time-Varying Perspective. *Appl. Energ.* 285, 116384. doi:10.1016/j.apenergy.2020.116384

Guo, Y. P., and Farouk, A. (2021). Financial Development and Carbon Emissions: Analyzing the Role of Financial Risk, Renewable Energy Electricity, and Human Capital for China. *Discrete Dyn. Nat. Soc.* 2021, 1025669. doi:10.1155/2021/1025669

He, A., Xue, Q., Zhao, R., and Wang, D. (2021). Renewable Energy Technological Innovation, Market Forces, and Carbon Emission Efficiency. *Sci. Total Environ.* 796, 148908. doi:10.1016/j.scitotenv.2021.148908

Hedi, B. H., Imed, M., and Al Dohaiman, M. (2020). Common Shocks, Common Transmission Mechanisms and Time-Varying Connectedness Among Dow Jones Islamic Stock Market Indices and Global Risk Factors. *Econ. Syst.* 44 (2), 100760. doi:10.1016/j.ecosys.2020.100760

Hirschman, A. O. (1958). *The Strategy of Economic Development*. New Haven: Yale University Press, 98–116.

Ji, Q., Zhang, D., and Geng, J.-b. (2018). Information Linkage, Dynamic Spillovers in Prices and Volatility between the Carbon and Energy Markets. *J. Clean. Prod.* 198, 972–978. doi:10.1016/j.jclepro.2018.07.126

Joanna, I. L. (2010). The Evolving Role of Carbon Finance in Promoting Renewable Energy Development in China. *Energy Policy* 38 (6), 2875–2886. doi:10.1016/j.enpol.2010.01.020

Jonathan, D., Paul, D. H. H., and Seth, B. (2013). Estimating the Impact of Fuel-Switching between Liquid Fuels and Electricity under Electricity-Sector Carbon-Pricing Schemes. *Socio-Economic Plann. Sci.* 47 (2), 76–88. doi:10.1016/j.seps.2012.09.004

Khamis, H. A., Walid, M., Ahmet, S., and Hoon Kang, S. (2019). Energy, Precious Metals, and GCC Stock Markets: Is There Any Risk Spillover? *Pacific-Basin Finance J.* 56, 45–70. doi:10.1016/j.pacfin.2019.05.006

Li, L., Yin, L. B., and Zhou, Y. M. (2015). Exogenous Shocks and the Spillover Effects between Uncertainty and Oil price. *Energ. Econ.* 54, 224–234. doi:10.1016/j.eneco.2015.11.017

Li, Y., Chen, K., Zheng, N., Cai, Q., Li, Y., and Lin, C. (2021). Strategy Research on Accelerating Green and Low-Carbon Development under the Guidance of Carbon Peak and Carbon Neutral Targets. *IOP Conf. Ser. Earth Environ. Sci.* 793 (1), 012009. doi:10.1088/1755-1315/793/1/012009

Lin, B., and Chen, Y. (2019). Dynamic Linkages and Spillover Effects between CET Market, Coal Market and Stock Market of New Energy Companies: a Case of Beijing CET Market in China. *Energy* 172, 1198–1210. doi:10.1016/j.energy.2019.02.029

Lin, B., and Jia, Z. (2019). Impacts of Carbon price Level in Carbon Emission Trading Market. *Appl. Energ.* 239, 157–170. doi:10.1016/j.apenergy.2019.01.194

Liu, B.-Y., Ji, Q., and Fan, Y. (2017). Dynamic Return-Volatility Dependence and Risk Measure of CoVaR in the Oil Market: A Time-Varying Mixed Copula Model. *Energ. Econ.* 68, 53–65. doi:10.1016/j.eneco.2017.09.011

Liu, B., Sun, Z., and Li, H. (2021). Can Carbon Trading Policies Promote Regional Green Innovation Efficiency? Empirical Data from Pilot Regions in China. *Sustainability* 13 (5), 2891. doi:10.3390/su13052891

Liu, H.-H., and Chen, Y.-C. (2013). A Study on the Volatility Spillovers, Long Memory Effects and Interactions between Carbon and Energy Markets: the Impacts of Extreme Weather. *Econ. Model.* 35, 840–855. doi:10.1016/j.econmod.2013.08.007

Ma, Y., Wang, L., and Zhang, T. (2020). Research on the Dynamic Linkage Among the Carbon Emission Trading, Energy and Capital Markets. *J. Clean. Prod.* 272, 122717. doi:10.1016/j.jclepro.2020.122717

Mansanet-Bataller, M., Pardo, A., and Valor, E. (2007). CO2 Prices, Energy and Weather. *Energy* 28 (3), 73–92. doi:10.5547/issn0195-6574-ej-vol28-no3-5

Qi, S.-Z., Zhou, C.-B., Li, K., and Tang, S.-Y. (2021). Influence of a Pilot Carbon Trading Policy on Enterprises' Low-Carbon Innovation in China. *Clim. Pol.* 21, 318–336. doi:10.1080/14693062.2020.1864268

Sandra, S., and Jūratė, J. (2018). Explaining the Interplay of Three Markets: Green Certificates, Carbon Emissions and Electricity. *Energ. Econ.* 71, 1–13. doi:10.1016/j.eneco.2018.01.012

Todd, L., Jonghwan, K., and Audun, B. (2019). The Long-Term Impacts of Carbon and Variable Renewable Energy Policies on Electricity Markets. *Energy Policy* 131, 53–71. doi:10.1016/j.enpol.2019.02.070

Wang, X. Y., Khurshid, A., Qayyum, S., and Cantemir Calin, A. (2021). The Role of green Innovations, Environmental Policies and Carbon Taxes in Achieving the Sustainable Development Goals of Carbon Neutrality. *Environ. Sci. Pollut. Res. Int.*, 11356-021–16208-Z. doi:10.1007/s11356-021-16208-z

Wang, Y., and Guo, Z. (2018). The Dynamic Spillover between Carbon and Energy Markets: New Evidence. *Energy* 149, 24–33. doi:10.1016/j.energy.2018.01.145

Wu, Q., Wang, M., and Tian, L. (2020). The Market-Linkage of the Volatility Spillover between Traditional Energy price and Carbon price on the Realization of Carbon Value of Emission Reduction Behavior. *J. Clean. Prod.* 245, 118682. doi:10.1016/j.jclepro.2019.118682

Xu, H., Wang, M. G., and Yang, W. G. (2020). Information Linkage between Carbon and Energy Markets: Multiplex Recurrence Network Approach. *Complexity* 2020, 5841609. doi:10.1155/2020/5841609

Xu, Y. (2021). Risk Spillover from Energy Market Uncertainties to the Chinese Carbon Market. *Pacific-Basin Finance J.* 67, 101561. doi:10.1016/j.pacfin.2021.101561

Yu, L., Li, J., Tang, L., and Wang, S. (2015). Linear and Nonlinear Granger Causality Investigation between Carbon Market and Crude Oil Market: A Multi-Scale Approach. *Energ. Econ.* 51, 300–311. doi:10.1016/j.eneco.2015.07.005

Zhang, Y.-J., and Sun, Y.-F. (2016). The Dynamic Volatility Spillover between European Carbon Trading Market and Fossil Energy Market. *J. Clean. Prod.* 112, 2654–2663. doi:10.1016/j.jclepro.2015.09.118

Zhang, Y., Shi, X., Qian, X., Chen, S., and Nie, R. (2021). Macroeconomic Effect of Energy Transition to Carbon Neutrality: Evidence from China's Coal Capacity Cut Policy. *Energy Policy* 155, 112374. doi:10.1016/j.enpol.2021.112374

Zhao, T., Zhang, X., and Bai, J. (2019). Analysis of Impact of National Carbon Market on thermal Power and Renewable Energy Development. *IOP Conf. Ser. Earth Environ. Sci.* 227 (4), 042001. doi:10.1088/1755-1315/227/4/042001

Zhou, W., Gu, Q., and Chen, J. (2021). From Volatility Spillover to Risk Spread: An Empirical Study Focuses on Renewable Energy Markets. *Renew. Energ.* 180, 329–342. doi:10.1016/j.renene.2021.08.083

Zhu, B., Han, D., Chevallier, J., and Wei, Y.-M. (2017). Dynamic Multiscale Interactions between European Carbon and Electricity Markets during 2005-2016. *Energy Policy* 107, 309–322. doi:10.1016/j.enpol.2017.04.051

Zhu, B., Lin, R., and Liu, J. (2020). Magnitude and Persistence of Extreme Risk Spillovers in the Global Energy Market: A High-Dimensional Left-Tail Interdependence Perspective. *Energ. Econ.* 89, 104761. doi:10.1016/j.eneco.2020.104761

Zou, C., Xiong, B., Xue, H., Zheng, D., Ge, Z., Wang, Y., et al. (2021). The Role of New Energy in Carbon Neutral. *Pet. Exploration Dev.* 48 (2), 480–491. doi:10.1016/s1876-3804(21)60039-3

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: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 03 January 2022
doi: 10.3389/fenrg.2021.821269

Enterprise Innovation, Executive Experience and Internationalization Strategy: Evidence From High-Carbon Industrial Enterprises Versus Low-Carbon Industrial Enterprises in China

Shuangchang Cui *

School of Foreign Languages, Zhejiang University of Finance and Economics, Hangzhou, China

OPEN ACCESS

Edited by:
Xiaohang Ren,
Central South University, China

Reviewed by:
Yan Zheng,
Central South University, China
Fahad Ali,
Zhejiang University, China

***Correspondence:**
Shuangchang Cui
cuishuangchang@outlook.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *24 November 2021*
Accepted: *02 December 2021*
Published: *03 January 2022*

Citation:
Cui S (2022) Enterprise Innovation, Executive Experience and Internationalization Strategy: Evidence From High-Carbon Industrial Enterprises Versus Low-Carbon Industrial Enterprises in China. Front. Energy Res. 9:821269. doi: 10.3389/fenrg.2021.821269

Industrial enterprises are the core subjects to reduce carbon emissions. Their innovations for low-carbon production are the key to determine the effect of carbon emission reduction. This paper examines the impact of executive experience, especially the overseas experience, on enterprise innovations across 3559 enterprises in low-carbon, medium-carbon and high-carbon industries respectively. Interestingly, it shows that the executive experience has only played a significant role in enterprise innovations of high-carbon industrial enterprises, indicating that the executive's international vision might help to promote innovation in high-carbon industry. Then, it's also discovered that there is a mediating effect of international strategy which helps to better understand the impact mechanism of executive experience on enterprise innovation in high-carbon industry.

Keywords: enterprise innovation, executive experience, internationalization strategy, high-carbon industry, low-carbon industry, mediating effect

1 INTRODUCTION

Industrial enterprises, especially high-carbon enterprises, are the main source of carbon emissions (Ren et al., 2021). To achieve independent emission reduction target, controlling carbon emissions of industrial enterprises is the top priority. The innovation on low-carbon production is the key factor to determine the low-carbon behavior and emission reduction effect of enterprises (Chen et al., 2020). Extensive literature has examined a mass of impact factors of enterprise innovations (Aghion et al., 2013; Acharya and Xu, 2017; Bronzini and Piselli, 2017; Zhang et al., 2020). Among them, executive experience and enterprise internationalization strategies may have particular roles in explaining the enterprise innovation, which may also be different across enterprises in high-carbon industry and low-carbon industry.

Existing literature shows that personal cognitive structure will have an important impact on their behavioral decisions and some decisions often cannot be explained by expected utility theory. The upper echelon theory (Hambrick and Mason, 1984) also states that executives are not completely rational and have limited cognition, and they often filter out decisions that are beyond their own cognitive scope. Therefore, executives' cognitive structure may influence enterprise decision-making. A large number of studies have found that the experience of executives, such as military background, disaster experience, academic experience and overseas experience, can significantly affect enterprise decision-making. For example, Benmelech and Frydman (2015) point out that the companies of CEOs with military backgrounds have lower investment levels and are less likely to be involved in fraud. Especially in a downturn, these companies perform even better. Quan et al. (2019) point out that executives with military experience have a tougher management style, which can promote enterprise innovation. Bernile et al. (2017) find a non-monotonic relationship between the intensity of executives' disaster experience and enterprise risk-taking. Xu and Li (2016) find that executives with "Great Famine" will make more charity. In terms of academic experience, Huang et al. (2019) point out that executives who have taught in universities can reduce information asymmetry inside enterprise, attract more attention from analysts and promote enterprise innovation. With the deepening of globalization, high-level executives begin to move across borders frequently. More interestingly, Giannetti et al. (2015) find that executives' overseas experience can reduce earnings management of the company. Yuan and Wen (2018) find that executives' overseas experience will promote enterprise innovation. Therefore, in this paper, we first examine the impact of executives' overseas experience and language ability on the enterprise innovation. We focus on comparing the results among Chinese enterprises in high-carbon, medium-carbon and low-carbon industries, considering the differences in innovations of different levels of carbon emissions.

Moreover, according to existing studies, enterprises can obtain a variety of potential benefits through internationalization, such as establishing economies of scale, enhancing market power, and diversifying operation risks (Lin, 2012). To achieve nationally determined contribution targets, China is increasingly launching a series of low-carbon development plans for heavy industry to reduce carbon emissions (Dong et al., 2021; Zheng et al., 2021; Wen et al., 2020). Meanwhile the delicate bond between internationalization strategies and low-carbon emission goals remains unrevealed. Thus, this paper further investigates another interesting question: whether the internationalization strategies have impacts on the above relationship between executive experience and enterprise innovation.

This paper contributes to the literature by finding following results. First, internationalized executives significantly impact enterprise innovation in high-carbon industry. Secondly, the impact of internationalized executives on enterprise innovation is realized by enhancing the enterprise internationalization strategy. That is, enterprises will have more opportunities to get in touch with scarce knowledge and technology, which significantly promotes enterprise innovation. Moreover, our findings suggest that Chinese governments' efforts in attracting internationalized talents seem to have generated positive impact on enterprise innovation. Our results are consistent when some robustness checks have been implemented.

The structure of this paper is as follows. **Section 2** develops the hypotheses. **Section 3** illustrates sample and research design. **Section 4** explains main empirical results about the impact of executive experience on enterprise innovation, and the potential mediating effect of internationalization strategies. **Section 5** concludes.

2 RESEARCH HYPOTHESES

2.1 Foreign-Language Executive and Enterprise Innovation

Innovation is risky, unpredictable, long-term, multistage, labor intensive, and idiosyncratic, which is different from general production activities. Most of the literatures are based on the legal environment (Atanassov, 2013; He and Tian, 2015; Ni and Zhu, 2016), tax environment (Mukherjee et al., 2017), industrial environment (Li and Zheng, 2016), internal enterprise governance factors (Ederer and Manso, 2013; Balsmeier et al., 2017), and internal company financial factors (Manso, 2011) to study the influencing factors of innovation. Their perspectives focus on the framework of traditional economics, this paper takes a different approach to study the influence of executives' foreign language competence on enterprise innovation. We suppose, compared with Chinese executives without foreign-language competence, executives with foreign-language proficiency or overseas experience, called internationalized executives hereafter, have relatively two advantages. The first is excellent foreign language communication and the second is the overseas background. From these two advantages, we discuss the impact of internationalized executives on enterprise innovation.

First of all, internationalized executives have excellent foreign language communication competence. Theoretically speaking, the improvement of enterprise innovation comes from no more than two aspects, the one is introduction of foreign advanced technology and another is relying on independent innovation (Tang et al., 2014). In China, limited by the short development time, lack of innovation resources, imperfect Chinese system and other factors, the innovations among enterprises are generally weak. In contrast, the west has sophisticated technological know-how, advanced management skills and a global innovation network, their level of enterprise innovation is generally high. Therefore, communication and cooperation with foreign enterprises is a strategic choice to promote enterprise innovation. However, due to a series of problems such as language barriers, cultural and legal differences, disadvantage of outsiders and so on, this external communication and cooperation is often meaningless and cannot bring substantial improvement to enterprise innovation. But for internationalized executives, these problems are where they come in. Their advantage in foreign languages can help enterprises overcome these difficulties and promote the in-depth communication with foreign enterprises so as to obtain high-quality innovation resources.

Secondly, although Chinese executives with foreign language teaching experience and foreign language major are included in the definition of internationalized executives in this paper, it cannot be denied that a considerable proportion of internationalized executives have overseas background. Therefore, compared with Chinese executives, internationalized executives' overseas experience is also an advantage that cannot be ignored. Generally speaking, these executives with overseas background are more willing to innovate than the Chinese executives. Here are the reasons.

First, executives with overseas experience have good scientific and cultural literacy and advanced management experience, which will encourage them to increase innovation (Chen and Tang, 2012). And due to the strict patent protection system in foreign countries, executives with overseas experience will pay more attention to patent application and protection while increasing innovation efforts. Second, innovation is highly dependent on resources, overseas-experience executives with international resources, social networks and relationships can help enterprises build bridges and channels with the holders of the advanced technology to acquire high quality resources. It will greatly increase enterprise innovation. Last but not least, executives with oversea experience have a higher tolerance for innovation. Unlike routine tasks, innovation involves a long multi-stage process that is full of uncertainty (Holmstrom, 1989). Most successful innovation opportunities result from a conscious and purposeful search and unexpected failure may be an important step towards a company's later success. Due to the future contingencies and intrinsically risky processes, exceptional tolerance for failure is necessary for effective innovation. Compared with Chinese executives, they have seen more failures abroad and they tend to focus more on the process of innovation than on the results of failure.

Therefore, based on the above analysis, we propose Hypothesis 1.

H1: Internationalized executives can significantly promote enterprise innovation by their advantages in language and overseas experience.

2.2 Mediating Effect of Internationalization Strategy

According to existing studies, enterprises can obtain a variety of potential benefits through internationalization, such as establishing economies of scale, enhancing market power, and diversifying operation risks (Lin, 2012). However, at the same time, the disadvantage of outsiders, the trap of new entrants, the lack of international market information and language barriers also hinder the formulation and implementation of enterprise internationalization strategy (Lin, 2012; Song et al., 2017). How to solve these potential problems is the key to the implementation of enterprise internationalization strategy. We believe that training and introducing a group of internationalized executives can help enterprises to promote the implementation of internationalization strategy.

Here are the reasons. First, according to psychological research, internationalized executives may have an international preference. Internationalized executives have excellent foreign language communication competence, and it may play an important role in the promotion of internationalization strategy which makes them psychologically satisfying. Second, internationalized executives have the advantage of information spillover. On the one hand, due to their foreign language advantages, internationalized executives tend to pay special attention to all kinds of foreign language reports in daily life and they can easily understand the policy trends of a certain country. This information is important to internationalization strategy. On the other hand, as mentioned above, a large proportion of internationalized executives have overseas experience. Such experience can help enterprises identify opportunities and risks in the international market, and have a deeper understanding of the culture, business rules, laws and regulations of the host country. Therefore, for those enterprises with internationalized executives, the probability of their internationalization strategy implementation will be greatly improved.

Furthermore, in the context of globalization, internationalization strategy will significantly promote enterprise innovation. First of all, after the implementation of enterprise internationalization strategy, enterprises are bound to scan, create and learn from the international market strategy, which can promote enterprises' ability of opportunity identification and utilization. With the improvement of opportunity identification and utilization, enterprises will acquire more innovative knowledge, put forward more innovative options, or grasp the innovation opportunities by internal resource integration and organizational restructuring, and ultimately improve the enterprise innovation. Second, by internationalization strategy, enterprises have more opportunities to get in touch with scarce knowledge and technology in the Chinese market. By using such knowledge and technology, enterprises will eventually improve their own innovation.

Therefore, we propose the Hypothesis 2.

H2: Internationalization strategy plays a mediating role in the influence of internationalized executives on enterprise innovation.

Given the stronger requirements by China's green policies, the carbon emission of an enterprise may have significant impacts on the motivation of enterprise innovations as well as the international strategies (Dou et al., 2021; Duan et al., 2021). We re-examine both two hypotheses across enterprises of low-carbon, medium-carbon and high-carbon industries.

3 DATA AND RESEARCH DESIGN

3.1 Data Sample

Our sample is comprised of listed firms on the Shanghai Stock Exchange (SHSE) and Shenzhen Stock Exchange (SZSE) during the period 2010–2018. We exclude financial firms (e.g., banks, insurance companies and investment trusts) as they have different structures from other companies. We then exclude observations with missing variables and get a final sample of 23808 observations.

Then we select new energy vehicles, photovoltaic, wind energy, nuclear energy, biological intelligence and circular economy as low-carbon industries, obtaining 4873 observations of 738 enterprises. According to the method of Jie et al. (2014), we select mining industry (B), textile industry (C17), paper industry (C22), petroleum processing industry (C25), chemical manufacturing industry (C26), metal smelting industry (C31, C32), thermal production and supply industry (D44) as high-carbon industries, obtaining 5190 observations of 667 enterprises. The remaining 2,154 enterprises with 13745 observations are taken as medium-carbon industries.

Enterprise innovation data are mainly from CNRDS database, which is supplemented with the website of China National Intellectual Property Administration. The data of foreign language competence of executives are mainly extracted from executives' resumes, which are derived from CSMAR database. In addition, we manually collect some executives' resumes in the company's annual report to complete the missing data. Other financial and enterprise data used in this study are obtained from the China Stock Market & Accounting Research (CSMAR) system. All the data are cross-checked for consistency.

3.2 Variables

3.2.1 Dependent Variable: Innovation

In China, there are three types of patent applications, including invention patents, design patents, and utility model patents. Following prior studies (Fang et al., 2014; Cornaggia et al., 2015; Jiang, 2016), we take the natural logarithm of plus 1 the number of invention patents to measure enterprise innovation, because invention patents have the highest technical content.

3.2.2 Test Variable: Internationalized Executives

According to the upper echelon theory (Hambrick and Mason, 1984), we suppose that senior executives include chairmen and general managers, because they have more power of decision. When defining an internationalized executive, we follow two principles: (1) The executive has experience of studying abroad. (2) The executive has experience of working abroad. We suppose that when at least one of the chairmen or general managers meets at least one of the above two conditions, this executive is considered an internationalized executive, and the dummy variable of the enterprise is 1, 0 otherwise.

3.2.3 Control Variables

Following prior studies (e.g., He and Tian, 2013; Chang et al., 2015; Yuan et al., 2015), we control for a vector of firm characteristics shown to affect innovation activities. The control variables include firm size (the natural logarithm of assets), ROA (net income divided by total assets), firm age, ownership concentration (the percentage of shares owned by the top 10 shareholder), proportion of independent directors (the proportion of independent directors in a board), CEO duality (The CEO and the chairman are the same person), ownership structure and industry competition (Herfindahl-Hirschman Index). Moreover, we add industry and year dummies to control for the industrial fixed effect and dynamic changes in the macroeconomic environment common to all firms over the sample period, respectively.

Table 1 provides definitions of all variables used in our analysis and all continuous variables are winsorized at 1% at both tails to mitigate the undue influence of extreme values.

3.3 Models

Following prior studies (He and Tian, 2013; Chemmanur et al., 2014; Fang et al., 2014; Yu et al., 2018; Yuan and Wen, 2018), we employ the OLS model to examine our hypotheses. To mitigate the potential endogeneity, we regress the contemporaneous innovation measures on the one-period lag values of managers with foreign experience and other explanatory variables. The basic empirical model employed is:

$$Lnpatent_{i,t} = \beta_0 + \beta_1 overseas_{i,t-1} + \sum \gamma_k control_{k,i,t-1} + \delta industry_i + \theta year_t + \varepsilon_{i,t} \quad (1)$$

where β_1 represents regression coefficients, ε is an error term. The dependent variable $Lnpatent_{i,t}$ is our proxy for corporate innovation, while executives with overseas experience is the test variable, which measures managers with overseas experience. Control variables include Firm size, ROA, Firm age, ownership concentration, proportion of independent directors, CEO Duality, ownership structure, Industry competition, Industry, and Year.

TABLE 1 | Definitions of all variables used in our analysis.

Variables	Definitions
lnpatent_invent	The natural logarithm of one plus enterprise invention patents
Overseas	Executives with overseas experience or language proficiency and 0 otherwise
For_sale	The proportion of enterprise foreign income
Lnsize	The natural logarithm of assets
ROA	Net income divided by total assets
Lnage	The natural logarithm of the age of one firm
Center	The percentage of shares owned by the top 10 shareholder
Indep	The proportion of independent directors in a board
Dual	A dummy variable which equals 1 if the CEO and the chairman are the same person and 0 otherwise
SOE	A dummy variable which equals 1 if the enterprise is State-Owned Enterprise and 0 otherwise
HHI	Herfindahl-Hirschman Index

TABLE 2 | Descriptive statistics. This table reports descriptive statistics of the main variables defined in **Table 1** during the sample period 2010–2018. All continuous variables are winsorized at 1% at both tails. L_ represents one-period lag.

Variables	N	Mean	SD	Min	Median	Max
lnpatent_invent	20357	0.388	0.894	0.000	0.000	8.327
L_overseas	20357	0.102	0.302	0.000	0.000	1.000
L_for_sale	20357	0.099	0.188	0.000	0.000	0.863
L_lnsize	20357	21.981	1.320	19.195	21.809	27.028
L_roa	20357	0.039	0.057	−0.278	0.038	0.206
L_lnage	20357	2.754	0.392	0.000	2.833	4.771
L_center	20357	0.585	0.158	0.218	0.597	0.961
L_indep	20357	0.373	0.055	0.125	0.333	0.800
L_dual	20357	0.736	0.441	0.000	1.000	1.000
L_SOE	20357	0.425	0.494	0.000	0.000	1.000
L_HHI	20357	0.202	0.204	0.036	0.125	1.000

4 EMPIRICAL ANALYSES

4.1 Descriptive Statistics

Table 2 presents the descriptive statistics for the variables used in our regressions. The mean and standard deviation of lnpatent_invent are 0.388 and 0.894, which demonstrate that there is a big difference in the outputs of innovation among

TABLE 3 | Internationalized executives and enterprise innovation. This table reports the impact of internationalized executives on innovation in different industries. t-Statistics in the brackets are based on standard errors adjusted for clustering at the firm level.*, ** and *** indicate significance at the 0.10, 0.05 and 0.01 level (two-tailed), respectively.

	(1)	(2)	(3)
	lnpatent_invent low-carbon	lnpatent_invent medium-carbon	lnpatent_invent high-carbon
L_overseas	−0.023	−0.003	0.155***
	(−0.58)	(−0.11)	(2.77)
L_lnsize	0.410***	0.216***	0.284***
	(23.00)	(22.09)	(18.83)
L_roa	0.016***	−0.001	0.101**
	(4.45)	(−0.25)	(2.54)
L_lnage	0.092**	−0.107***	−0.193***
	(2.16)	(-4.84)	(-5.00)
L_center	−0.293***	-0.333***	0.446***
	(−2.77)	(−6.76)	(5.00)
L_indep	1.209***	0.341**	0.345
	(4.12)	(2.38)	(1.41)
L_dual	0.006	−0.061***	−0.070**
	(0.19)	(−3.73)	(−2.41)
L_SOE	−0.062	0.067***	0.031
	(−1.55)	(4.06)	(1.12)
L_HHI	−0.395***	−0.160***	0.320**
	(−3.68)	(−4.86)	(2.39)
_cons	−8.795***	−4.041***	−5.608***
	(−20.09)	(−18.35)	(−15.60)
Year	Yes	Yes	Yes
Industry	Yes	Yes	Yes
N	4163	11691	4503
r2	0.231	0.162	0.234

sample firms. On average, only 10.2% of firm-year observations have at least one internationalized executive, which indicates internationalized executives are still relatively rare in China.

As for control variables, the firms in our sample have an average lnsize of 21.981, ROA of 0.039, lnage of 2.754, center of 0.585, indep of 0.373, dual of 0.736, SOE of 0.425, and HHI of 0.202.

4.2 Multivariate Results

Table 3 reports the results of the impact of internationalized executives on enterprise innovation in different industries. We can find the coefficient of internationalized executives is 0.155, significant at the 1% level, indicating that compared with high-carbon firms that do not have internationalized executives, high-carbon firms that hire internationalized executives have higher innovations. But in low-carbon and medium-carbon industries, the coefficients of internationalized executives are not significant, which indicates there is no evidence to prove that internationalized executives can promote enterprise innovation in low-carbon and medium-carbon industries. Hypothesis 1 is confirmed.

In terms of control variables, the coefficients are generally consistent with prior studies (Song et al., 2017; Yuan and Wen, 2018; He et al., 2019). In high-carbon industry, firm size and ROA are positively and significantly related to enterprise innovation, which indicates that the larger the enterprise scale and the more sufficient the capital, the stronger the motivation for innovation. After all, innovation is a highly resource-dependent activity. Firm age and dual are significantly and negatively related to innovation. The former indicates that older and more matured firms lack the incentives to innovate and the latter shows that the CEO and the chairman are the same person is not good to enterprise innovation. Ownership concentration and the industry competition also affect the enterprise innovation.

4.3 Endogeneity

Our evidence above indicates that a positive relation between internationalized executives and enterprise innovation in high-carbon industry. However, the results can be driven by an endogeneity bias. For example, it may not be random that a firm appoints internationalized executives and this may cause a self-selection bias. Moreover, there is a reverse causality concern that firms with high innovation potential attract internationalized executives. Thus, in addition to using lagged internationalized executives and control variables in the main model, in this section, we further address the potential endogeneity issue in several alternative ways, including PSM procedure and instrumental variable.

4.3.1 PSM Procedure

To mitigate the potential endogeneity arising from reverse causality, we compare firms having at least one internationalized executives (i.e., treatment firms) to a sample of control firms having no internationalized executives (i.e., control firms) matched on the propensity for a firm to appoint internationalized executives. The primary benefit of using a control sample matched on propensity scores is that it allows us to more clearly attribute any observed effects to the appointment of internationalized executives itself, rather than to

TABLE 4 | PSM procedure. This table reports the results of covariate balance checks (pstest) on the mean difference in the covariates used in the logit model between the treatment firms and the control firms in high-carbon industry, matched on PSM approach. t-Statistics in the brackets are based on standard errors adjusted for clustering at the firm level.*, ** and *** indicate significance at the 0.10, 0.05 and 0.01 level (two-tailed), respectively.

Variables	Unmatched matched	Mean		%bias	t-Test
		Treat	Control		
L_lnsize	U	22.215	22.263	−3.1	−0.64
	M	22.215	22.171	2.8	0.40
L_roa	U	0.042	0.032	6.0	0.87
	M	0.042	0.038	2.5	1.04
L_lnage	U	2.709	2.773	−18.1	−3.38***
	M	2.709	2.694	4.3	0.58
L_center	U	0.614	0.577	23.1	4.37***
	M	0.614	0.603	6.9	0.99
L_indep	U	0.369	0.370	−1.7	−0.33
	M	0.369	0.372	−6.9	−0.96
L_dual	U	0.738	0.776	−8.9	−1.74*
	M	0.738	0.725	2.9	0.40
L_SOE	U	0.330	0.574	−50.5	−9.46***
	M	0.330	0.295	7.2	1.07
L_HHI	U	0.161	0.141	15.1	3.24***
	M	0.161	0.144	12.8	1.70*

the firm characteristics associated with the appointment of internationalized executives. Specifically, we estimate a logit model using the high-carbon industry sample and calculate a propensity score for each firm. For each treatment firm, we select one control firm with the closest propensity score. Finally, these firms constitute the propensity-score matched sample (i.e., PSM Sample). To ensure that the matching is satisfactory, we assess covariate balance by testing whether the means of the covariates differ between the treatment firms and matched control firms and report the results in **Table 4**. We can find there are no significant differences in the means of any covariates, indicating that the propensity-score matched control sample resembles the treatment firms along virtually all dimensions.

We then re-estimate model (1) using the PSM sample, and report the results in column 1 of **Table 5**. The results show that the coefficient on internationalized executives is significantly positive at the 5% level, suggesting a positive association between internationalized executive and enterprise innovation in high-carbon industry.

4.3.2 Instrumental Variable

Then we further use 2SLS model to estimate the impact of internationalized executives on enterprise innovation. The instrumental variable we used is average number of internationalized executives industry as suggested by Meng et al. (2019), which has significant correlation with enterprise internationalized executives but has no direct impact on enterprise innovation. The F-value of the first stage of 2SLS is much greater than 10, which indicates the selected instrumental variables are not weak instrumental variables. The second-stage results are shown in **Table 4** columns (2). The coefficients on overseas is 0.185, significant at the 10% level, which is consistent with OLS model (described in **Section 4.2**). The findings further confirm the above results.

TABLE 5 | PSM and 2SLS. This table reports the result of PSM procedure and 2SLS model. t-Statistics in the brackets are based on standard errors adjusted for clustering at the firm level.*, ** and *** indicate significance at the 0.10, 0.05 and 0.01 level (two-tailed), respectively.

	(1)	(2)
	lnpatent_invent PSM	lnpatent_invent 2SLS
L_overseas	0.148**	0.185*
	(2.08)	(1.85)
L_lnsize	0.378***	0.284***
	(8.70)	(18.99)
L_roa	2.479***	0.101**
	(3.74)	(2.55)
L_lnage	−0.370***	−0.193***
	(−4.04)	(−5.00)
L_center	0.000	0.004***
	(0.15)	(5.02)
L_indep	1.395**	0.346
	(1.99)	(1.42)
L_dual	−0.105	−0.070**
	(−1.45)	(−2.42)
L_SOE	0.130*	0.033
	(1.72)	(1.18)
L_HHI	0.459	0.317**
	(1.41)	(2.40)
_cons	−7.222***	−5.689***
	(−7.65)	(−15.28)
Year	Yes	Yes
Industry	Yes	Yes
The first-stage F statistic		581.177
N	740	4503
r2	0.352	0.234

4.4 Robustness Test

In addition to considering the endogeneity, we further do some other robustness tests, such as replacing the model and replacing the dependent variable.

Considering patent have the feature of counting, we use the poisson model to study the impact of internationalized executives on enterprise innovation (Aghion et al., 2013; Jiang and Yuan, 2018). The result is reported in Column 1) of **Table 6**. The coefficient of internationalized executives is 0.22, significant at 5% level, which confirms the above result.

We further use the tobit model to study the relationship between the above two. The result is in **Table 6** column (2). The coefficient of internationalized executives is still significant. The above results remain valid.

Finally, we change the measure of innovation and use the total number of patents as an innovation indicator, which includes invention patents, design patents, and utility model patents (Yuan and Wen, 2018). The above results remain valid.

4.5 The Mediating Effect of Internationalization Strategy

In order to test whether the impact of internationalized executives on enterprise innovation is realized through the path of internationalization strategy, this paper uses the Sobel mediation factor test method of Baron and Kenny, (1986), and sets the model as follows:

TABLE 6 | Robustness test. This table reports the result of three kinds of robustness test. t-Statistics in the brackets are based on standard errors adjusted for clustering at the firm level.*, ** and *** indicate significance at the 0.10, 0.05, and 0.01 level (two-tailed), respectively.

	(1)	(2)	(3)
	Patent_invent Poisson	lnpatent_invent tobit	lnpatent_all replace variable
L_overseas	0.220**	0.275*	0.155**
	(–2.47)	(1.93)	(2.54)
L_lnsize	0.516***	0.804***	0.346***
	(–19.88)	(22.33)	(20.95)
L_roa	0.323***	0.466**	0.117**
	(–3.73)	(2.27)	(2.52)
L_lnage	–0.428***	–0.871***	–0.240***
	(–4.10)	(–6.41)	(–5.19)
L_center	0.005**	0.006**	0.006***
	(–2.30)	(2.19)	(5.85)
L_indep	–1.125*	0.896	0.369
	(–1.90)	(1.20)	(1.28)
L_dual	0.186**	–0.070	–0.084**
	(–2.40)	(–0.66)	(–2.43)
L_SOE	0.024	0.004	0.051
	(–0.30)	(0.03)	(1.57)
L_HHI	–0.815***	0.062	0.403***
	(–3.27)	(0.16)	(2.71)
_cons	–9.179***	–17.464***	–6.757***
	(–15.27)	(–20.13)	(–16.97)
Year	Yes	Yes	Yes
Industry	Yes	Yes	Yes
N	4503	4503	4503
r2			0.261

$$For\_sale_{i,t-1} = \beta_0 + \beta_1 \text{overseas}_{i,t-1} + \sum \gamma_k control_{k,i,t-1} + \delta industry_i + \theta year_t + \varepsilon_{i,t} \quad (2)$$

$$Lnpatent_{i,t} = \beta_0 + \beta_1 overseas_{i,t-1} + \beta_2 For\_sale_{i,t-1} + \sum \gamma_k control_{k,i,t-1} + \delta industry_i + \theta year_t + \varepsilon_{i,t} \quad (3)$$

Following prior studies (Sun et al., 2015; Song et al., 2017), we define the proportion of enterprise foreign income as the enterprise's internationalization strategy. Then, we use the method of Baron and Kenny, (1986) to test whether the internationalization strategy has a mediating effect on the relationship between the internationalized executives and enterprise innovation. This method concludes three steps. Specifically, we use model (1) described in **Section 3.3** to estimate the impact of internationalized executives on enterprise innovation. And in the second step, we use model (2) to estimate the impact of internationalized executives on internationalization strategy. Finally, we put internationalized executives and internationalization strategy into model together, as model (3) shows.

Table 7 reports the mediating effect results. The coefficients on internationalized executives in Columns (1) are 0.087, significant at the 1% level, which indicates that internationalized executives can comprehensively improve the enterprise internationalization strategy. Then, Column (2) shows that when internationalization strategy is added to model (1), the coefficient of overseas decreases and the Sobel value is significantly positive, indicating that internationalization strategy does play a mediating role in the impact of internationalized executives on enterprise innovation. Finally, in the proportion of mediating effect, the internationalization strategy accounts for about 17.3%. This result is consistent with

TABLE 7 | The mediating effect of internationalization strategy in high-carbon industry. This table reports the mediating effect results. The first step is to estimate the impact of internationalized executives on enterprise innovation (see model (1)). The second step is to estimate the impact of internationalized executives on enterprise internationalization strategy (see model (2)). The last step is to estimate the impact of internationalized executives on enterprise innovation after joining internationalization strategy (see model (3)).

	L_for_sale	lnpatent_invent
	(1)	(2)
L_overseas	0.087***	0.128*
	(9.46)	(2.78)
L_for_sale		0.309***
		(4.15)
_cons	0.426***	–5.748***
CV	(7.94)	(–21.37)
	Yes	Yes
Year	Yes	Yes
Industry	Yes	Yes
N	4503	4503
r2	0.089	0.237
Sobel Z		0.000***
		(3.803)
Goodman-1 Z		0.000***
		(3.785)
Goodman-2 Z		0.000***
		(3.821)
Mediating Effect		17.3%

the expected results. According to the upper echelon theory, executives, as decision-makers of enterprises, prefer to guide the development of enterprises in the fields they are familiar with. Internationalized executives have excellent language communication skills and advanced concepts, which can help enterprises better grasp the risks of overseas investment and optimize the decision-making of enterprises in the international environment. So internationalized executives prefer to promote internationalization strategy.

5 CONCLUSION

In the context of globalization, the cross-border flow of capital, technology and other factors of production becomes more and more frequent, and the corresponding internationalized executives are gradually pursued by the capital market. So we take Chinese-listed companies from 2010 to 2018 as the research object and analyze the impact of internationalized executives on enterprise innovation. To sum up, we contribute to the literature from the following aspects.

Firstly, internationalized executives have an incentive effect on enterprise innovation in high-carbon industry. This is because internationalized executives have excellent foreign language communication skills and advanced concepts, which can facilitate enterprises to establish bridge of cooperation with foreign enterprises and acquire advanced resources. However, the internationalized executives have no real impact on enterprise innovation in low-carbon and medium-carbon industries. The possible reason is that the low-carbon and medium-carbon industries have certain advantages in the world compared to higher-carbon industries, and Chinese talents continue to emerge, which reduces the role of internationalized executives in promoting innovation.

Secondly, the impact of internationalized executives on enterprise innovation is realized by enhancing the enterprise internationalization strategy. According to the upper echelon theory, internationalized executives may prefer to promote the implementation of the internationalization strategy. Moreover, in the international market, enterprises will have more opportunities to get in touch with scarce knowledge and technology, which are also the key elements of enterprise innovation.

Finally, the results are beneficial to enterprises and governments interested in promoting innovation. Those entities, especially high-carbon firms, can pay more attention to the internationalized executives. In addition, our findings suggest that Chinese governments' efforts in attracting internationalized talents seem to have generated positive impact on enterprise innovation.

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

The author confirms being the sole contributor of this work and has approved it for publication.

REFERENCES

Acharya, V., and Xu, Z. (2017). Financial Dependence and Innovation: The Case of Public versus Private Firms. *J. Financial Econ.* 124 (2), 223–243. doi:10.1016/j.jfineco.2016.02.010

Aghion, P., Van Reenen, J., and Zingales, L. (2013). Innovation and Institutional Ownership. *Am. Econ. Rev.* 103 (1), 277–304. doi:10.1257/aer.103.1.277

Atanassov, J. (2013). Do Hostile Takeovers Stifle Innovation? Evidence from Antitakeover Legislation and Corporate Patenting. *J. Finance* 68 (3), 1097–1131. doi:10.1111/jofi.12019

Balsmeier, B., Fleming, L., and Manso, G. (2017). Independent Boards and Innovation. *J. Financial Econ.* 123 (3), 536–557. doi:10.1016/j.jfineco.2016.12.005

Baron, R. M., and Kenny, D. A. (1986). The Moderator-Mediator Variable Distinction in Social Psychological Research: Conceptual, Strategic, and Statistical Considerations. *J. Personal. Soc. Psychol.* 51 (6), 1173–1182. doi:10.1037/0022-3514.51.6.1173

Benmelech, E., and Frydman, C. (2015). Military CEOs. *J. Financial Econ.* 117 (1), 43–59. doi:10.1016/j.jfineco.2014.04.009

Bernile, G., Bhagwat, V., and Rau, P. R. (2017). What Doesn't Kill You Will Only Make You More Risk-Loving: Early-Life Disasters and CEO Behavior. *J. Finance* 72 (1), 167–206. doi:10.1111/jofi.12432

Bronzini, R., and Piselli, P. (2017). The Impact of R&D Subsidies on Firm Innovation. *Res. Pol.* 45 (2), 442–457.

Chang, X., Fu, K., Low, A., and Zhang, W. (2015). Non-Executive Employee Stock Options and Corporate Innovation. *J. Financial Econ.* 115 (1), 168–188. doi:10.1016/j.jfineco.2014.09.002

Chemmanur, T. J., Loutskina, E., and Tian, X. (2014). Corporate Venture Capital, Value Creation, and Innovation. *Rev. Financ. Stud.* 27 (8), 2434–2473. doi:10.1093/rfs/hhu033

Chen, S., and Tang, B. (2012). The Moderating Role of Managerial Freedom. *Stud. Sci. Sci.* 030 (011), 1723–1734. (in Chinese).

Chen, X., Li, Y., Xiao, J., and Wen, F. (2020). Oil Shocks, Competition, and Corporate Investment: Evidence from China. *Energ. Econ.* 89, 104819. doi:10.1016/j.eneco.2020.104819

Cornaggia, J., Mao., Y., Tian, X., and Wolfe, B. (2015). Does Banking Competition Affect. *Innovation J. Financial Econ.* 115 (1), 189~209. doi:10.1016/j.jfineco.2014.09.001

Dong, K., Ren, K., and Zhao, J. (2021). How Does Low-Carbon Energy Transition Alleviate Energy Poverty in China? A Nonparametric Panel Causality Analysis. *Energy Econ.* 8, 105620. doi:10.1016/j.eneco.2021.105620

Dou, Y., Li, Y., Dong, Y., and Ren, X. (2021). Dynamic Linkages between Economic Policy Uncertainty and the Carbon Futures Market: Does Covid-19 Pandemic Matter?. *Resour. Policy* 75, 102455. doi:10.1016/j.resourpol.2021.102455

Duan, K., Ren, X., Shi, Y., Mishra, T., and Yan, C. (2021). The Marginal Impacts of Energy Prices on Carbon Price Variations: Evidence from a Quantile-On-Quantile Approach *Energ. Econ.* 95, 105131. doi:10.1016/j.eneco.2021.105131

Ederer, F., and Manso, G. (2013). Is Pay for Performance Detrimental to Innovation? *Manage. Sci.* 59 (7), 1496–1513. doi:10.1287/mnsc.1120.1683

Fang, V. W., Tian, X., and Tice, S. (2014). Does Stock Liquidity Enhance or Impede Firm Innovation? *J. Finance* 69 (5), 2085~2125. doi:10.1111/jofi.12187

Giannetti, M., Liao, G., and Yu, X. (2015). The Brain Gain of Corporate Boards: Evidence from China. *J. Finance* 70 (4), 1629–1682. doi:10.1111/jofi.12198

Hambrick, D. C., and Mason, P. A. (1984). Upper Echelons: The Organization as a Reflection of its Top Managers. *Amr* 9 (2), 193–206. doi:10.5465/amr.1984.4277628

He, J., and Tian, X. (2015). *SHO Time for Innovation: The Real Effects of Short Sellers*. Bloomington, Indiana: Kelley School of Business Research Paper.

He, J., and Tian, X. (2013). The Dark Side of Analyst Coverage: the Case of Innovation. *J. Financial Econ.* 109, 856–878. doi:10.1016/j.jfineco.2013.04.001

He, Y., Yu, W., Dai, Y., and Wang, Y. (2019). Professional Experience of Executives and Corporate Innovation. *Manag. World* 35 (11), 174–192. (in Chinese).

Holmstrom, B. (1989). Agency Costs and Innovation. *J. Econ. Behav. Organ.* 12 (3), 305–327. doi:10.1016/0167-2681(89)90025-5

Huang, C., Rongwei, N., Jiang, Q., and Zheng, H. (2019). Will Literati Going to Sea_ Promote Corporate Innovation? *J. Econ. Res.* 045 (005), 111–124. (in Chinese).

Jiang, X. (2016). Government Decentralization and State-owned Enterprise Innovation: A Research Based on the Perspective of the Pyramid Structure of Local State-owned Enterprises. *Manag. World* 4 (9), 120–135. (in Chinese)

Jiang, X., and Yuan, Q. (2018). Institutional Investors' Corporate Site Visits and Corporate Innovation. *J. Corp. Finance* 48, 148–168. doi:10.1016/j.jcorpfin.2017.09.019

Jie, M., Wang, J., and Liu, D. (2014). Environmental Regulation, Technological Innovation and Business Performance. *Nankai Bus. Rev. Int.* 17 (6), 106–113. (in Chinese).

Li, W., and Zheng, M. (2016). Substances and Strategic Innovation: The Impact of Macro-Industrial Policy on Micro-firm Innovation. *Econ. Res. J.* (4), 60–73. (in Chinese).

Lin, W.-T. (2012). Family Ownership and Internationalization Processes: Internationalization Pace, Internationalization Scope, and Internationalization Rhythm. *Eur. Manage. J.* 30 (1), 47–56. doi:10.1016/j.emj.2011.10.003

Manso, G. (2011). Motivating Innovation. *J. Finance* 66 (5), 1823–1860. doi:10.1111/j.1540-6261.2011.01688.x

Meng, Q., Li, X., and Zhang, P. (2019). Do employee Stock Ownership Plans Promote enterprise Innovation?-- Empirical Evidence from the Perspective of Employees. *Manage. World* 35 (11), 20.

Mukherjee, A., Singh, M., and Žaldokas, A. (2017). Do Corporate Taxes Hinder Innovation? *J. Financial Econ.* 124 (1), 195–221. doi:10.1016/j.jfineco.2017.01.004

Ni, X., and Zhu, Y. (2016). Labor Protection, Labor Intensification and Firm Innovation: Evidence from the Implementation of the Labor Contract Law in 2008. *Manage. World* (7), 154–167. (in Chinese).

Quan, X., Bai, W., and Yin, H. (2019). Senior Management Experience, Management Style and Company Innovation. *Nankai Manage. Rev.* 022 (006), 140–151. (in Chinese).

Ren, X., Cheng, C., Wang, Z., and Yan, C. (2021). Spillover and Dynamic Effects of Energy Transition and Economic Growth on Carbon Dioxide Emissions for the European Union: A Dynamic Spatial Panel Model. *Sustain. Dev.* 29 (1), 228–242. doi:10.1002/sd.2144

Song, J., Wen, W., and Wang, D. (2017). Can Overseas Returnees Promote Enterprise Risk Taking -- Empirical Evidence from China's A-Share Listed Companies. *Finance Trade Econ.* 38 (012), 111–126. (in Chinese).

Song, T., Zhong, X., and Chen, W. (2017). Expectation gap and Firm Internationalization Speed: Evidence from China's Manufacturing Industry. *China Ind. Econ.* (6). (in Chinese).

Sun, S. L., Peng, M. W., Lee, R. P., and Tan, W. (2015). Institutional Open Access at Home and Outward Internationalization. *J. World Business* 50, 234–246. doi:10.1016/j.jwb.2014.04.003

Tang, W., Fu, Y., and Wang, Z. (2014). Technological Innovation, Technology Import and Economic Growth Mode Transformation. *Econ. Res. J.* (7), 31–43. (in Chinese).

Wen, F., Zhao, L., He, S., and Yang, G. (2020). Asymmetric Relationship between Carbon Emission Trading Market and Stock Market: Evidences from China. *Energ. Econ.* 91, 104850. doi:10.1016/j.eneco.2020.104850

Xu, N., and Li, Z. (2016). Executive Poverty Experience and Corporate Charitable Giving. *Econ. Res. J.* 051 (012), 133–146. (in Chinese).

Yu, Y., Zhao, Q., and Ju, X. (2018). Inventor Executives and Enterprise Innovation. *China Ind. Econ.* 000 (003), 136–154. (in Chinese).

Yuan, J., Hou, Q., and Chen, C. (2015). The Curse Effect of Enterprise Political Resources: Based on the Investigation of Political Connection and Enterprise Technological Innovation. *Manage. World* (1), 139–155. (in Chinese).

Yuan, R., and Wen, W. (2018). Managerial Foreign Experience and Corporate Innovation. *J. Corporate Finance* 48, 752–770. doi:10.1016/j.jcorpfin.2017.12.015

Zhang, Y. J., Shi, W., and Jiang, L. (2020). Does China's Carbon Emissions Trading Policy Improve the Technology Innovation of Relevant Enterprises? *Bus Strat Env* 29 (3), 872–885. doi:10.1002/bse.2404

Zheng, Y., Zhou, M., and Wen, F. (2021). Asymmetric Effects of Oil Shocks on Carbon Allowance price: Evidence from China. *Energ. Econ.* 97 (6), 105183. doi:10.1016/j.eneco.2021.105183

Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 07 January 2022
doi: 10.3389/fenrg.2021.821686

Can the Target Responsibility System of Air Pollution Control Achieve a Win-Win Situation of Pollution Reduction and Efficiency Enhancement?

Jie Wang, Hao Xu and Jingxuan Xu**

School of Economics, Beijing Technology and Business University, Beijing, China

OPEN ACCESS

Edited by:
Kangyin Dong,
University of International Business and Economics, China

Reviewed by:
Jian Yu,
Central University of Finance and Economics, China
Yu Hao,
Beijing Institute of Technology, China
Xingle Long,
Jiangsu University, China

****Correspondence:***
Hao Xu
xh1374078163@163.com
Jingxuan Xu
xujingxuan@btbu.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *24 November 2021*
Accepted: *13 December 2021*
Published: *07 January 2022*

Citation:
Wang J, Xu H and Xu J (2022) Can the Target Responsibility System of Air Pollution Control Achieve a Win-Win Situation of Pollution Reduction and Efficiency Enhancement? Front. Energy Res. 9:821686. doi: 10.3389/fenrg.2021.821686

Whether the environmental target responsibility system, a typical mandatory environmental regulation, can realize the coordinated development of environmental protection and economic growth has attracted widespread attention. With the difference-in-differences (DID) method, this paper utilizes a policy, "China's Key Cities for Air Pollution Control to Meet the Standards within the Time Limit (APCMS)," as a quasi-natural experiment to empirically examine the target responsibility system of air pollution control's effect on both firms' pollutant emissions and their total factor productivity (TFP). The corresponding mechanisms are also investigated. The results show: 1) The policy not only significantly decreases firms' pollutant emissions, but also improves their TFP. The results are robust to the exclusion of the impact of other policies in the same period, propensity score matching DID (PSM-DID) test, the adoption of alternative dependent variables, and altering sample interval; 2) The dynamic analysis shows that the policy effect on reducing pollutant emissions has increased over years after a lag of 2 years; 3) The policy reduces pollutant emissions mainly through stimulating the internal innovation rather than end-pipe treatment or production cuts. 4) Capital-intensive and private firms and firms in regions with a high degree of marketization or strong environmental law enforcement are found more responsive to the environmental target responsibility system.

Keywords: target responsibility system, APCMS, pollutant emission, TFP, innovation

1 INTRODUCTION

Balancing the relationship between environmental sustainability and continuous economic growth is a challenge for policymakers, and also an important research topic for scholars. As the second-largest economy in the world, China's remarkable economic growth has been accompanied by serious environmental problems. The report of the 19th National Congress of the Communist Party of China pointed out that "building an ecological civilization is a millennium plan for the sustainable development of the Chinese nation." In order to effectively deal with environmental pollution and degradation, the environmental target responsibility system, which has been initially established by the "Environmental Protection Law" promulgated in 1989, is an important feature of China's environmental regulatory policies (Zhang et al., 2021). Different from developed economies, as a transitional economy in China, local governments have tremendous influence and massive resources.

However, the incentives of local governments to implement the central government's environmental policies are seriously inadequate. Therefore, how to effectively encourage local governments has become an important challenge facing China's environmental governance.

The environmental target responsibility system is an important means of goal-oriented and responsibility-based environmental governance. It has two typical characteristics: one is the top-down environmental goal setting. The central government stipulates major pollutant reduction targets, and then decomposes targets and tasks from top to bottom. The other is the responsibility scheme of environmental assessment. Local government officials assume the main responsibility for environmental protection, and the upper-level government assesses the fulfillment of environmental targets, and the results of the assessment are linked to the rewards, punishments, appointments and promotion of officials. The environmental target responsibility system has incorporated environmental protection goals into the assessment mechanism for local officials, and directly linked the promotion of officials with the implementation of environmental policies (Zhang and Hao, 2020). It has changed the behaviors of local officials from simply focusing on economic development to realizing coordinated development of the economy and ecology. The incentives of local governments for environmental governance have been greatly strengthened (Gao, 2010).

Since the formulation of environmental protection targets is from top to bottom, and the upper-level government assesses and supervises the implementation of environmental goals of local government officials, the environmental target responsibility system is a typical mandatory environmental regulation. Its pollutant emission reduction effect has been demonstrated by many scholars (Calel and Dechezleprêtre, 2016; Wu et al., 2019; Zheng et al., 2021). However, some scholars still question whether the effects of mandatory environmental regulations are sustainable. Becker (2011) and Greenstone (2002) believe that the emission reduction effect faces long-term uncertainty. In addition, there are two completely opposite views on whether the target responsibility system can harm or improve firms' TFP. Some scholars argue that it will adversely affect the TFP through squeezing resources or delaying investment decisions. In addition, it imposes additional burdens, such as the installation of abatement equipment, which leads firms to shift resources from production and R&D to pollution control; It also increases the uncertainty faced by firms, which may delay the investment decisions, and even affects the R&D of new products and new production processes (Gollop and Roberts, 1983). However, Porter and van der Linde (1995) insist that appropriate environmental regulation can help upgrade firms' TFP through a variety of channels such as innovation incentive, improvement of resource allocation efficiency, organizational reforms and so on. Whether the target responsibility system can reduce pollutant emissions and improve firms' TFP at the same time is still not well known empirically despite the controversial qualitative arguments. Moreover, existing research on the similar issue is mainly concentrated in developed countries such as the United States, Germany and Japan (Barbera and McConnell, 1990; Gollop and Roberts, 1983; Viscusi, 1983; Hamamoto, 2006; Testa et al., 2011; Albrizio et al., 2017). There is still a lack of in-depth research in developing countries, particularly in China, which is the world's largest SO_2 emissions and with stricter environmental regulations. This paper is aimed at answering the question, whether the environmental target responsibility system can balance the relationship between environmental protection and economic development.

China's Key Cities for Air Pollution Control to Meet the Standards within the Time Limit (APCMS) policy implemented since January 2003 provides a good quasi-experimental environment to study the effect of mandatory environmental regulation in developing countries. It is a typical representative of the environmental target responsibility system. Firstly, it is a large-scale top-down environmental regulation. 113 key cities designated by the central government were required to reach national atmospheric and water environmental quality standards before 2005. Secondly, the fulfillment of this policy is explicitly incorporated into the assessment and promotion of local government officials. It has a strong binding force to motivate local government officials. This paper uses this policy as a quasi-natural experiment, constructs a panel data set from 1998 to 2014, and uses the difference-in-differences (DID) estimator to identify the impact of the environmental target responsibility system on firms' pollutant emissions and their TFP. This is to answer our research question, whether the mandatory environmental regulation can reduce pollutant emissions at the sacrifice of the economic development (e.g., lower firms' TFP) or also upgrade the economic growth (i.e., higher firms' TFP). Our empirical results show that this policy significantly reduces SO_2 emissions, smoke and dust and industrial wastewater. Besides, the policy has significantly improved the firms' TFP. The mechanism analysis results show that the key to realizing a win-win situation between environmental protection and economic growth lies in promoting technological progress, rather than end-pipe treatment or production cuts.

This paper has made contributions to the existing literature in the following three aspects: First, there is still no consensus as to whether the environmental target responsibility system can realize the coordinated development of the economy and ecology (Kostka, 2016; Yuan and Xiang, 2018; Chang et al., 2021; Zheng et al., 2021). Based on the APCMS policy implemented in China, this paper confirms that the policy achieves a win-win situation of pollution reduction and efficiency improvement. It provides further evidence for the debate about whether the mandatory environmental regulation and economic performance are "complementary" or "conflicting" for developing countries. Contrary to previous studies (Greenstone, 2002; Becker, 2011), empirical results demonstrate that pollution reduction effects are sustainable in the long term. Second, this paper analyzes the specific mechanism of the target responsibility system. That is, whether the target responsibility system decreases pollutant emissions and enhances efficiency through technological innovation, end-pipe treatment, or production scale adjustment. This enriches the mechanism research on the analysis of the mandatory environmental regulation. Third, this paper uses the firm-level data available from the China's Industrial Enterprise database (CIED) and China's Environmental Statistics database (CESD), while most studies use macro-level data (Jin et al., 2019; Wang et al., 2019; Zhang and Hao, 2020; Jiang et al., 2021). Thus, our estimations could be more accurate and useful to infer on the micro-level impact of the environmental regulation, particularly on each individual affected firm.

The rest of the paper is organized as follows. **Section 2** clarifies the theory and hypothesis development. **Section 3** summarizes the background of the APCMS policy. **Section 4** introduces the research design. **Section 5** shows and discusses the results of empirical analysis; **Section 6** concludes the paper with some policy recommendations as well.

2 LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

2.1 Environmental Target Responsibility System and Pollutant Emission Reduction

There has yet been empirical consensus on the relationship between environmental target responsibility system and pollutant emissions. First, disputes exist on whether this mandatory environmental regulation can indeed reduce pollutant emissions. Some scholars believe that environmental target responsibility system can reduce pollutant emissions. The environmental target responsibility system has added environmental criteria to the original performance assessment system, directly linking environmental governance to the promotion of local officials. It has realized the transformation from "soft constraint" to "hard constraint" on environmental protection, effectively restrained the internal impulse of local officials to sacrifice the environment for economic growth, and strengthened the enthusiasm of local governments for environmental protection and governance (Hong et al., 2019; Zhang et al., 2021). China's mandatory environmental targets have reduced the total amounts of mandatory pollutant emissions (Schreifels et al., 2012; Kostka, 2016). The Blue Sky Defense War has effectively reduced the average concentration of PM2.5 and PM10 (Jiang et al., 2021). The system takes effect by inducing firms' technological innovation and providing them direct financial incentives to abate emissions and pollutants. Moreover, it promotes the development and adoption of renewable energy, lowing the demand for fossil fuels and the associated carbon dioxide emissions (Zhao et al., 2013; He et al., 2020). However, some argue that the intensity of environmental regulation directly affects whether compliance costs will be considered in firms' production process. If compliance costs are insufficient, environmental regulation lacks a binding force on behaviors, and the effect of reducing pollutant emissions may not be obvious (Jin et al., 2019). Second, the effect of the environmental target responsibility system faces uncertainty in the long-term and the system may result in undesirable consequences. Becker (2011) finds that the effect of pollutant emission reduction brought by mandatory environmental regulation may be offset by insufficient incentives and constraints. Taking the Clean Air Act in the United States as an example, the bill has been revised several times due to its poor effect (Greenstone, 2002). Kostka (2016) shows that the binding environmental targets have generated numerous problems, such as target rigidity, cyclical behavior, and so on. Liang and Langbein (2015) indicate that performance assessment reduced pollutant emissions only for the most visible air pollutants among the targeted pollutants.

Most literature confirms that the environmental target responsibility system can effectively reduce pollutant emissions. China has a vertical official performance appraisal system. The APCMS policy is a top-down mandatory environmental regulation. The central government assigns administrative environmental goals to local governments at all levels. Controlling pollutant emissions will naturally become performance appraisal indicators of local government officials. Therefore, the local governments must vigorously obey and control pollutant emissions within their jurisdiction. The pollutant emission reduction effect is sustainable. Based on the above analysis, the first hypothesis of this paper is proposed:

Hypothesis 1. *The environmental target responsibility system will significantly reduce pollutant emissions.*

2.2 Environmental Target Responsibility System and TFP

The impact of the environmental target responsibility system on firms' TFP is unclear ex-ante. Most studies confirm that this mandatory environmental regulation has a negative impact on firms' TFP (Gollop and Roberts, 1983; Albrizio et al., 2017). On the one hand, it not only increases the non-productive investment, such as the installation of abatement equipment, which makes the firms' resources flow into end-pipe treatment; it also increases the production costs of firms, such as the utilization of higher-cost clean energy, and upgrading of production lines, which hinders the increase of TFP. Barbera and McConnell (1990) studied polluting industries in the United States and found that the TFP of regulated firms decreased sharply under environmental regulation. The negative effects of mandatory environmental regulations are divided into direct and indirect effects. The direct effect is that the abatement equipment occupies resources, and the indirect effect refers to increased production costs due to changes in traditional producing techniques. He et al. (2020) found that China's water quality monitoring system has an adverse effect on the TFP of polluting firms. Polluting firms located upstream of the river are affected by water quality monitoring stations and their TFP drop by 24%. On the other hand, the environmental target responsibility system may increase the uncertainty faced by firms and delay their investment decisions (Viscusi, 1983). And this uncertainty will further affect the R&D of new products and new production processes (Becker, 2011).

However, economists represented by Porter disagree with the above view. They believe that an appropriate environmental regulation may enhance innovation or encourage firms to adopt new organizational modes, improving TFP as a result (Yuan and Xiang, 2018). Hamamoto (2006) studied five manufacturing sectors in Japan and the results demonstrated that the environmental regulation increased firms' R&D investment, which led to a continuous TFP growth over the past 20 years. The environmental regulation in the EU construction industry also significantly increased the firm's R&D, thus improving their TFP (Testa et al., 2011; Rubashkina et al., 2015).

Based on the above analysis, we believe that the environmental target responsibility system may increase the burdens of firms in the short term, but in the long term, it enhances the incentives of innovation, which offsets the compliance costs of environmental regulation, and thus improves firms' TFP. Therefore, the second hypothesis is proposed as follows:

Hypothesis 2. *The environmental target responsibility system will significantly increase the TFP of firms.*

2.3 Impact Mechanism of the Environmental Target Responsibility

Based on existing literature, there exist three possible impact mechanisms of the environmental target responsibility system on pollutant reduction and TFP: adjustments of production scale, end-pipe treatment, or technological innovation. Firstly, mandatory environmental regulations increase the production costs of enterprises, reduce their production efficiency and operating profits, certain firms have no choice but to close some high-polluting production lines, adjust production scales and even exit the heavily-polluting industries. For example, Greenstone (2002) demonstrated that Clean Air Act in the United States had significantly reduced the production and operation scales of firms. Liu et al. (2017) also found that stricter wastewater discharge standards reduced the labor demand and production scales of enterprises. Secondly, the installation of abatement equipment is widely used by many firms to reduce pollutant emissions (Becker, 2011; Li et al., 2020). Thirdly, the "Porter Hypothesis" insists that appropriate environmental regulation will stimulate enterprises to carry out technological innovation and produce innovation compensation effect. Clarke et al. (1994) argue that whether the environmental target responsibility system can realize pollutant emission reduction and the improvement of the TFP lies in whether firms can incorporate compliance costs into the strategic decisions and focus on innovation and product upgrading. If firms only focus on passive end-pipe treatment or production scale adjustment, the effect of reducing pollutant emissions may be significant in the short term, but it may have a negative impact on their TFP. If it enhances innovation incentives and firms focus on internal innovation to improve efficiency, the coordinated development of ecology and economy can be achieved at the same time.

However, there are two opposite views on whether the mandatory environmental regulations enhance technological innovation. Some scholars insist that the environmental target responsibility system hinders firms' innovation. Innovation activities rely heavily on large capital investments and have a high risk of failure (Long et al., 2017; Luo et al., 2020). Under the pressure of mandatory environmental regulation, firms purchase abatement equipment and even take measures such as production cuts and shutdown, which squeezes necessary funds to finance R&D and innovation activities. Thus, it adversely impacts firms' TFP (Albrizio et al., 2017; Petroni et al., 2019). On the contrary, others support that the environmental target responsibility system enhances innovation. It is believed that appropriate environmental regulation enables firms to allocate resources efficiently and actively engage in innovation activities, which may weaken or offset the impact of the compliance costs (Poter and van der Linde, 1995; Wang et al., 2021; Ouyang and You, 2021). By exerting strong external pressure, it can overcome firms' inertia, enhance the enthusiasm of innovation, and form a good complementary relationship with the internal governance mechanism (Ambec and Barla, 2002).

Based on the above literature review, we believe that the environmental target responsibility system can improve firm's TFP by stimulating their innovations. Borghesi et al. (2015) insist that due to the high risks of failure of innovation activities, the willingness of innovation depends largely on firms' incentives. The environmental target responsibility system may promote innovation through the following two paths: firstly, it provides firms with more market information for technology upgrading (Goulder and Parry, 2008), which reduces the uncertainty of innovation. Secondly, it imposes high compliance costs on firms and enhances their willingness and motivation to innovate. Therefore, this paper puts forward the third hypothesis:

Hypothesis 3. *The key reason for the effect of reducing pollutant emissions and improving TFP of the environmental target responsibility system is that it induces firm innovation.*

3 BACKGROUND OF THE APCMS POLICY IN CHINA

In order to grapple with the problem of air pollution, the central government of China has implemented a series of top-down environmental regulations. The earliest one is the "Two Control Areas" policy. A lot of research has evaluated the effect of this policy (Tanaka, 2015; Cai et al., 2016). The APCMS policy discussed in this paper is also a top-down mandatory environmental regulation based on the target responsibility system (Liu et al., 2021). As early as 1998, the State Environmental Protection Administration promulgated a specific work plan, that is, the National Work Plan for Meeting the Discharge Standards of Industrial Pollution Sources and Environmental Function Zones in Key Environmental Protection Cities in 2000 (referred to as the "Two Compliance Policy"), which designated 47 cities as the first batch of key cities for air pollution control. These cities include Municipalities directly under the Central Government, provincial capital cities, coastal open cities and so on. They were required to reach urban atmospheric and water environmental quality standards before December 31, 2000. The ranking and implementation of the first batch of key cities were announced in

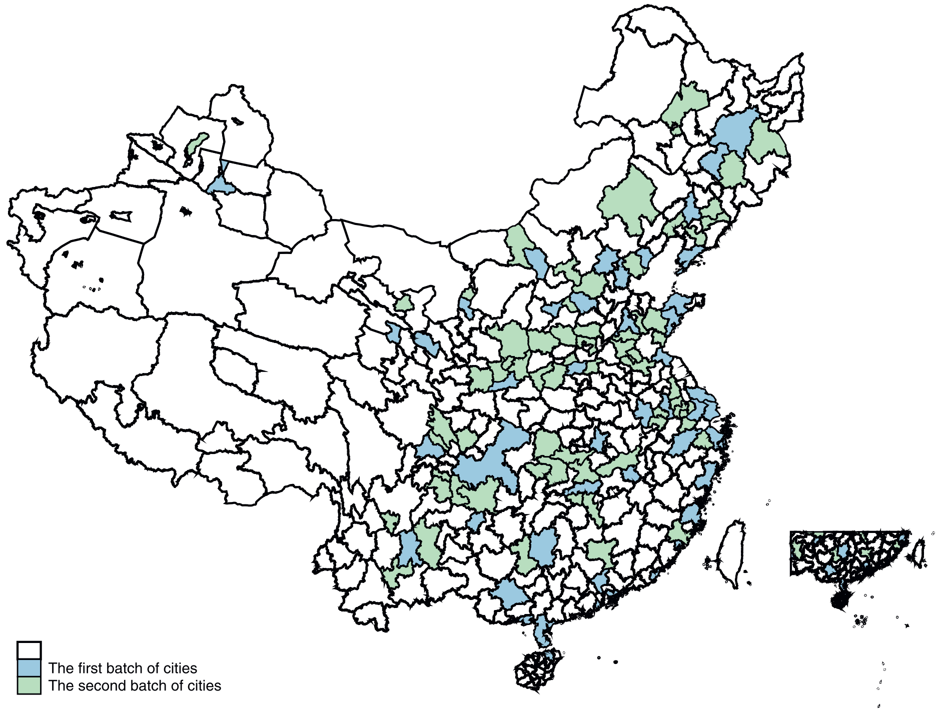


FIGURE 1 | The distribution of cities in the APCMS.

the Statistical Bulletin of Environmental Conditions and released to the public.

In order to ensure that the air quality of key cities meets the target requirements within time limit, the State Environmental Protection Administration issued the Designation Plan of Key Cities for Air Pollution Control at the end of 2002. Through the analysis of comprehensive economic conditions and pollution status of each city, and the commitment of certain provincial governments to meeting atmospheric standards by 2005, the document designated other 66 cities as the second batch of key cities for air pollution control. The air quality of the 113 key cities mentioned above must meet the national environmental atmospheric quality standards by 2005. The distribution of key cities is shown in **Figure 1**.

Since January 2003, the State Environmental Protection Administration promulgated the APCMS policy. It is a typical mandatory environmental regulation based on a target responsibility system. Firstly, above 113 key cities were required by the central government to reach urban atmospheric and water environmental quality standards before 2005. Secondly, the State Environmental Protection Administration would strictly supervise and regularly announce the air quality of each key city. Performance of environmental protection targets were incorporated into the assessment and promotion of local officials. For key cities that failed to meet the standards before 2005, new projects that caused air pollution would be strictly restricted. The specific contents of the relevant documents are shown in **Table 1**.

This paper uses 66 key cities designated in the second batch of air pollution control to investigate the impact of the environmental target responsibility system on pollutant emissions and TFP of firms. On the one hand, this design is limited by the availability of data. The China's Industrial Enterprise database (CIED) and China's Environmental Statistics database (CESD) used in this paper have been counted since 1998. On the other hand, the first batch of designated cities are Municipalities directly under the Central Government, provincial capital cities, coastal open cities, key tourist cities, and special economic zone cities, which are among the richest areas in China. Their economic and social conditions are quite different from that of other cities. It is difficult to find similar control groups in the samples not affected by the policy.

4 RESEARCH DESIGN

4.1 Model Specification

4.1.1 DID Model of Pollutant Emissions

In order to test the impact of the environmental target responsibility system on firm's pollutant emissions, this paper constructs a DID model as follows (Long et al., 2018; Zhang et al., 2018; Wu et al., 2019; Chen et al., 2021):

$$ln(Pollutant)_{itjp} = \beta_0 + \beta_1 Treat_i \times Year_t + \beta_2 X_{itjp} + \alpha_i + \gamma_t + \eta_{jt} + \delta_{pt} + \varepsilon_{itjp} \quad (1)$$

$ln(Pollutant)_{itjp}$ denotes the logarithm of pollutant emissions of firm i in year t and in the industry j and province p. To investigate the comprehensive effect of environmental regulation, we select SO_2 emissions, smoke and dust emissions, and industrial wastewater emissions to measure air and water pollution. We assign the value of 1 to $Treat_i$ if the firm belongs to the second batch of 66 key cities and assigns the value of 1 to $Year_t$ if the year is 2003 and afterward. The interactive term $Treat_i \times Year_t$ of the two dummy variables of experimental grouping and the experimental stage is the core explanatory variable of this paper. If the coefficient β_1 is negative, it indicates that the environmental target responsibility system has effectively reduced pollutant emissions. This paper expects the coefficient to be negative to confirm our Hypothesis 1. X_{itjp} represents a series of control variables, including the firm's size, capital intensity, total liabilities, the nature of property rights and whether it is an exporting firm. α_i, γ_t and η_{jt} represent firm fixed effects, year fixed effects, and the intersection of industry fixed effects and year fixed effects. In addition, the DID model also controls the intersection of province fixed effects and year fixed effects δ_{pt} to account for the macroeconomic factors among different provinces. Considering that the policy concerned in this paper is implemented at the city level, the robust standard errors are clustered into intersection term of city and year.

4.1.2 DID Model of TFP

In order to test whether the environmental target responsibility system can promote the efficiency of firms, we construct the following model:

$$ln(TFP)_{itjp} = \theta_0 + \theta_1 Treat_i \times Year_t + \theta_2 X_{itjp} + \alpha_i + \gamma_t + \eta_{jt} + \delta_{pt} + \varepsilon_{itjp} \tag{2}$$

$ln(TFP)_{itjp}$ represents the logarithm of the firm's TFP. $Treat_i \times Year_t$ is the core explanatory variable, which is the same as **Formula 1**. If the coefficient θ_1 is positive, it indicates that the environmental target responsibility system has significantly enhanced the firm's TFP. We expect the coefficient to be positive. The control variables, fixed effect, and robust standard errors are consistent with **Formula 1**.

4.2 Data Sources and Sample Selection

The China's Environmental Statistics database (CESD) provides data on firms' pollutant emissions that account for 85% of China's total emissions. The indicators include industrial output, SO_2 emissions, smoke and dust, industrial wastewater and so on, as well as end-pipe treatment equipment. These data are reported by firms, collected and monitored by environmental protection departments to ensure data quality. They are considered to be the most comprehensive and reliable environmental micro-economic data in China (Zhang et al., 2018).

In order to comprehensively investigate the impact of the environmental target responsibility system on pollutant emission reduction and TFP, this paper merges the China's Environmental Statistics Database (1998–2014) and the China's Industrial Enterprise database (1998–2014). 44.4% of the samples are successfully matched, with a total of 734,290 samples. The reasons for the mismatch of the remaining samples are as follows: First, the two databases have different coverage. CIED only includes industrial firms, while CESD covers a wider range and also includes non-industrial firms that emit pollutants, such as hospitals; Second, CIED only contains industrial firms whose main business income exceeds 5 million yuan (10 million yuan after 2011), while CESD contains some high-polluting firms whose main business income is less than 5 million yuan (10 million yuan after 2011) (Liu et al., 2021). In addition, in order to verify the mechanisms of the environmental target responsibility system, this paper also uses the China's Patent Database (CPD) from 1998 to 2014.

4.3 Variable Description

4.3.1 Dependent Variable

Firm's Pollutant emissions. Considering the availability of data and requirements of this policy, this paper selects SO_2 emissions, smoke and dust and industrial wastewater as explanatory variables and examines the comprehensive effect of the environmental regulation on pollutant emissions.

Firm's TFP. The commonly used methods of measuring the TFP include OLS and fixed effect regression, OP method, LP method and ACF method proposed by Ackerberg et al. (2015). It is generally believed that OLS and fixed effect regression will produce large deviations in calculating the TFP. Therefore, this paper uses the ACF method to calculate TFP, and uses the OP method and LP method for robustness test (Olley and Pakes, 1996; Levinsohn and Petrin, 2003). These methods can solve the endogenous problem. This paper uses them to fit the production function, and the residual error obtained is TFP. For the fitting process, we follow the practice of Brandt et al. (2017), and the variables used in the function include the industrial added value, capital stock, investment, intermediate inputs, the number of employees and so on. All data for calculating TFP come from China's Industrial Enterprise Database from 1998 to 2014.

Since 2007, the database lacked key variables for calculating the TFP such as industrial value-added, depreciation, intermediate input, wages, and so on. In order to calculate the TFP from 2008 to 2014, the missing variables need to be estimated. Following the practice of Yu et al. (2018), the depreciation rates after 2007 equal the depreciation rate of 2007, which equals the ratio of depreciation amount to fixed assets in 2007. For firms without depreciation in 2007, take the average depreciation rate of each industry by using a four-digit code. Since there is no industrial added value, the income approach is used to calculate the value. The specific formula is: industrial added value = accrued wages + value-added tax + income tax + business tax + total profit + depreciation amount of the current year (Zhu and Chen, 2020). For missing values of intermediate input, this paper assumes that intermediate input = total output value + value-added tax-added value. Considering there is a lack of wage data in certain years, the sum of the main business cost and administration expenses are used as the conversion basis for labor costs. Take the wages of 2009 for example, wages of 2009 = wages of 2008 × the growth rate of the conversion basis for labor costs. Due to the serious lack of enterprise code in 2010, it is difficult to guarantee the data quality, and many key variables are

TABLE 1 | Relevant documents.

Time and document name	Motivation and contents	Pilot cities
In November 1998, National Work Plan for Meeting the Discharge Standards of Industrial Pollution Sources and Environmental Function Zones in Key Environmental Protection Cities in 2000	The document aims to improve the air quality in designated key cities. By 2000, emissions of industrial pollution sources must meet the SO_2 and TSP emission standards; air and water quality of key cities must meet national standards, that is, "Two Compliance Policy". Local governments are required to formulate plans and specific targets for pollution control; the Ministry of Environmental Protection will conduct assessments, prepare a bulletin, and publish it to the public	There are 47 cities in total, including municipalities, provincial capitals, coastal open cities, key tourist cities, and special economic zone cities, as shown in **Figure 1**
In December 2002, the Designation Plan of Key Cities for Air Pollution Control	Based on the analysis of the current situation of urban air pollution, the Chinese government has designated other 66 key cities for air pollution control, a total of 113 cities. The document requires that by 2005, the air quality of key cities must meet the national atmospheric quality standards. The following preventive measures are required: promote the use of clean energy such as electricity, natural gas, and so on; promote clean production; strengthen the supervision of motor vehicle pollution emission; reduce the concentration of suspended particulates in the urban atmospheric environment; strengthen environmental monitoring and regularly release atmospheric quality information	In addition to the first batch of 47 cities, 66 cities have been added, including Karamay, Shizuishan, Jinchang, Xianyang, Yan'an, Baoji, Tongchuan, Tangshan, etc, as shown in **Figure 1**
In January 2003, Notice on China's Key Cities for Air Pollution Control to Meet the Standards within the Time Limit	The State Environmental Protection Administration strictly urges 113 key cities to reach the national second-level standard for ambient air quality in 2005. The document requires all key cities to complete the planning and the calculation of environmental capacity by the end of 2003; Strengthen the construction of key projects, and provide appropriate support for environmental infrastructure construction, pollution control, environmental capacity research, and supervision; Strictly control new, reconstruction and expansion projects and strengthen environmental supervision and management	Including the first batch and second batch of designated key cities for air pollution control, a total of 113 cities, as shown in **Figure 1**

missing in 2010 and cannot be estimated and supplemented, so the TFP of enterprises in 2010 is not calculated. Samples of 2010 are not included in the model of TFP.

In theory, the production technology adopted by each firm is different. If a unified production function is used to calculate the firm's TFP, it is at variance with reality. Therefore, we assume that the firm's production mode in the same industry is relatively similar, and then estimate the capital and labor elasticity coefficient by industry based on the two-digit industry classification, so as to calculate the firm's TFP. In addition, since the index in the CIED is the book value, it is necessary to convert it into real value. Specifically, the calculation of TFP also requires an output deflation index and input deflation index. The output deflation index comes from the chain price index of total output by industry in the "China Urban (Town) Life and Prices Yearbook." According to the method of Brandt et al. (2012), the input deflation index is calculated using the input-output (IO) table.

4.3.2 Key Independent Variable

$Treat_i$ is an experimental grouping dummy variable. In this paper, the firms that belong to the second batch of the 66 key cities for air pollution control are taken as the experimental group, and $Treat_i$ is set to be 1. Other firms are taken as the control group, $Treat_i$ is set to be 0. This paper assigns the value of 1 to $Year_t$ if the year is 2003 and afterward.

4.3.3 Control Variable

In order to reduce the endogenous problem caused by possible omitted variables, this paper includes as many as control variables, including the firm's size (total assets), total liabilities, capital intensity, the nature of property rights, and whether it is an exporting firm. Capital intensity is the ratio of the total fixed assets to the number of employees. This paper takes the natural logarithm of size, total liabilities and capital intensity. Finally, to reduce the influence of outliers, we shrink the tail of continuous variables. The descriptive statistics of variables are shown in **Table 2**.

5 EMPIRICAL RESULTS AND ANALYSIS

5.1 Benchmark Regression

5.1.1 Empirical Analysis of Pollutant Emissions

Table 3 reports the regression results of the impact of the APCMS policy on firm's pollutant emissions. The dependent variables in

TABLE 2 | Descriptive statistics of variables.

Variable name	Sample size	Mean	SD	Minimum	Maximum
SO_2 emissions	346,271	10.009	2.191	0	21.503
Smoke and dust emissions	263,492	9.743	2.509	0	18.425
Wastewater discharge	361,033	17.406	2.31	0	27.466
TFP of ACF Method	237,504	1.86	1.272	−8.155	10.151
TFP of LP Method	237,504	6.812	1.474	−2.614	14.048
TFP of OP Method	124,623	2.488	1.15	−7.677	9.264
Target responsibility system	467,888	0.269	0.443	0	1
Size	467,888	10.865	1.57	7.011	15.898
Capital intensity (CI)	467,888	4.229	1.373	0	9.347
Total liabilities (Liab)	467,888	10.202	1.767	4.745	15.48
State-Owned Enterprise (SOE)	467,888	0.1	0.3	0	1
Collective Enterprise (CE)	467,888	0.061	0.239	0	1
Private Enterprise (PE)	467,888	0.314	0.464	0	1
Mixed-Ownership Enterprise (MOE)	467,888	0.404	0.491	0	1
Hong Kong, Macao and Taiwan Enterprise (HMTE)	467,888	0.068	0.251	0	1
Exporting Enterprise (EXE)	467,888	0.388	0.487	0	1

Note: Variables including SO_2 emissions, smoke and dust emissions, wastewater discharge, TFP of ACF Method, TFP of LP Method and TFP of OP Method are taken the natural logarithm.

TABLE 3 | The impact of the environmental target responsibility system on pollutant emissions.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	SO_2	SO_2	Smoke and dust	Smoke and dust	Wastewater	Wastewater
Treat × Year	−0.1160*** (−4.38)	−0.1130*** (−4.28)	−0.105*** (−3.03)	−0.0998*** (−2.91)	−0.0740*** (−2.79)	−0.0697*** (−2.66)
Size		0.1760*** (20.29)		0.1990*** (15.63)		0.2260*** (25.08)
CI		−0.0312*** (−8.07)		−0.0410*** (−7.65)		−0.0384*** (−9.37)
Liab		0.0071 (1.46)		0.0104 (1.45)		−0.0019 (−0.35)
SOE		0.0024 (0.08)		0.0049 (0.14)		0.0814*** (3.19)
CE		−0.0572** (−2.03)		0.0256 (0.69)		−0.0635** (−2.40)
PE		−0.0023 (−0.10)		−0.0046 (−0.16)		−0.0260 (−1.53)
MOE		0.0188 (0.85)		0.0088 (0.30)		−0.0136 (−0.76)
HMTE		−0.0121 (−0.47)		−0.0662** (−2.04)		0.0016 (0.09)
EXE		0.0417*** (4.11)		−0.0058 (−0.44)		0.0472*** (4.58)
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry × Year	Yes	Yes	Yes	Yes	Yes	Yes
Province × Year	Yes	Yes	Yes	Yes	Yes	Yes
Obs	303,247	303,247	226,023	226,023	311,819	311,819
R^2	0.789	0.790	0.798	0.799	0.801	0.803

*Note: Industry classification in industry fixed effects is based on two-digit industry codes. Industry × Year refers to the intersection of industry-fixed effects and year-fixed effects, and Province × Year refers to the intersection of province-fixed effects and year-fixed effects. The parentheses are the t-values. The standard error of clustering robustness selects the intersection of city and year. ***, **, * denotes the significance level of 1, 5, and 10%, respectively.*

Table 3 are SO_2 emissions, smoke and dust emissions, and industrial wastewater emissions in order. Column (1) controls firm fixed effects, year fixed effects, the intersection term of industry fixed effects and year fixed effects, and the intersection term of province fixed effects and year fixed effects. The result shows that the coefficient of the policy variable is significantly negative, indicating that the environmental target responsibility system has significantly reduced the firm's SO_2 emissions. Control variables are added to the column (2), the coefficient of the policy variable is still negative. It also confirms the emission reduction effect of the environmental target responsibility system. Columns (3) to (6) examine the impact of the policy on the emissions of smoke and dust and industrial wastewater. The coefficients of the policy variable are all significantly negative, indicating that the policy has also decreased the firm's smoke and dust emissions and industrial wastewater discharge. Therefore, the environmental target responsibility system has effectively reduced pollutant emissions, and Hypothesis 1 has been verified.

5.1.2 Empirical Analysis of TFP

Table 4 demonstrates the estimation results of the effect of the environmental target responsibility system on firms' TFP. The result of column (1) shows that the coefficient of this policy is 0.0669, which is significantly at 1% level, indicating that the environmental target responsibility system has increased the firm's TFP. Column (2) adds the intersection of industry and year fixed effects and the intersection of province and year fixed

TABLE 4 | The impact of the environmental target responsibility system on TFP of firms.

Variables	(1)	(2)	(3)
	TFP	TFP	TFP
Treat × Year	0.0669*** (3.27)	0.0577*** (3.42)	0.0639*** (3.80)
Size	—	—	0.1320*** (14.53)
CI	—	—	0.0300*** (4.47)
Liab	—	—	−0.0540*** (−10.20)
SOE	—	—	−0.1030*** (−4.31)
CE	—	—	0.0215(0.98)
PE	—	—	−0.0052 (−0.32)
MOE	—	—	−0.0242 (−1.43)
HMTE	—	—	−0.0017 (−0.10)
EXE	—	—	0.0034 (0.44)
Firm FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Industry × Year	No	Yes	Yes
Province × Year	No	Yes	Yes
Obs	219,460	219,460	219,460
R^2	0.697	0.719	0.721

*Note: The parentheses are the t-values. ***, **, * denotes the significance level of 1, 5, and 10%, respectively.*

effects, and the result is basically unchanged. Column (3) adds control variables, and the result is consistent with columns (1) and (2). Therefore, the environmental target responsibility system has increased the firm's TFP, thus confirming our Hypothesis 2.

5.2 Parallel Trend Test and Estimation of Dynamic Effects

The validity of the DID model lays on the fundamental common trend or parallel trend assumption. That is, the experimental and control group should exhibit the same trend of outcomes in the counterfactual case where the experiment does not occur. Thus, we need to verify an assumption to guarantee the validity of the above DID estimation results. In addition, since the policy may take some time to be effective, which is the lagging policy effect. We thus examine the possible dynamic effects of the environmental regulation on firms' pollutant emissions and TFP in this subsection. Specifically, we follow the event study approach for empirical testing (Greenstone and Hanna, 2014) and build the following models:

$$ln(Pollutant)_{itjp} = \beta_0 + \beta_1 \sum\nolimits_{t=1999}^{2014} Treat_i \times \gamma_t + \alpha_i + \gamma_t + \eta_{jt} + \delta_{pt} + \varepsilon_{itjp} \quad (3)$$

$$ln(TFP)_{itjp} = \theta_0 + \theta_1 \sum_{t=1999}^{2014} Treat_i \times \gamma_t + \alpha_i + \gamma_t + \eta_{jt} + \delta_{pt} + \varepsilon_{itjp} \quad (4)$$

We take 1998 as the base year, β_1 and θ_1 represent a series of estimated values from 1999 to 2014. The definitions of other variables are the same as **Formulas 1** and **2**.

Figure 2 plots the estimated results of β_1 under the 95% confidence interval. It is found that the estimated coefficient β_1 is not significant before the policy was enacted, indicating that there is no significant difference in the dependent variables between the experimental group and the control group before the implementation of the policy, and the parallel trend hypothesis is thus supported. In addition, the estimated coefficient β_1 after the implementation of the policy is significant until 2005 and afterward, indicating that the impact of the policy on reducing pollutant emissions has increased year by year after a lag of 2 years. The reason for its lagging impact may be that industrial firms do not achieve pollutant emission reduction through the increase of end-pipe treatment facilities, but through technological innovation. From innovation investment to the conversion of innovation outputs requires a long period. Therefore, the pollutant emission reduction effect has hysteresis. This conclusion will be further verified in the mechanism analysis later.

Besides, the pollution reduction effect of the environmental target responsibility system has a certain degree of sustainability. The reasons for the increasing impact of the policy may come from the following two aspects: First, industrial firms continue to invest in clean production-related innovation under the external pressure of compliance costs, so as to reduce pollutant emissions; Second, new environmental regulations have exerted additional impact on firms. In 2007, the State Council promulgated the "Eleventh Five-Year Plan for National Environmental Protection," which designated 113 cities as key environmental protection cities. Among the 66 key cities for air pollution control discussed in this paper, 59 cities were designated as key environmental protection cities except for Weinan, Yuxi, Zigong, Deyang, Nanchong, Zhenjiang, and Sanmenxia. Therefore, these key cities are simultaneously affected by two policies after 2007. There exists a positive synergy between the two policies, which makes pollution reduction effects gradually increase over time. The parallel trend assumption is also verified for smoke and dust emissions and industrial wastewater discharge. The pollution reduction effect of the environmental target responsibility system becomes larger over time. Due to space limitations, the results are not included in the main text, and interested readers can ask the author for it.

Figure 3 plots the estimated results of θ_1 under the 95% confidence interval. It is found that the coefficient θ_1 is not significant before the policy was enacted, indicating that there is no significant difference between the experimental and the control group before the implementation, and the parallel trend assumption is also verified. In addition, the estimated coefficient θ_1 after the implementation of the policy is significant from the second year of 2004. The impact of this policy on the firm's TFP is not significant from 2007 to 2009. The reason may be that the breakout of the global financial crisis had an adverse impact on the development of firms and led to a decline in the TFP.

5.3 Robustness Test

5.3.1 Exclude the Impact of Other Policies in the Same Period

Since the beginning of this century, China has implemented a number of environmental regulations. The representative ones are the "Two Control Areas" policy and "Regulation on the

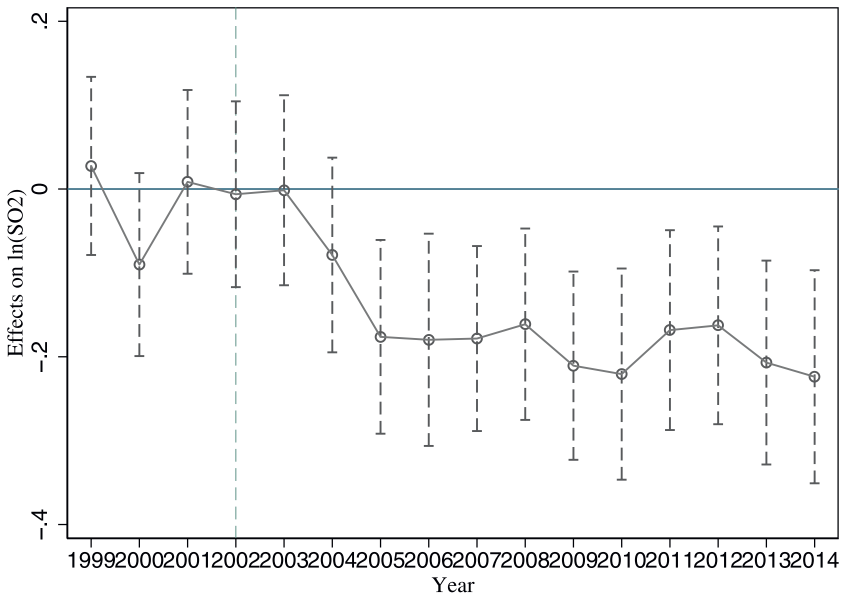


FIGURE 2 | Parallel trend test of SO_2 emissions.

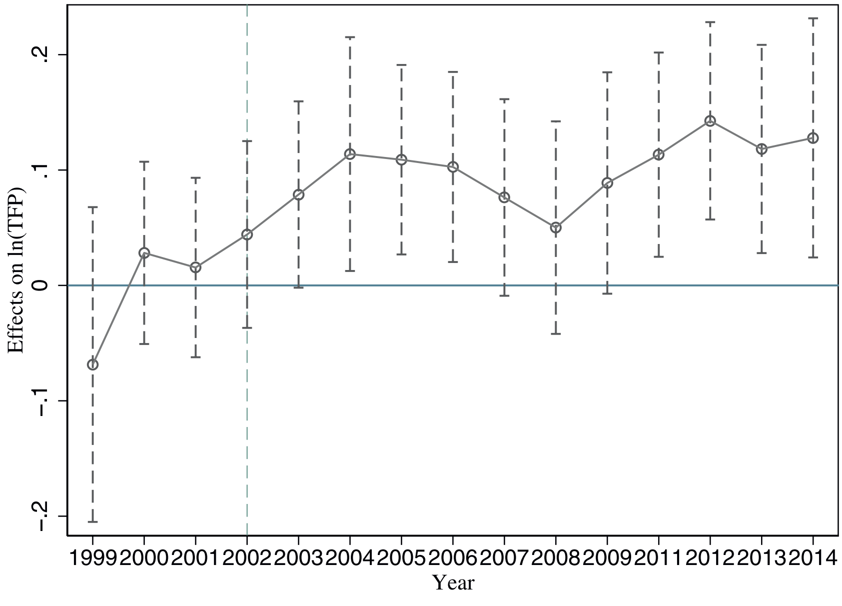


FIGURE 3 | Parallel trend test of TFP.

Collection and Use of Pollutant Discharge Fees" of 2003 (referred to as the "Pollutant Discharge Fees" policy). The implementation of multiple policies at the same period may lead to the inclusion of the influence of other policies in the estimated results of the above model.

In order to exclude the influence of other policies on our policy effect estimations, more control variables of these other policies have also been added for robustness check. The "Two Control Areas" policy is represented by the intersection of two dummy variables of grouping dummy variable and year dummy variable (Fujii et al., 2013; Tanaka, 2015). If the firms are located in the city specified by the "Two Control Areas" policy, the grouping dummy variable is assigned a value of 1 and 0 otherwise. The year dummy variable is set to 1 in 2000 and afterward.

According to the "Pollutant Discharge Fees" policy, the management of pollutant discharge fees had become more

TABLE 5 | Results of excluding the impact of policies of the same period.

Variables	(1)	(2)	(3)	(4)
	SO_2	Smoke and dust	Wastewater	TFP
Treat × Year	−0.112*** (−4.05)	−0.0927*** (−2.59)	−0.0808*** (−2.92)	0.0672*** (3.85)
"Pollutant Discharge Fees" policy	−0.0373 (−1.32)	−0.0643 (−1.59)	−0.0628** (−2.02)	0.0294* (1.72)
"Two Control Areas" policy	−0.0985*** (−2.62)	−0.0832* (−1.75)	0.0144 (0.41)	0.0569** (2.00)
Control variables	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Industry × Year	Yes	Yes	Yes	Yes
Province × Year	Yes	Yes	Yes	Yes
Obs	294,448	217,077	303,071	214,032
R^2	0.790	0.800	0.802	0.720

*Note: The parentheses are the t-values. ***, **, * denotes the significance level of 1, 5, and 10%, respectively.*

stringent after 2003, and the charging fees for unit pollutants had been greatly increased, which constituted a relatively good "quasi-natural experiment." In the Economic Census of 2004, CIED contained statistics on the pollution discharge fees in the management expenses item, which laid an important basis for dividing the experimental group and the control group. We assign a value of 1 to the firms that paid the pollution fees as the experimental group, and 0 to those that did not pay as the control group. The year dummy variable is set 1 in 2003 and afterwards. Similarly, the "Pollutant Discharge Fees" policy is represented by the intersection of grouping dummy variable and year dummy variable.

Table 5 reports the results after accounting for the possible effects of the "Pollutant Discharge Fees" policy and "Two Control Areas" policy. The results of columns (1) to (3) show that the APCMS policy still has a significant impact on reducing the three types of pollutants. "Two Control Areas" policy has significantly reduced SO_2 emissions and smoke and dust emissions but has no effect on wastewater discharges. However, the "Pollutant Discharge Fees" policy has reduced wastewater discharges but has no effect on air pollutants. Column (4) estimates the impact on firm's TFP after controlling for these two other policies. The result shows that the coefficient of the policy variable is significantly positive, indicating the results are robust. Besides, the other two policies also exert a positive impact on the TFP of firms.

5.3.2 PSM-DID

It is possible that the selection of pilot cities by the central government is not random under the APCMS policy. Then, the pilot cities (i.e., the experimental group) can have very heterogeneous characteristics compared to the non-pilot cities (i.e., the control group). Then, the DID estimation could be subject to the "uncommon support bias" due to such selection bias caused by the non-random policy assignments. In order to overcome such possible selectivity bias, we adopt the propensity score matching (PSM) to select the most resembling control group cities for the DID estimation. This is basically the widely adopted PSM-DID for robustness testing (Dehejia and Wahba, 2002; Greenstone, 2004). PSM method has been widely used in the field of policy analysis. For example, PSM was used to study the impact of the United States Clean Air Act on SO_2 emissions and analyze the impact of environmental regulation on employment in the power industry (Ferris et al., 2014).

The selection of key cities in the APCMS policy is likely to be based on some economic conditions and their pollutant emissions. Therefore, this paper selects the pollutant emissions and economic conditions of key cities as covariants for propensity score matching. Samples are matched using a one-to-one nearest neighbor matching method. 60 cities are successfully matched for our PSM-DID.

Table 6 reports the results of the PSM-DID model. The results show that the environmental target responsibility system has reduced the pollutant emissions of firms and improved their TFP significantly, which is basically consistent with the results in **Table 3**.

5.3.3 Adoption of Alternative Dependent Variables

This paper divides the firm's pollutant emissions by the total output as the dependent variables, SO_2 emission intensity for example (Petroni et al., 2019). In addition, the measurement of the TFP is replaced with the LP and OP methods. As the Industrial Enterprise Database of 2007 did not provide relevant basic data for the OP method, and it could not be estimated by other indicators, the sample interval of TFP measured by OP method is 1998–2007. **Table 7** reports the results of using alternative dependent variables. The results of columns (1) and (2) show that the policy has significantly reduced the intensity of SO_2 emissions. The results of columns (3) and (6) demonstrate that the environmental target responsibility system has improved the TFP of firms. It is consistent with the results in **Tables 3**, **4**, which confirms the robustness and reliability of the above conclusions of this paper.

5.3.4 Altering Sample Interval

This paper estimates the TFP of industrial enterprises from 1998 to 2014. However, the Industrial Enterprise Database after 2007 did not provide basic data required for measuring TFP, such as industrial added value and intermediate investment. For those missing data, we estimate according to the accounting standards and related literature, which may lead to the deviation between

TABLE 6 | Results of PSM-DID.

Variables	(1) SO_2	(2) Smoke and dust	(3) Wastewater	(4) TFP
Treat × Year	−0.1350*** (−2.99)	−0.1590*** (−3.18)	−0.1850*** (−4.27)	0.0632** (2.40)
Control variables	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Industry × Year	Yes	Yes	Yes	Yes
Province × Year	Yes	Yes	Yes	Yes
Obs	136,553	108,315	140,058	100,018
R^2	0.798	0.807	0.806	0.730

*Note: The parentheses are the t-values. ***, **, * denotes the significance level of 1, 5, and 10%, respectively.*

TABLE 7 | Results of replacing dependent variables.

Variables	(1) SO_2 intensity	(2) SO_2 intensity	(3) TFP_LP	(4) TFP_LP	(5) TFP_OP	(6) TFP_OP
Treat × Year	−4.2470*** (−3.16)	−4.3430*** (−3.24)	0.0392** (2.28)	0.0601*** (3.69)	0.0462*** (2.89)	0.0496*** (3.11)
Control variables	No	Yes	No	Yes	No	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry × Year	Yes	Yes	Yes	Yes	Yes	Yes
Province × Year	Yes	Yes	Yes	Yes	Yes	Yes
Obs	317,219	317,219	219,460	219,460	110,707	110,707
R^2	0.587	0.587	0.807	0.820	0.750	0.750

*Note: The parentheses are the t-values. ***, **, * denotes the significance level of 1, 5, and 10%, respectively.*

TABLE 8 | Results of changing the sample time range.

Variables	(1) SO_2	(2) Smoke and dust	(3) Wastewater	(4) TFP
Treat × Year	−0.1050*** (−3.61)	−0.0775** (−2.17)	−0.0684** (−2.39)	0.0755*** (4.44)
Control variables	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Industry × Year	Yes	Yes	Yes	Yes
Province × Year	Yes	Yes	Yes	Yes
Obs	136,521	111,075	134,603	106,676
R^2	0.790	0.815	0.827	0.707

*Note: The parentheses are the t-values. ***, **, * denotes the significance level of 1, 5, and 10%, respectively.*

the estimated index and the actual value. In addition, some scholars argue that the data quality after 2007 is relatively poor. Therefore, in order to mitigate the impact of TFP measurement on the results, this section deletes the samples after 2007 to test the robustness of the results. Columns 1–4 in **Table 8** are the regression results of the APCMS policy on SO_2 emissions, smoke and dust emissions, wastewater discharges and TFP, respectively. The regression results are basically consistent with those in **Tables 3**, **4**. The corresponding parallel trend test is shown in **Figures 4**, **5**, verifying the parallel trend assumption. Altering the sample interval does not affect the conclusions of this paper.

5.4 Heterogeneity Analysis

This paper has confirmed that the environmental target responsibility system can achieve a win-win situation of environmental protection and economic efficiency, but is there any heterogeneity in the effect of this policy? In order to answer this question, this paper conducts a heterogeneity analysis.

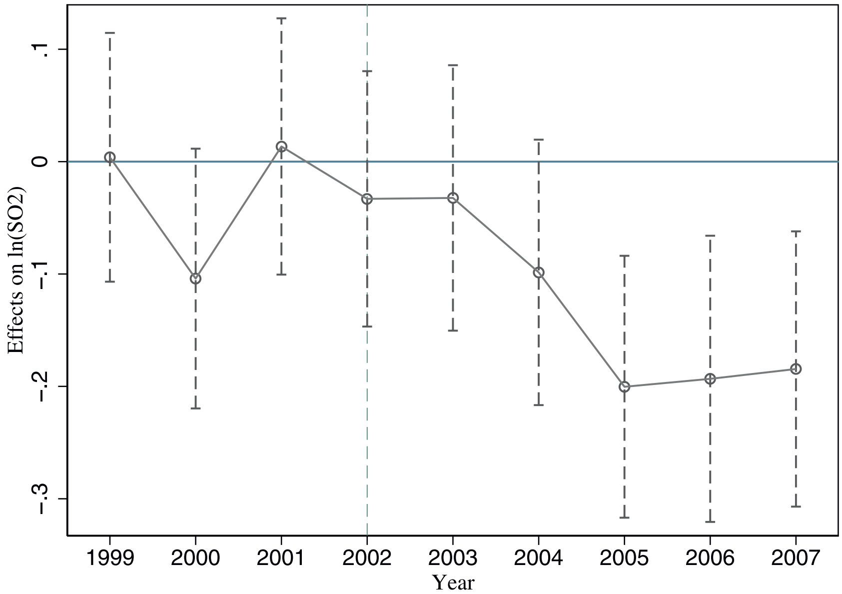


FIGURE 4 | Parallel trend test of SO_2 from 98 to 07.

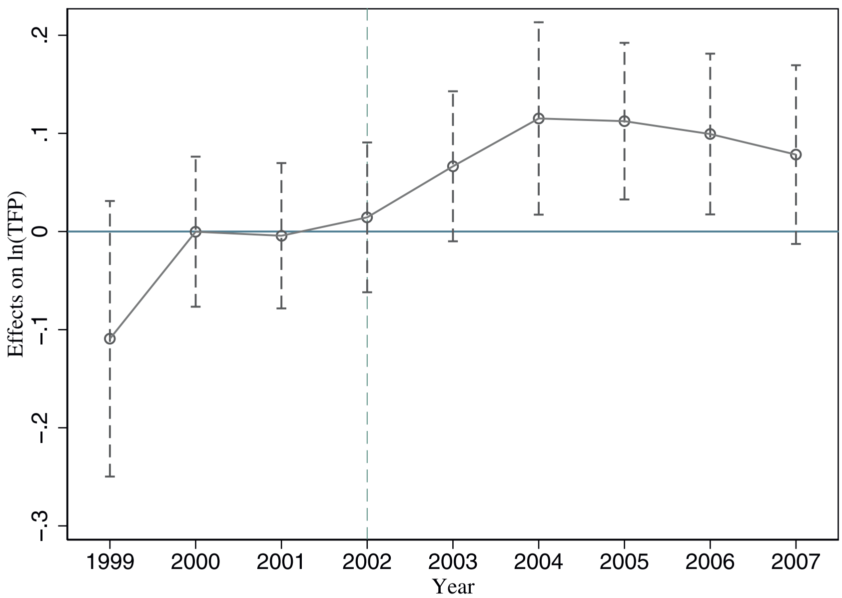


FIGURE 5 | Parallel trend test of TFP from 98 to 07.

5.4.1 Heterogeneity of Factor Intensity

The impact of the environmental target responsibility system on different factor-intensive firms may be totally different. **Table 9** shows the results of group-level regression based on factor intensity. Panel A is the estimation of SO_2 emissions; Panel B is the estimation of the TFP; Columns (1) and (2) are samples of capital-intensive firms and labor-intensive firms respectively.

Based on empirical results in **Table 9**, we find that the policy has reduced pollutant emissions of capital-intensive firms, while also increasing their TFP. The environmental target responsibility

TABLE 9 | Heterogeneity regression results of factor intensity.

Variables	(1)	(2)	(3)	(4)
	Capital intensive	**Capital intensive**	**Labor intensive**	**Labor intensive**
Panel A: SO_2 emissions				
Treat × Year	−0.1410*** (−4.66)	−0.1370*** (−4.55)	−0.0463 (−0.79)	−0.0446 (−0.78)
Control variables	No	Yes	No	Yes
Obs	211,723	211,723	90,614	90,614
R^2	0.771	0.773	0.828	0.829
Panel B: TFP				
Treat × Year	0.0479*** (2.59)	0.0536*** (2.90)	0.0464 (0.99)	0.0538 (1.15)
Control variables	No	Yes	No	Yes
Obs	156,672	156,672	62,421	62,421
R^2	0.725	0.726	0.703	0.704

Note: The parentheses are the t-values. ****, **, * denotes the significance level of 1, 5, and 10%, respectively.*

TABLE 10 | Heterogeneity regression results of property rights.

Variables	(1)	(2)	(3)	(4)
	State-owned	**State-owned**	**Private**	**Private**
Panel A: SO_2 emissions				
Treat × Year	−0.0559 (−1.23)	−0.0625 (−1.38)	−0.1470*** (−4.75)	−0.1400*** (−4.54)
Control variables	No	Yes	No	Yes
Obs	47,733	47,733	249,330	249,330
R^2	0.813	0.813	0.789	0.790
Panel B: TFP				
Treat×Year	0.0627 (1.31)	0.0625 (1.30)	0.0614*** (2.99)	0.0978*** (3.28)
Control variables	No	Yes	No	Yes
Obs	30,542	30,539	179,364	179,364
R^2	0.763	0.768	0.709	0.717

Note: The parentheses are the t-values. ****, **, * denotes the significance level of 1, 5, and 10%, respectively.*

system has no significant impact on labor-intensive firms. The possible reasons are: Firstly, compared with labor-intensive firms, capital-intensive firms are more dependent on innovation. In addition, the profit margins of capital-intensive firms are generally higher than that of labor-intensive firms, so they have more funds for innovative activities. Therefore, the environmental target responsibility system has a greater impact on capital-intensive firms. The heterogeneity regression results of smoke and dust emissions and industrial wastewater emissions are not reported in the text due to space limitations.

5.4.2 Heterogeneity of Firm Property Rights

The impact of the environmental target responsibility system on state-owned and private firms may be quite different. Panel A in **Table 10** is the result of the impact on SO_2 emissions; Panel B is the result of the impact on TFP; Columns (1) and (2) report results of state-owned firms without and with control variables respectively. Results indicate that the environmental target responsibility system has no significant impact on state-owned firms. Columns (3) and (4) report the results of private firms without and with control variables. Results show that for private firms, the environmental target responsibility system not only reduces their pollutant emissions, but also increases the overall TFP. Private firms are more sensitive to the environmental target responsibility system and more likely to realize the coordinated development of environmental protection and economic development.

The possible reason for the above heterogeneous effect is that the environmental target responsibility system promotes firms to reduce pollutant emissions and improve the TFP under the pressure of compliance costs. State-owned firms are under the control of the central government or local governments, which have great advantages in resource allocation, especially in financial support. They have soft budget constraints and may not be sensitive to the compliance cost pressure brought by environmental regulation. In contrast, private firms are responsible for their own profits and losses, and they hope to make up for the economic losses caused by compliance pressure by improving production efficiency.

5.4.3 Heterogeneity of Environmental Law Enforcement

The effect of the policy may be impacted by environmental law enforcement. If local officials relax environmental regulation and ignore the illegal discharge and leakage of polluting enterprises in order to protect local interests, it may result in the failure to achieve

TABLE 11 | Heterogeneity regression results of environmental law enforcement.

Variables	(1)	(2)	(3)	(4)
	High environmental law enforcement		Low environmental law enforcement	
Panel A: SO_2 emissions				
Treat × Year	−0.1460*** (−4.73)	−0.1440*** (−4.68)	0.0334 (0.60)	0.0395 (0.72)
Control variables	No	Yes	No	Yes
Obs	226,925	226,925	66,992	66,992
R^2	0.793	0.794	0.786	0.788
Panel B: TFP				
Treat × Year	0.0623*** (3.32)	0.0673*** (3.59)	0.0348 (0.86)	0.0450 (1.14)
Control variables	No	Yes	No	Yes
Obs	172,445	172,445	40,067	40,067
R^2	0.723	0.725	0.704	0.706

*Note: The parentheses are the t-values. ***, **, * denotes the significance level of 1, 5, and 10%, respectively.*

TABLE 12 | Heterogeneity regression results of marketization degree.

Variables	(1)	(2)	(3)	(4)
	Hign degree of marketization		Low degree of marketization	
Panel A: SO_2 emissions				
Treat × Year	−0.1220*** (−3.58)	−0.1160*** (−3.45)	−0.0939 (−1.32)	−0.0951 (−1.35)
Control variables	No	Yes	No	Yes
Obs	184,756	184,756	109,177	109,177
R^2	0.803	0.804	0.769	0.771
Panel B: TFP				
Treat × Year	0.0756*** (3.69)	0.0839*** (4.11)	0.0330 (1.07)	0.0363 (1.19)
Control variables	No	Yes	No	Yes
Obs	156,251	156,251	56,146	56,146
R^2	0.721	0.723	0.715	0.715

*Note: The parentheses are the t-values. ***, **, * denotes the significance level of 1, 5, and 10%, respectively.*

the goal of reducing pollutant emissions within a time limit. Generally speaking, the greater the intensity of environmental law enforcement, the higher the cost of violations faced by the company and the stronger the effect of the policy. In order to test the heterogeneity of the effects of the policy under different environmental law enforcement, this paper uses the number of environmental administrative punishments cases in each province to measure the intensity of environmental law enforcement, and divides the samples into two groups according to the median. The results of columns (1) and (2) in **Table 11** show that in regions with high environmental law enforcement, the APCMS policy significantly reduces SO_2 emissions and improves the TFP of enterprises. The results of columns (3) and (4) indicate that in regions with low environmental law enforcement, the policy has no significant impact on pollutant emissions and TFP. The results demonstrate that the effective implementation of environmental regulation relies on environmental law enforcement of local governments.

5.4.4 Heterogeneity of Marketization Degree

Enterprises in regions with a high degree of marketization often have better legal mechanisms and more transparent enterprise information. In order to explore whether the degree of marketization level will impact the implementation effect of mandatory environmental regulations, this study uses the marketization index to measure the degree of marketization (Wang et al., 2019). The samples are divided according to the median of the marketization index. The results of grouping regressions are shown in **Table 12**. The results of columns (1) and (2) illustrate that in regions with a high degree of marketization, the policy significantly reduces SO_2 emissions and also enhances the TFP of enterprises. The results of columns (3) and (4) indicate that in regions with a low degree of marketization, the policy has no significant impact. This result shows that enterprises in regions with a high degree of marketization are more sensitive to the environmental target responsibility system.

TABLE 13 | Results of the mechanism of end-pipe treatment.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	Desulfurization	Desulfurization	Wastewater treatment	Wastewater treatment	Waste gas treatment	Waste gas treatment
Treat × Year	−0.00889 (−0.96)	−0.00876 (−0.94)	−0.0106 (−1.07)	−0.0107 (−1.09)	−0.00137 (−0.14)	−0.000834 (−0.08)
Control variables	No	Yes	No	Yes	No	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Industry × Year	Yes	Yes	Yes	Yes	Yes	Yes
Province × Year	Yes	Yes	Yes	Yes	Yes	Yes
Obs	122,560	122,560	301,055	301,055	216,913	216,913
R^2	0.716	0.716	0.707	0.708	0.769	0.770

Note: The parentheses are the t-values*. ***, **, * denotes the significance level of 1, 5, and 10%, respectively.*

TABLE 14 | Results of the mechanism of production scale adjustment.

Variables	(1)	(2)	(3)	(4)
	Output value	Output value	Sales value	Sales value
Treat × Year	−0.0054 (−0.20)	0.0121 (0.57)	−0.0029 (−0.11)	0.0145 (0.69)
Control variables	No	Yes	No	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Industry × Year	Yes	Yes	Yes	Yes
Province × Year	Yes	Yes	Yes	Yes
Obs	400,901	400,901	400,896	400,896
R^2	0.889	0.914	0.887	0.912

Note: The parentheses are the t-values*. ***, **, * denotes the significance level of 1, 5, and 10%, respectively.*

5.5 Mechanism Test

5.5.1 The Mechanism of End-Pipe Treatment

The above empirical results show that the environmental target responsibility system has achieved the win-win between ecology and economy. There are three possible paths for the environmental target responsibility system to reduce pollutant emissions: Firstly, firms install emission reduction facilities, which effectively reduces pollutant emissions; secondly, firms close some high-polluting production lines or adjust production scales; thirdly, environmental compliance pressure forces firm to carry out technological innovations, which has a profound effect on pollutant emission reduction. These three paths have completely different effects on the TFP of firms. If firms have only relied on end-pipe treatment or production cuts, it will be difficult to increase the TFP. At the same time, the effect of pollutant emission reduction may not be sustainable in the long term. However intrinsic technological innovation not only helps firms increase the TFP, but also consolidates the achievements of emission reduction.

This paper uses the wastewater treatment facilities, desulfurization facilities and waste gas treatment facilities in the CESD as proxy variables for end-pipe treatment and verifies whether the policy reduces pollutant emissions through end-pipe governance. The results in **Table 13** show that the environmental target responsibility system has no significant impact on the end-pipe treatment facilities.

5.5.2 The Mechanism of Production Scale Adjustment

The APCMS policy sets strict limits on the emissions of pollutants. Under the pressure of environmental regulation, companies may shut down certain high-pollution production lines or cut down production. In order to test the mechanism of production scale adjustment, this paper selects the industrial output value and industrial sales value as proxy variables for production scale.

Table 14 demonstrates the estimation results of the effect of the mandatory environmental regulation on firm's production scale. The explained variables are industrial output value and industrial sales value respectively. The results of columns (1) to (4) indicate that the coefficients of the policy are not significantly different from 0. The environmental target responsibility system will not significantly reduce the production scale of enterprises.

5.5.3 The Mechanism of Technological Innovation

In order to test the mechanism of technological innovation, this paper merges CIED and CPD, and obtains a panel data set from 1998 to 2014, with a total of 734,290 samples. The total number of patent applications is selected as a proxy variable for technological innovation. In order to test whether the

TABLE 15 | Results of the mechanism of technological innovation.

Variables	(1)	(2)	(3)	(4)
	Patent applications	Invention	Utility model	Design
Treat × Year	0.257** (2.43)	0.0951* (1.82)	0.0890** (2.08)	0.0734** (2.08)
Control variables	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Industry × Year	Yes	Yes	Yes	Yes
Province × Year	Yes	Yes	Yes	Yes
Obs	432,083	432,083	432,083	432,083
R^2	0.502	0.435	0.474	0.461

*Note: The parentheses are the t-values. ***, **, * denotes the significance level of 1, 5, and 10%, respectively.*

environmental target responsibility system exerts heterogeneous effects on different types of patents, this paper divides patents into invention patents, utility model patents and design patents. Among them, invention patents have the highest degree of innovation. The results in **Table 15** show that the environmental target responsibility system has not only significantly increased the total number of patent applications, but also increased different types of patents. It indicates that the APCMS policy not only increases the number of innovations, but also improved the quality of innovation.So we can conclude that the policy reduces pollutant emissions and improves the TFP by inducing technological innovation rather than passive end-pipe treatment or production cuts, which verifies Hypothesis 3.

6 CONCLUSION

6.1 Discussion

Achieving the coordinated development of both environmental protection and economic efficiency is not only important for high-quality economic development, but also vital for the sustainable environmental protection for developing countries. Our empirical results based on the environmental target responsibility system, namely the APCMS policy, have shown that, the target responsibility system significantly reduces pollutant emission reduction. This finding is consistent with many previous studies (Zhao et al., 2013; Hong et al., 2019; He et al., 2020; Jiang et al., 2021). Although Becker (2011) argued that the pollution reduction effect of the mandatory environmental regulation faces uncertainty in the long-term, our empirical results confirm that the impact of the policy on reducing pollutant emissions is sustainable. And more importantly, results of dynamic effects show that the impact has increased year by year. The main reason for it is that the system enhances the enthusiasm of enterprises for technological innovation, which consolidates the effect of the environmental regulation. Besides, it can also be conducive to firm's efficiency measured by TFP. Results are essential and inspiring for developing countries. It indicates that it is feasible to achieve a win-win outcome to improve the economy and ecology at the same time, through the mandatory environmental regulations. The environmental target responsibility system serves as a good instrument for encouraging local governments for environmental governance. This paper proposes and explores three possible mechanisms of mandatory environmental regulations (Greenstone, 2002; Albrizio et al., 2017; Liu et al., 2017; Petroni et al., 2019). The results of the mechanism analysis show that the inherent technological innovation rather than passive end-pipe treatment or production cuts is the key path for firms to achieve pollutant emission reduction and TFP improvement at the same time, verifying the "Porter Hypothesis". Heterogeneity analysis shows that private firms and capital-intensive firms are more sensitive to the environmental target responsibility system. Only for enterprises in regions with a high degree of marketization or strong environmental law enforcement, the policy can play a significant positive role, indicating whether the effect of the environmental target responsibility can give full play depends heavily on the improvement of the external institutional environment.

6.2 Implications

Based on the above conclusions, this paper puts forward the following policy suggestions:

First, deepen the reform of the environmental target responsibility system, and strengthen the environmental protection incentives of local governments. The results of this paper illustrate that the environmental target responsibility system has effectively reduced enterprise pollutant emissions. Therefore, it is necessary to increase the proportion of environmental performance in the performance appraisal and audit on the departure of local officials. In addition, in order to improve the scientificity of environmental performance assessment, big data technology should be fully used in environmental monitoring, implementation, etc., to achieve real-time monitoring and upload of environmental data, and to ensure the accuracy of environmental monitoring data.

Second, it is essential to pay attention to the synergy between different environmental regulations. The results of dynamic effects suggest that the pollutant emission reduction effects of environmental regulation have gradually increased since 2007, indicating that the "Eleventh Five-Year Plan for National Environmental Protection" promulgated in 2007 also exerted a positive effect. The objectives and policy tools of this policy are similar to that of APCMS policy concerned in this paper. Besides, there is little difference in the coverage of cities, which has played a good synergistic effect. Therefore, the proper utilization of similar types of policies should be advocated.

Third, it is necessary to improve the pertinence and applicability of the environmental target responsibility system and related environmental regulatory policies. Our heterogeneity analysis demonstrates that the private firms are more sensitive to environmental regulation, while the impact on state-owned firms is particularly weak. Thus, it is essential to optimize the performance appraisal system of state-owned firms, incorporating relevant indicators of ecological environment protection, and strengthen the incentives and restraints of state-owned firms.

Fourth, it is vital to be vigilant about the adverse impact of technological progress incurred by the environmental target responsibility system on employment and other social issues. Our empirical results confirm that the environmental target responsibility system can achieve the coordinated development of ecology and economy through internal technological innovations of firms. However, the technological progress brought about by the mandatory environmental regulation may lead to the substitution of capital for labor, which in turn leads to the unemployment of low-skilled workers. The government needs to provide subsidies re-employment training to the unemployed, so as to reduce the possible negative effects of the environmental target responsibility system on social issues.

6.3 Research Gaps and Direction of Further Studies

This study explores the effect of the environmental target responsibility system on pollutant emissions and TFP. However, due to data limitations, there are still areas that need to be improved and expanded. First, due to the availability of data, this article selects non-listed industrial enterprises as samples. However, there are still a large number of listed companies in China. For listed enterprises, follow-up research needs to be carried out through the manual collection of data. Second, the environmental target responsibility system is in the process of advancing and expanding. With the increase of data disclosure, more dimensions of research can be carried out, such as environmental investment, environmental information disclosure of enterprises and so on.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

Conceptualization: JX, JW, and HX. Methodology: JX, JW, and HX. Software: HX. Data curation: HX. Writing—original draft preparation: HX, JW, and JX. Writing—review and editing: JW, JX, and HX. All authors have read and agreed to the published version of the manuscript.

FUNDING

This research was funded by the National Natural Science Foundation of China (Grant number 71903008) and the Research Plan of Beijing Municipal Education Commission (Grant number SM202010011012).

REFERENCES

Ackerberg, D. A., Caves, K., and Frazer, G. (2015). Identification Properties of Recent Production Function Estimators. *Econometrica* 83, 2411–2451. doi:10.3982/ECTA13408

Albrizio, S., Kozluk, T., and Zipperer, V. (2017). Environmental Policies and Productivity Growth: Evidence across Industries and Firms. *J. Environ. Econ. Manage.* 81, 209–226. doi:10.1016/j.jeem.2016.06.002

Ambec, S., and Barla, P. (2002). A Theoretical Foundation of the Porter Hypothesis. *Econ. Lett.* 75, 355–360. doi:10.1016/S0165-1765(02)00005-8

Barbera, A. J., and McConnell, V. D. (1990). The Impact of Environmental Regulations on Industry Productivity: Direct and Indirect Effects. *J. Environ. Econ. Manage.* 18, 50–65. doi:10.1016/0095-0696(90)90051-Y

Becker, R. A. (2011). Local Environmental Regulation and Plant-Level Productivity. *Ecol. Econ.* 70, 2516–2522. doi:10.1016/j.ecolecon.2011.08.019

Borghesi, S., Cainelli, G., and Mazzanti, M. (2015). Linking Emission Trading to Environmental Innovation: Evidence from the Italian Manufacturing Industry. *Res. Pol.* 44, 669–683. doi:10.1016/j.respol.2014.10.014

Brandt, L., Van Biesebroeck, J., Wang, L., and Zhang, Y. (2017). WTO Accession and Performance of Chinese Manufacturing Firms. *Am. Econ. Rev.* 107, 2784–2820. doi:10.1257/aer.20121266

Brandt, L., Van Biesebroeck, J., and Zhang, Y. (2012). Creative Accounting or Creative Destruction? Firm-Level Productivity Growth in Chinese Manufacturing. *J. Dev. Econ.* 97, 339–351. doi:10.1016/j.jdeveco.2011.02.002

Cai, X., Lu, Y., Wu, M., and Yu, L. (2016). Does Environmental Regulation Drive Away Inbound Foreign Direct Investment? Evidence from a Quasi-Natural Experiment in China. *J. Dev. Econ.* 123, 73–85. doi:10.1016/j.jdeveco.2016.08.003

Calel, R., and Dechezleprêtre, A. (2016). Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market. *Rev. Econ. Stat.* 98, 173–191. doi:10.1162/REST_a_00470

Chang, L., Wang, J., Xiang, Z., and Liu, H. (2021). Impact of Green Financing on Carbon Drifts to Mitigate Climate Change: Mediating Role of Energy Efficiency. *Front. Energ. Res.* 9, 785588. doi:10.3389/fenrg.2021.785588

Chen, Y., Long, X., and Salman, M. (2021). Did the 2014 Nanjing Youth Olympic Games Enhance Environmental Efficiency? New Evidence from a Quasi-Natural experiment. *Energy Policy* 159, 112581. doi:10.1016/j.enpol.2021.112581

Clarke, R. A., Stavins, R. N., Ladd Greeno, J., Bavaria, J. L., Cairncross, D., and Etsy, D. C. (1994). The Challenge of Going Green. *Harv. Bus. Rev.* 72, 37–48.

Dehejia, R. H., and Wahba, S. (2002). Propensity Score-Matching Methods for Nonexperimental Causal Studies. *Rev. Econ. Stat.* 84, 151–161. doi:10.1162/003465302317331982

Ferris, A. E., Shadbegian, R. J., and Wolverton, A. (2014). The Effect of Environmental Regulation on Power Sector Employment: Phase I of the Title IV SO2 Trading Program. *J. Assoc. Environ. Resource Economists* 1, 521–553. doi:10.1086/679301

Fujii, H., Managi, S., and Kaneko, S. (2013). Decomposition Analysis of Air Pollution Abatement in China: Empirical Study for Ten Industrial Sectors from 1998 to 2009. *J. Clean. Prod.* 59, 22–31. doi:10.1016/j.jclepro.2013.06.059

Gao, J. (2010). Hitting the Target but Missing the Point: The Rise of Non-Mission-Based Targets in Performance Measurement of Chinese Local Governments. *Adm. Soc.* 42, 56S–76S. doi:10.1177/0095399710361854

Gollop, F. M., and Roberts, M. J. (1983). Environmental Regulations and Productivity Growth: The Case of Fossil-Fueled Electric Power Generation. *J. Polit. Economy* 91, 654–674. doi:10.1086/261170

Goulder, L. H., and Parry, I. W. H. (2008). Instrument Choice in Environmental Policy. *Rev. Environ. Econ. Pol.* 2, 152–174. doi:10.1093/reep/ren005

Greenstone, M. (2004). Did the Clean Air Act Cause the Remarkable Decline in Sulfur Dioxide Concentrations? *J. Environ. Econ. Manage.* 47, 585–611. doi:10.1016/j.jeem.2003.12.001

Greenstone, M., and Hanna, R. (2014). Environmental Regulations, Air and Water Pollution, and Infant Mortality in India. *Am. Econ. Rev.* 104, 3038–3072. doi:10.1257/aer.104.10.3038

Greenstone, M. (2002). The Impacts of Environmental Regulations on Industrial Activity: Evidence from the 1970 and 1977 Clean Air Act Amendments and the Census of Manufactures. *J. Polit. Economy* 110, 1175–1219. doi:10.1086/342808

Hamamoto, M. (2006). Environmental Regulation and the Productivity of Japanese Manufacturing Industries. *Resource Energ. Econ.* 28, 299–312. doi:10.1016/j.reseneeco.2005.11.001

He, G., Wang, S., and Zhang, B. (2020). Watering Down Environmental Regulation in China. *Q. J. Econ.* 135, 2135–2185. doi:10.1093/qje/qjaa024

Hong, T., Yu, N., and Mao, Z. (2019). Does Environment Centralization Prevent Local Governments from Racing to the Bottom? --Evidence from China. *J. Clean. Prod.* 231, 649–659. doi:10.1016/j.jclepro.2019.05.181

Jiang, X., Li, G., and Fu, W. (2021). Government Environmental Governance, Structural Adjustment and Air Quality: A Quasi-Natural Experiment Based on the Three-Year Action Plan to Win the Blue Sky Defense War. *J. Environ. Manage.* 277, 111470. doi:10.1016/j.jenvman.2020.111470

Jin, W., Zhang, H.-q., Liu, S.-s., and Zhang, H.-b. (2019). Technological Innovation, Environmental Regulation, and Green Total Factor Efficiency of Industrial Water Resources. *J. Clean. Prod.* 211, 61–69. doi:10.1016/j.jclepro.2018.11.172

Kostka, G. (2016). Command without Control: The Case of China's Environmental Target System. *Regul. Governance* 10, 58–74. doi:10.1111/rego.12082

Levinsohn, J., and Petrin, A. (2003). Estimating Production Functions Using Inputs to Control for Unobservables. *Rev. Econ. Stud.* 70, 317–341. doi:10.1111/1467-937X.00246

Li, W., Sun, H., Du, Y., Li, Z., and Taghizadeh-Hesary, F. (2020). Environmental Regulation for Transfer of Pollution-Intensive Industries: Evidence from Chinese Provinces. *Front. Energ. Res.* 8, 335. doi:10.3389/fenrg.2020.604005

Liang, J., and Langbein, L. (2015). Performance Management, High-Powered Incentives, and Environmental Policies in China. *Int. Public Manage. J.* 18, 346–385. doi:10.1080/10967494.2015.1043167

Liu, M., Shadbegian, R., and Zhang, B. (2017). Does Environmental Regulation Affect Labor Demand in China? Evidence from the Textile Printing and Dyeing Industry. *J. Environ. Econ. Manage.* 86, 277–294. doi:10.1016/j.jeem.2017.05.008

Liu, M., Tan, R., and Zhang, B. (2021). The Costs of "Blue Sky": Environmental Regulation, Technology Upgrading, and Labor Demand in China. *J. Dev. Econ.* 150, 102610. doi:10.1016/j.jdeveco.2020.102610

Long, X., Chen, B., and Park, B. (2018). Effect of 2008's Beijing Olympic Games on Environmental Efficiency of 268 China's Cities. *J. Clean. Prod.* 172, 1423–1432. doi:10.1016/j.jclepro.2017.10.209

Long, X., Chen, Y., Du, J., Oh, K., and Han, I. (2017). Environmental Innovation and its Impact on Economic and Environmental Performance: Evidence from Korean-Owned Firms in China. *Energy Policy* 107, 131–137. doi:10.1016/j.enpol.2017.04.044

Luo, Y., Lu, Z., and Long, X. (2020). Heterogeneous Effects of Endogenous and Foreign Innovation on CO2 Emissions Stochastic Convergence across China. *Energ. Econ.* 91, 104893. doi:10.1016/j.eneco.2020.104893

Olley, G. S., and Pakes, A. (1996). The Dynamics of Productivity in the Telecommunications Equipment Industry. *Econometrica* 64, 1263–1297. doi:10.2307/2171831

Ouyang, L., and You, D. (2021). The Green Innovation Effect on Heavy-Polluting Enterprises under the Environmental Protection Law. *Front. Energ. Res.* 9, 681334. doi:10.3389/fenrg.2021.681334

Petroni, G., Bigliardi, B., and Galati, F. (2019). Rethinking the Porter Hypothesis: The Underappreciated Importance of Value Appropriation and Pollution Intensity. *Rev. Pol. Res.* 36, e0001–140. doi:10.1111/ropr.12317

Porter, M. E., and Linde, C. V. D. (1995). Toward a New Conception of the Environment-Competitiveness Relationship. *J. Econ. Perspect.* 9, 97–118. doi:10.1257/jep.9.4.97

Rubashkina, Y., Galeotti, M., and Verdolini, E. (2015). Environmental Regulation and Competitiveness: Empirical Evidence on the Porter Hypothesis from European Manufacturing Sectors. *Energy Policy* 83, 288–300. doi:10.1016/j.enpol.2015.02.014

Schreifels, J. J., Fu, Y., and Wilson, E. J. (2012). Sulfur Dioxide Control in China: Policy Evolution during the 10th and 11th Five-Year Plans and Lessons for the Future. *Energy Policy* 48, 779–789. doi:10.1016/j.enpol.2012.06.015

Tanaka, S. (2015). Environmental Regulations on Air Pollution in China and Their Impact on Infant Mortality. *J. Health Econ.* 42, 90–103. doi:10.1016/j.jhealeco.2015.02.004

Testa, F., Iraldo, F., and Frey, M. (2011). The Effect of Environmental Regulation on Firms' Competitive Performance: The Case of the Building & Construction Sector in Some EU Regions. *J. Environ. Manage.* 92, 2136–2144. doi:10.1016/j.jenvman.2011.03.039

Viscusi, W. K. (1983). Frameworks for Analyzing the Effects of Risk and Environmental Regulation on Productivity. *Am. Econ. Rev.* 73, 793–801.

Wang, P., Dong, C., Chen, N., Qi, M., Yang, S., Nnenna, A. B., et al. (2021). Environmental Regulation, Government Subsidies, and Green Technology Innovation-A Provincial Panel Data Analysis from China. *Ijerph* 18, 11991. doi:10.3390/ijerph182211991

Wang, Y., Sun, X., and Guo, X. (2019). Environmental Regulation and Green Productivity Growth: Empirical Evidence on the Porter Hypothesis from OECD Industrial Sectors. *Energy Policy* 132, 611–619. doi:10.1016/j.enpol.2019.06.016

Wu, X., Gao, M., Guo, S., and Maqbool, R. (2019). Environmental and Economic Effects of Sulfur Dioxide Emissions Trading Pilot Scheme in China: A Quasi-Experiment. *Energ. Environ.* 30, 1255–1274. doi:10.1177/0958305X19843104

Yu, M. J., Jin, Y., and Zhang, R. (2018). Capacity Utilization Rate Measurement and Productivity Estimation for Industrial Firms. *Econ. Res. J.* 53, 56–71.

Yuan, B., and Xiang, Q. (2018). Environmental Regulation, Industrial Innovation and Green Development of Chinese Manufacturing: Based on an Extended CDM Model. *J. Clean. Prod.* 176, 895–908. doi:10.1016/j.jclepro.2017.12.034

Zhang, B., Chen, X., and Guo, H. (2018). Does Central Supervision Enhance Local Environmental Enforcement? Quasi-Experimental Evidence from China. *J. Public Econ.* 164, 70–90. doi:10.1016/j.jpubeco.2018.05.009

Zhang, P., and Hao, Y. (2020). Rethinking China's Environmental Target Responsibility System: Province-Level Convergence Analysis of Pollutant Emission Intensities in China. *J. Clean. Prod.* 242, 118472. doi:10.1016/j.jclepro.2019.118472

Zhang, P., Yu, T., Lu, S., and Huang, R. (2021). How Does Target-Based Performance Evaluation Affect the Accuracy of Energy-Saving Data: Evidence from China. *Front. Energ. Res.* 9, 704317. doi:10.3389/fenrg.2021.704317

Zhao, X., Ma, Q., and Yang, R. (2013). Factors Influencing CO2 Emissions in China's Power Industry: Co-integration Analysis. *Energy Policy* 57, 89–98. doi:10.1016/j.enpol.2012.11.037

Zheng, Y., Sun, X., Zhang, C., Wang, D., and Mao, J. (2021). Can Emission Trading Scheme Improve Carbon Emission Performance? Evidence from China. *Front. Energ. Res.* 9, 759572. doi:10.3389/fenrg.2021.759572

Zhu, P. H., and Chen, L. (2020). Industrial Added Value and Total Factor Productivity Estimation——Evidence from the Quasi-Monte-Carlo Experiment of China's Manufacturing Industry. *China Indust. Econ.* 388, 24–42. doi:10.19581/j.cnki.ciejournal.2020.07.013

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: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 10 January 2022
doi: 10.3389/fenrg.2021.821219

Does the Carbon Emissions Trading Policy Increase Corporate Tax Avoidance? Evidence from China

Chen Feng[1], Xingshu Zhu[1], Yu Gu[2] and Yuecheng Liu[2]*

[1]School of Public Economics and Administration, Shanghai University of Finance and Economics, Shanghai, China, [2]School of Public Finance and Taxation, Zhongnan University of Economics and Law, Wuhan, China

Based on the natural experiment of carbon emissions trading pilots in China, this paper investigates the effect of environmental regulation on corporate tax avoidance. The results show that: 1) Market-incentivized environmental regulation significantly increase the level of corporate tax avoidance. 2) Heterogeneity analysis shows that the effect is more obvious on the non-state-owned firms, firms with severe financing constraints, and firms in highly competitive industries. 3) We find that the reduction of cash flow is the channel for environmental regulation to affect corporate tax avoidance. 4) Further analysis shows that government subsidies can alleviate the enhancement of tax avoidance by environmental regulation. The more government subsidies a company receives, the less tax avoidance it has.

Keywords: carbon emissions trading policy, corporate tax avoidance, environmental regulation, cash flow, China

OPEN ACCESS

Edited by:
Kangyin Dong,
University of International Business and Economics, China

Reviewed by:
Haochang Yang,
Xi'an Jiaotong University, China
Guoxiang Li,
Nanjing Normal University, China
Xuan Leng,
Southwestern University of Finance and Economics, China

Correspondence:
Yu Gu
201901030001@stu.zuel.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *24 November 2021*
Accepted: *13 December 2021*
Published: *10 January 2022*

Citation:
Feng C, Zhu X, Gu Y and Liu Y (2022) Does the Carbon Emissions Trading Policy Increase Corporate Tax Avoidance? Evidence from China. Front. Energy Res. 9:821219. doi: 10.3389/fenrg.2021.821219

1 INTRODUCTION

Climate change is a global issue, which threatens human production and development, and has received widespread attention from governments. In 2016, *The Paris Agreement* proposed to achieve the goal of net-zero emissions in the second half of this century, setting off a global wave of "carbon neutrality". Subsequently, several countries put forward the goal of "carbon neutral". To control greenhouse gas emissions, governments have introduced a series of environmental regulations (Dong et al., 2018). Countries have favored carbon emissions trading policies for their ability to reduce carbon emissions in the most cost-effectively way. Since the European Union was the first to establish a carbon emissions trading market in 2005, several regional carbon trading systems have played an essential role in reducing CO_2 emissions (Peng et al., 2015). The core idea of carbon trading is to impose total emission control on carbon emissions. Specifically, the government allocates carbon emission allowances to firms, which can only emit within the limits of the carbon emission allowances they own and purchase in the trading market. By internalizing the external emission cost into the production cost of firms, the establishment of a carbon emission trading system provides a compelling incentive for carbon emission reduction. Specifically, it reduces the total carbon emission and improves the carbon emission performance of firms (Zhang et al., 2019; Xuan et al., 2020; Zheng et al., 2021; Dong et al., 2022).

Theoretically, carbon emissions trading policy can achieve carbon emission reduction targets at the lowest total cost. However, in the short term, after the establishment of the carbon emissions trading market, carbon emissions will have the cost of compliance for firms in addition to the direct effect of reducing their carbon emissions. Implementing a carbon emissions trading policy is equivalent to imposing new constraints on corporate production and operation decisions. After establishing the carbon emissions market, firms need additional costs for quota trading, investment, innovation, management, and other behavior adjustments. Environmental regulation may also influence the adjustment of corporate tax decisions (Geng et al., 2021; Yu et al., 2021). As local governments pay more attention to environmental governance, the bargaining power of environmental firms increases, which may help firms obtain a more lenient tax collection environment and tax incentives (Mills et al., 2013). When firms have stronger connections with local governments, firms can reduce their own tax burden by exerting political influence (Yu et al., 2021). In addition, there may be a trade-off between corporate tax behavior and corporate environmental performance disclosure as two important CSR elements. Fallana and Fallan (2019) found that firms with the highest mandatory environmental reporting disclosure also have less tax avoidance, while firms with higher voluntary disclosure have more tax avoidance. Sari and Tjen (2016) found that corporate environmental performance strengthens the negative relationship between corporate social responsibility and corporate tax avoidance. Higher corporate environmental performance scores are associated with less corporate tax avoidance. Strict environmental regulations may also cause changes in local taxing behavior by creating fiscal pressure for local governments, affecting corporate tax burden. Ye and Lin (2020) explored the effects of environmental regulations on local government taxing behavior and corporate tax burden in China and found that strict environmental regulations cause tax base erosion and lower local government tax revenues. Under fiscal pressure, local governments will increase tax rates by strengthening inspect, bringing additional tax costs to enterprises, leading to unfair tax distribution.

Environmental regulations can impose costs on firms. When facing liquidity constraints, firms may also adjust their tax avoidance behavior to increase retained earnings and cash flows through tax avoidance activities to undertake endogenous financing, alleviate financing constraints, and cope with external risks (Beck et al., 2014). Geng et al. (2021) found that environmental regulations promote corporate tax avoidance by increasing business risks and financing constraints. The environmental regulation has a spillover effect on corporate tax burden. In terms of costs, when faced with command-controlled environmental regulation, firms focus on end treatment to achieve immediate pollution reduction targets (Shao et al., 2021), while market-incentive environmental regulations can bring long-term compliance cost expectations for firms, and firms may have less incentive to avoid taxes. The "innovation offset effect" (Porter and Linde, 1995) induced by the implementation of carbon emissions trading may reduce or offset its burden on firms and increase their total factor productivity (Peng et al., 2021), improving their financial position and cash flow (Abrell et al., 2008; Oestreich and Tsiakas, 2015). Therefore, its impact on corporate tax avoidance is not clear. Next, based on the carbon emissions trading policy, this paper uses a quasi-natural experiment approach to explore the causal effect of implementing market-incentivized environmental regulation on corporate tax avoidance.

This paper contributes to extant research in the following aspects. First, this paper broadens the understanding of how market-incentivized environmental regulation affect corporate behavior. Existing studies confirm the effects of environmental regulation on industrial structural upgrading (Wang et al., 2021), corporate total factor productivity (Gray, 1987), and corporate behaviors such as innovation, investment, location, export, and labor demand (Porter and Linde, 1995; Hering and Poncet, 2014; Cai et al., 2016; Shen et al., 2017; Shi et al., 2018; Li et al., 2021). Geng et al. (2021) and Yu et al. (2021) validate the effect of command and control on the behavior of firms based on the 11th Five-Year Plan and the Environmental Protection Law in China, respectively. Compared with other policies, market-incentivized environmental regulation can provide strong incentives for firms to sell emission permits that exceed the standards. After implementing the carbon pilot, firms can even sell emission permits that exceed the standard to gain additional revenue and compensate for the cost of environmental regulation (Porter and Linde, 1995). Does market-incentivized environmental regulation affect corporate tax avoidance? Based on a quasi-natural experiment approach, this paper reveals that firms may actively avoid taxes in response to the impact of carbon emissions trading, a market-incentivized environmental regulation policy. Second, the paper broadens the understanding of the external factors of corporate tax avoidance. Tax avoidance is a fundamental challenge commonly faced by developing countries, and even rich countries with strong monitoring systems face high rates of tax avoidance (Pomeranz and Vila-Belda, 2019). Existing research suggests that corporate tax avoidance is influenced by corporate characteristics such as size, the structure of ownership, characteristics of executives, internal control mechanisms, and other internal factors (Rego, 2003; Khurana and Moser, 2013; Richardson et al., 2013; Olsen and Stekelberg, 2016). In addition, there are external factors such as tax systems, collection techniques, product markets, media scrutiny, and economic policy uncertainty (Falkinger, 1995; Kleven et al., 2011; Kubick et al., 2015; Kanagaretnam et al., 2018; Dang et al., 2019). This paper explores the effect of carbon emissions trading policy, which are widely used by governments for carbon emission reduction, on corporate tax avoidance.

The rest of the paper is structured as follows. **Section 2** introduces the background of China's carbon emissions trading policy and presents the research hypothesis. **Section 3** presents the model construction and data description. **Section 4** is the empirical findings, including baseline results and robustness checks. **Section 5** focuses on heterogeneity and the mechanism of influence and analyzes the role of government subsidies, which is followed by conclusion in the last section.

2 INSTITUTIONAL BACKGROUND AND RESEARCH HYPOTHESIS

2.1 China's ETS Emissions Policy

As the world's largest carbon emitter, China set the goal of "striving to peak by 2030 and achieving carbon neutrality by 2060" in 2020. According to *the World Energy Statistics Yearbook 2020*, China's carbon dioxide emissions reached 9.81 billion tons in 2019, accounting for 28.6% of global emissions, far exceeding the United States, which is the second-largest emitter with 5.03 billion tons of carbon emissions, accounting for 14.6% of global emissions. At present, China's carbon emission intensity per unit of GDP is about three times the world average, which is still at a high level globally. In 2009, China proposed the goal to achieve a 40–45% reduction in carbon emissions per unit of GDP in 2020 compared to 2005. In response to global climate change and fulfilling its carbon emission reduction commitments, seven pilot carbon emission trading provinces and cities of Shenzhen, Shanghai, Beijing, Guangdong, Tianjin, Hubei, and Chongqing were identified in 2011. The carbon emission trading market was gradually launched in 2013 and2014[1]. As of September 2017, the cumulative quota turnover of the seven pilot carbon markets exceeded 197 million tons of carbon dioxide equivalent, with a turnover of over RMB 4.5 billion. After implementing the pilot carbon emission trading market, China has achieved the carbon emission reduction targets of 17 and 18% per unit of GDP for the 12th and 13th Five-Year Plan periods in 2015 and 2020, respectively. Emission reduction targets were set in 2010 and 2015, respectively. The carbon emission intensity in 2020 will be reduced by 48.1% compared to 2005, fulfilling the carbon emission reduction targets promised to the international community.

Unlike command-controlled environmental regulation, carbon emissions trading policy aim to treat the right to emit carbon emissions as an asset underlying and use market-based trading instruments to achieve CO_2 emission reduction targets. The operation of China's carbon emissions trading policy is Chinese Emission Allowances (CEA), supplemented by Chinese Certified Emission Reduction (CCER). In the specific implementation, the relevant functional departments determine the maximum carbon emissions. Combining the number of regional emission units and the carbon emission intensity of each unit, the carbon emission allowances are decomposed into the compulsory emission companies. If the actual carbon emissions of the emission-controlled firms exceed the quotas, the firms can purchase their carbon dioxide emission rights for the excess emissions from the firms with surplus through the carbon trading platform. When the corporate carbon dioxide emissions are lower than the obtained quotas, they can sell the remaining carbon emission rights in the market. To complement this, a voluntary emission reduction market is introduced in addition to the quota market. Companies that exceed emissions standards are allowed to purchase certified emission reductions from companies that carry out "carbon offset" activities, and voluntary emission reduction companies can sell certified emission reductions to achieve profitability.

2.2 Theoretical Analysis and Research Hypothesis

Based on different logics, the effect of carbon emissions trading on corporate tax avoidance has different expectations. Therefore, we propose two different hypotheses on the effect of carbon emissions trading policy on corporate tax avoidance.

Implementing carbon emissions trading policy may enhance the degree of corporate tax avoidance in the following ways. First, implementing carbon emissions trading pilot breaks the original equilibrium of enterprises and increases the cost of pollution control, allowance trading, or fines. Environmental regulations create additional expenses for firms, inevitably increasing their costs and affecting their competitive advantage (Zhao and Sun, 2015). When facing greater competitive pressure, firms avoid taxes to reserve more money to maintain their market position (Cai and Liu, 2009). Second, establishing the carbon trading market has prompted the public and government to pay more attention to climate change issues. Investors expect stricter regulations in the future, higher required rates of return will be demanded for high-emitting firms. The uncertainty of environmental regulatory policies further exacerbates the difficulty and cost of raising external finance for firms (Koch and Bassen, 2013; Jong et al., 2014). When the cost of exogenous financing is high and internal cash flow is insufficient, firms may use tax avoidance as a way to obtain funds (Beck et al., 2014; Edwards et al., 2016). Third, environmental regulation policy will cause increased uncertainty in the business environment, and the management of firms will become inaccurate in predicting future cash flows. Firms will tend to respond to future adverse risks by hoarding extra cash (Dudley and Zhang, 2016). Tax avoidance can reduce corporate cash outflows and the cost of raising external funds. The degree of corporate tax avoidance for precautionary motives may be enhanced. Fourth, carbon emission policies may enhance corporate social responsibility and reputation, reducing the opportunity cost of reputation loss when corporate tax avoidance is detected, so firms may improve the degree of tax avoidance. The corporate tax avoidance faces the cost of being discovered and penalized by tax authorities and the corresponding loss of reputation (Allingham and Sandmo, 1972). Godfrey (2005) argued that firms can rely on a good social reputation to improve their ability to resist risks, and firms may see the fulfillment of environmental responsibility and disclosure of environmental information as a way to enhance a good reputation. Firms are less negatively affected by tax avoidance risks and thus enhance their tax avoidance activities. Although firms can choose other ways to counteract the risk of carbon emissions trading policies, tax avoidance has less impact on normal production and business activities than cutting expenses and investments (Edwards et al., 2016). In addition, the risk of tax avoidance for firms is not too high due to the large information asymmetry (Cai and Liu, 2009). When corporate liquidity decreases and faces financing constraint dilemmas, the opportunity cost of corporate tax avoidance consequently decreases and, at the margin, induces more corporate tax avoidance. As a result, we propose hypothesis 1.

Market-incentivized environmental regulation represented by carbon emissions trading will enhance corporate tax avoidance.

Implementing carbon emissions trading policies may weaken the degree of tax avoidance of firms in the following ways. First,

[1]In December 2016, a carbon emission trading market was also established in Fujian Province. The sample period of this paper is from 2008–2016, so Fujian Province is not taken into consideration

carbon emissions trading may bring additional benefits to firms. Liu et al. (2021) show that carbon emissions trading policies increase the non-operating income of firms included in carbon emission controls. Meanwhile, existing studies find that carbon emissions trading may increase corporate total factor productivity (Peng et al., 2021), and improve their financial position and cash flow (Abrell et al., 2008; Oestreich and Tsiakas, 2015). Since corporate tax avoidance is not costless, the incentive to avoid taxes will decrease when the financial performance of firms improves. Second, environmental regulations can cause firms to reduce, shut down, or relocate their production, resulting in a potential loss of revenue for local governments and creating fiscal pressure on governments. Unlike other countries that usually take initiatives to cut spending in response to fiscal pressure, local governments in China tend to increase revenue by strengthening tax collection efforts to raise corporate tax rates when facing fiscal pressure from reduced revenue (Chen, 2017; Ye and Lin, 2020). When the tax authorities strengthen inspect, the space for corporate tax avoidance is compressed, and the degree of corporate tax avoidance is reduced (Allingham and Sandmo, 1972). Third, the implementation of carbon emissions trading policy will enhance the environmental information disclosure of enterprises, which will reduce corporate tax avoidance. Although the carbon market disclosure in China is weak in terms of the carbon markets in each pilot region (Dong et al., 2019), implementing the carbon emissions trading policy still strengthens corporate carbon information disclosure to some extent. Environmental information disclosure increases corporate visibility and liquidity, attracting public scrutiny and government regulation. When firms are subject to stricter regulation, the probability of corporate tax avoidance being detected increases and may reduce tax avoidance activities. Wang et al. (2020) found that corporate environmental information disclosure can improve corporate take performance, and the improvement of corporate financial performance may also reduce corporate tax avoidance to some extent. As a result, we propose hypothesis 2.

Market-incentivized environmental regulation represented by carbon emissions trading will decrease corporate tax avoidance.

3 STUDY DESIGN

3.1 Model Settings

Carbon emissions trading policies are implemented gradually at the provincial level with rich temporal and regional differences. This paper explores the effect of environmental regulation on corporate tax avoidance using a quasi-natural experiment with carbon emissions trading policy carried out in seven regions after 2011, using a difference-in-differences approach (DID). The specific model is as follows.

$$DDBTD_{it} = \alpha + \beta ETS_{it} + \gamma X_{it} + \mu_i + \delta_t + \varepsilon_{it} \tag{1}$$

where $DDBTD_{it}$ indicates corporate tax avoidance of firm i in year t. ETS_{it} represents whether firm i is in the pilot area of carbon emission trading reform in year t. If firm i is in the pilot area in year t, then ETS_{it} is 1. Otherwise, it is 0. X_{it} is the set of control variables, μ_i and δ_t represent firm and year fixed effect, and ε_{it} is the error term.

3.2 Variables and Data

3.2.1 The Explained Variable

The explained variable is the extent of corporate tax avoidance. The difference between corporate pre-tax accounting earnings and taxable earnings effectively conveys corporate tax evasion (Wilson, 2009). In general, the greater the degree of corporate tax evasion, the greater the difference between pre-tax accounting earnings and taxable earnings. Desai and Dharmapala (2006) developed a method to measure corporate tax avoidance regarding the difference between pre-tax accounting earnings and taxable earnings after excluding corporate surplus management. The regression model is as follows.

$$BTD_{it} = \alpha_0 + \alpha_1 \times TA_{it} + \mu_i + \varepsilon_{it} \tag{2}$$

$$DDBTD_{it} = \mu_i + \varepsilon_{it} \tag{3}$$

In model (2), BTD_{it} indicates tax accounting difference of firm i in year t, measured as the difference between the pre-tax accounting profit and the taxable income of the firm at the end of the year as a share of total assets. TA_{it} is the accrued profit of firm i in year t, measured by the difference between net profit and net cash flow from economic activities as a percentage of total assets. The residual term $DDBTD_{it}$ is the tax difference after excluding the surplus management factor, which is used to measure the tax avoidance of the firm by regressing the tax difference BTD_{it} on the total accrued profit TA_{it}. The larger the value of $DDBTD_{it}$ the larger the corporate tax difference and the higher the degree of corporate tax avoidance.

3.2.2 Explanatory Variable

The explanatory variable is the dummy variable of carbon emissions trading policy implementation (ETS_{it}), which represents whether firm i is in a pilot region of carbon emissions trading policy in year t. ETS_{it} is the interaction term of the policy dummy variable ($Treatment_i$) and the time dummy variable ($Post_t$). $Treatment_i = 1$ represents the dummy variable of whether the pilot carbon emission trading policy is implemented in the region where the firm is located, including Beijing, Tianjin, Shanghai, Chongqing, Hubei, and Guangdong (Shenzhen belongs to Guangdong), and $Treatment_i = 0$ represents the region where the firm does not implement the pilot carbon emission trading policy. $Post_t = 1$ represents the dummy variable after implementing carbon emissions trading policy. Specifically, the starting time of carbon emissions trading varies among regions, with Shanghai, Beijing, Guangdong, and Shenzhen starting the pilot in 2012, Hubei, Tianjin, and Chongqing starting their pilot projects in 2013.

3.2.3 Control Variables

Based on previous studies, we also control for other characteristics that may affect tax avoidance, including Size, return on assets (ROA), asset-liability ratio (Leverage), the

TABLE 1 | Descriptive statistics.

Variable	Observation	Mean	Std.Dev	Min	Max
DDBTD	9,008	−0.012	0.034	−0.172	0.155
ETS	9,008	0.263	0.440	0.000	1.000
Size	9,008	21.974	1.204	19.646	25.652
ROA	9,008	0.052	0.041	0.000	0.205
Leverage	9,008	0.409	0.196	0.046	0.856
Capital	9,008	0.244	0.154	0.004	0.698
Inventory	9,008	0.153	0.122	0.003	0.675
Age	9,008	2.640	0.398	0.693	3.611
Cash	9,008	0.190	0.131	0.014	0.698

intensity of fixed assets (Capital), inventory density (Inventory), Age, and level of cash holdings (Cash). Of these, Size is calculated as the log of the corporate total assets, ROA is measured as net income to total assets, Leverage is calculated as total liabilities to total assets, Capital is calculated as fixed assets to total assets at year-end, Inventory is calculated as net inventory to total assets at the end of year, Age is calculated as the log of the corporate years of existence, and Cash is calculated as the balance of cash and cash equivalents as a share of total assets (Stickney and McGee, 1982; Zimmerman, 1983; Gupta and Newberry, 1997; Rego, 2003; Cai and Liu, 2009; Richardson et al., 2016; Yu et al., 2021).

3.3 Data Sources

The firm-level data used in this paper are obtained from the China Stock Market and Accounting Research (CSMAR) database. The sample period of this paper is from 2008–2016. We cleaned the data as follows. First, we only kept the industrial firm because the industries covered by the carbon emission trading market are mainly industrial firms. To ensure the accuracy of the estimation results, we removed the non-industrial firms. Second, we removed the samples with ST and ST* in the current year. Third, we removed the samples with missing main variables. Fourth, we removed the samples with the actual tax burden greater than 1 or less than 0. Fifth, we performed winsorize treatment on continuous variables at the 1 and 99% quartiles. In the section on robustness checks, this paper employs some macro-level variables, and the data are obtained from *the China Statistical Yearbook*. **Table 1** presents the descriptive statistics for main variable.

4 EMPIRICAL RESULTS

4.1 Basic Regression Results

4.1.1DID Estimation

Table 2 reports the baseline regression results of model 1). Column 1) of the regression controls only for annual fixed effects and firm fixed effects only. And in column 2), we further control firm-level factors. We find that coefficients are both positive, which are significant at the 5% confidence level. This result suggests that implementing the pilot of carbon emissions trading increases the tax avoidance, indicating that market-incentivized environmental regulation have an elevating effect on corporate tax avoidance. This result verifies hypothesis 1. In terms of control variables, consistent with the findings of existing studies, the coefficient of the corporate profitability variable is significantly positive, indicating that tax avoidance is relatively more frequent among enterprises with higher profitability. The coefficient of the corporate gearing variable is significantly negative, indicating that companies with high gearing have relatively fewer tax avoidance activities and lower tax avoidance. Inventory intensity is negatively correlated with tax avoidance behavior, and the higher the inventory intensity, the lower the degree of corporate tax avoidance. The higher the level of cash flow of the enterprise, the more liquid the enterprise is and the lower the degree of tax avoidance of the enterprise.

TABLE 2 | Baseline results.

Dependent variable	DDBTD	DDBTD	DDBTD	DDBTD
	DID		PSM-DID	
	(1)	(2)	(3)	(4)
ETS	0.0091***	0.0083**	0.0094***	0.0086**
	(0.0035)	(0.0034)	(0.0035)	(0.0035)
Size		0.0008		0.0012
		(0.0014)		(0.0015)
Roa		0.1721***		0.1745***
		(0.0274)		(0.0277)
Leverage		−0.0244***		−0.0249***
		(0.0058)		(0.0059)
Capital		−0.0075		−0.0092
		(0.0062)		(0.0064)
Inventory		−0.0214*		−0.0214*
		(0.0110)		(0.0110)
Age		0.0003		−0.0012
		(0.0052)		(0.0052)
Cash		−0.0134**		−0.0138**
		(0.0055)		(0.0055)
Constant	−0.0071***	−0.0178	−0.0075***	−0.0209
	(0.0021)	(0.0317)	(0.0022)	(0.0320)
Observations	9,008	9,008	8,935	8,924
R-squared	0.0066	0.0352	0.0064	0.0361
Firm FE	Y	Y	Y	Y
Year FE	Y	Y	Y	Y

*Note: ***, **, and * represent the significance levels at 1, 5, and 10%, respectively. The robust standard error is reported in parentheses.*

4.1.2 PSM-DID Estimation

Considering the effect of possible group differences between the treatment and control groups on the policy assessment results, this paper uses PSM-DID for robustness test. Drawing on Blundell and Costa Dias (2020), we use a year-by-year matching method to find a matching treatment group for each year. The specific matching process using PSM is as follows. In each sample year, the propensity score is calculated using Logit model with whether the sample firm is a firm in the carbon trading region as the dependent variable and Size, Age, Leverage, Capital, and ownership nature as the independent variables. Then, based on the calculated propensity score, we use one-to-one neighbor matching to screen out companies similar to the treatment group[2]. After eliminating the unsuccessful matches, a

[2]In order to ensure the reliability of the matching results, we carry out a matching balance test. It is found that the observable variables of the treatment group and the control group are basically not significantly different after matching

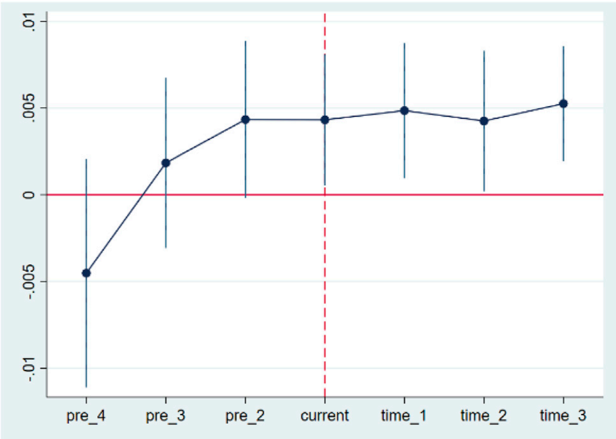


FIGURE 1 | Parallel trend test.

new treatment group with similar characteristics to the treatment group was obtained, and the DID estimation of the model 1) was re-estimated. The specific results are presented in columns 3) and 4) of **Table 2**. It can see that the implementation of the carbon emissions trading policy still has a significant elevating effect on the level of corporate tax avoidance. This indicates the results of DID estimation are robust.

4.2 Parallel Trend Test

One of the basic prerequisites for the validity of the DID approach is the assumption of parallel trends, i.e., if the treatment group is not subject to policy interventions, its trend effect should be the same as that of the control group, i.e., the difference between the treatment and control groups should not change over time. Since the "counterfactual" state in which the treatment group is not subject to policy shocks is unobservable, the only way to test for differences in time trends between the treatment and control groups is by looking at the pre-pilot period. To test whether the time trends between the treatment and control groups were the same before the reform, we refer to the time analysis proposed by Jacobson et al. (1993) to determine the dynamic effect of the carbon trading pilot. The model is set up as follows.

$$DDBTD_{it} = \alpha + \beta_k \sum\nolimits_{k \geq -4}^{3} ETS_{t_{i0+k}} + \gamma X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (4)$$

Among them, the dummy variable $ETS_{t_{i0+k}}$ is a series of time dummy variables, t_{i0} denotes the year when the carbon trading emission rights policy started to be implemented, k represents the k-th year of carbon trading emission rights policy implementation (k ≤ −4, −3, −2,0,1,2,3), and the omitted year is k = −1, so the reported treatment effect is relative to the time of the year before the reform started. By focusing on the coefficient β_k, it is possible to determine whether there is a pre-existing ex-ante trend between the control and treatment groups. **Figure 1** shows the distribution of the coefficient β_k for each year before and after the implementation of the carbon emissions trading policy. We see that the coefficient of β_k is not statistically significant before implementing the carbon trading emission rights policy, which implies that there is no systematic difference between the treatment group and the treatment group before implementing the policy assumption of parallel trend holds. Meanwhile, after implementing the carbon trading pilot, the effect of environmental regulation on corporate tax avoidance is revealed.

4.3 Contemporaneous Policy Interference

In addition to implementing carbon emissions trading policy, China has adopted several other environmental regulatory policies during the sample period of this paper. Implementing other policies during the sample period may lead to biased estimates, and we test the robustness of our results by excluding these confounding effects.

4.3.1 Excluding the Confounding Effect of the Emissions Trading Reimbursement and Trading Policy (ETRT)

Since 2007, China has gradually implemented a system of paid use and trading of emission rights in 11 regions in Jiangsu, Zhejiang, Tianjin, Hubei, Hunan, Inner Mongolia, Shanxi, Chongqing, Shaanxi, Hebei, and Henan to reduce pollutant emissions. Within the sample interval, Chongqing, Hubei, and Tianjin are pilot regions of both carbon trading rights system and the emissions trading reimbursement and trading system, which may make our observed results not by carbon trading rights system but by emission rights paid use and trading system. Therefore, in column 1) of **Table 2**, we control for the dummy variable of whether the firm was a pilot of ETRT in the year. The conclusions show that the coefficients of the ETS variables remain significant at the 5% level, and we do not observe a decrease in the coefficients compared to the results in column 2) of **Table 2**, implying that the baseline results are not affected by the ETRT.

4.3.2 Excluding the Interference of Low-Carbon Provinces and Low-Carbon Cities Pilot Policies

To control greenhouse gas emissions, China launched pilot low-carbon provinces and low-carbon cities in five provinces and eight cities in 2010, with the explicit goal of reducing carbon emission intensity in the pilot areas[3]. In 2012, the country further expanded the scope of the pilot program and launched the second batch of national pilot low-carbon provinces and low-carbon cities. Implementing of the pilot policies of low-carbon provinces, regions, and cities likewise increases the degree of environmental regulation in the pilot areas, affecting the accuracy of the baseline regression estimates. Column 2) of **Table 3** reports the estimation results after controlling for the dummy variable of whether the firm was in a low-carbon province and low-carbon city pilot region in that year. It can see that the coefficients of the ETS variables, although slightly decreasing, are still significant at the

[3]The pilot areas are the five provinces of Guangdong, Liaoning, Hubei, Shaanxi and Yunnan and the eight cities of Tianjin, Chongqing, Shenzhen, Xiamen, Hangzhou, Nanchang, Guiyang and Baoding

TABLE 3 | Robustness checks.

Dependent variable	DDBTD (1)	DDBTD (2)	DDBTD (3)	DDBTD (4)	ETR (5)	DDBTD (6)	DDBTD (7)	DDBTD (8)
ETS	0.0082**	0.0080**	0.0082**		−0.0110*	0.0154*	0.0090***	0.0033
	(0.0034)	(0.0034)	(0.0034)		(0.0062)	(0.0083)	(0.0034)	(0.0056)
ETS1				0.0131***				
				(0.0043)				
Constant	−0.0157	−0.0170	−0.0186	−0.0080	0.0284	−0.0271	−0.0312	0.0154
	(0.0315)	(0.0309)	(0.0309)	(0.0710)	(0.1034)	(0.0332)	(0.0397)	(0.0615)
Observations	9,008	9,008	9,008	2,127	9,002	9,008	9,008	2,206
R-squared	0.0353	0.0354	0.0352	0.0349	0.0384	0.0784	0.0358	0.0475
Province*Trend	N	N	N	N	N	Y	N	N
Province characteristics	N	N	N	N	N	Y	Y	N
Firm characteristics	Y	Y	Y	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y	Y	Y

*Note: ***, **, and * represent the significance levels at 1, 5, and 10%, respectively. The robust standard error is reported in parentheses.*

5% level, which indicates that our estimation results are not affected by the low-carbon region policy.

4.3.3 Excluding the Disturbance of "Replace Business Tax With Value-Added Tax Policy"

To reduce double taxation, China started a pilot reform in 2012 to convert firms to replace business tax with Value-Added Tax. The implementation of the reform has changed the phenomenon of industrial firms not being able to obtain credits for services they previously purchased, eliminating tax barriers between upstream and downstream industries such as transportation and manufacturing, and also reducing the tax burden (Liao and Pan, 2015). The reduced tax burden of firms brought by the "replace business tax with Value-Added Tax policy" may offset the effect of the carbon emissions trading policy on corporate tax avoidance, leading to an underestimation of our results. In column 3) of **Table 3**, we control for the dummy variable of whether or not the "camp reform" was implemented in the year in which the firm is located, and conclude that the coefficient of the ETS variable is still significantly positive, indicating that our results are robust again.

4.4 Further Robustness Tests

4.4.1 Redefining the Treatment and Control Groups

In the basic regressions, we define the firms located in the pilot regions of carbon emissions trading as the treatment group and the firms in the non-pilot areas as the control group. To exclude the differences between provinces, we narrow the study to the pilot regions. Theoretically, the policy effects of the pilot reform of carbon emission trading rights are mainly concentrated on firms in high-carbon industries and have less effect on other firms. Based on the list of key emission control firms announced by each region, we have identified high carbon industries. We set the companies that belong to the high-carbon industry in the pilot area as the treatment group, and the companies that do not belong to the high-carbon industry as the control group. Then re-regress the model 1). The results in column 4) of **Table 3** show that the coefficient of ETS is positive and slightly increasing. Significant at the 1% significance level, indicating that implementing the carbon emission trading rights policy significantly enhances the level of tax avoidance of firms affected by the carbon emission trading rights system. The basic conclusion is robustly present.

4.4.2 Replacement of Explanatory Variable

In column 5) of **Table 3**, we test whether the baseline results depend on the measure of corporate tax avoidance. Instead of the DDBTD indicator after excluding the surplus management factor, we use the ETR indicator, which is also widely used in the literature to measure corporate tax avoidance (Hanlon and Heitzman, 2010; Geng et al., 2021). The lower the value, the higher the level of tax avoidance. Column 5) of **Table 3** shows that the regression coefficient of ETS is significantly negative. This indicates that the carbon ETS policy significantly reduces the actual tax burden of firms, i.e., it increases the level of corporate tax avoidance, indicating that our result is not affected by index of corporate tax avoidance.

4.4.3 Adding Control Variables

To reduce the effect of omitted variables on the estimation results, we include an interaction term between the province dummy variable and the time trend term in column 6) of **Table 3** to control changes over time across provinces. We control province-level control variables in column 7) of **Table 3**, such as regional industrial structure, total imports and exports as a share of GDP, and regional tax revenue growth rate. The results show that the baseline results are robust.

4.5 Placebo Test

4.5.1 Substitution for Firms Not Subject to Policy Intervention

In the parallel trend test, we confirm no systematic difference between the treatment and control groups before the carbon trading rights policy pilot. However, if there is an effect of other potentially unobservable factors that make systematic differences between the treatment and control groups after the introduction of the carbon trading pilot, it may result in our baseline results being due to other factors. A reasonable conjecture is that if corporate tax avoidance in pilot and non-pilot areas is affected by

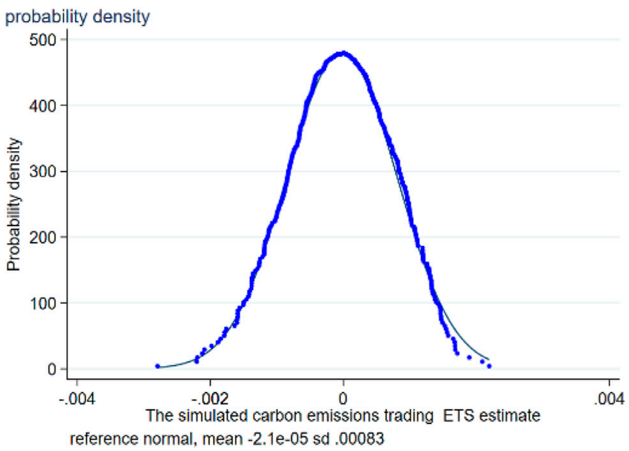


FIGURE 2 | Placebo test.

other factors, it will inevitably also affect firms not affected by the carbon trading rights policy. As a result, we conducted a placebo test on firms in the pilot and non-pilot regions that are not part of the high-carbon industries, defined as the treatment and control groups according to the definition of high-carbon industries defined in **Section 4.4.1**. Theoretically, suppose the pilot carbon trading rights cause the increase in tax avoidance. In that case, the newly defined treatment group and control group are not affected by the pilot carbon trading rights. So the coefficient of ETS should not be significant at this time. Column 8) of **Table 3** reports the results of the placebo test, and the coefficients of ETS are not significant, indicating that our baseline results are robust.

4.5.2 Configuration of Spurious Treatment Groups

To check whether the results are affected by omitted variables, referring to Chetty et al. (2009) and Li et al. (2016), we randomly assign the implementation of the carbon trading rights policy to each region to conduct the placebo test. By randomly assigning each province's treatment status, we can make the policy shock of carbon trading rights to firms in each province random and obtain random fictitious treatment groups and random coefficient estimates. If the spurious treatment variables significantly affect tax avoidance, it indicates that our baseline results may be biased. **Figure 2** illustrates the distribution of the random coefficient estimates $\hat{\beta}^{random}$ extracted by repeating model 1) 500 times, and it can observe that the mean value of the random coefficient estimates is close to zero, and the estimated coefficients reported in column 2) of **Table 2** are significant outliers in the placebo test. These observations suggest that the baseline results are driven by carbon emissions trading policy rather than unobserved factors.

5 FURTHER DISCUSSION

5.1 Heterogeneity Analysis

5.1.1 Nature of Ownership

State-owned enterprises (SOEs) and non-SOEs may differ in terms of their tax avoidance actions. SOEs are naturally more politically connected to the government and have greater bargaining power with regulators. Furthermore, they can absorb the additional costs associated with policies (Huang, 2003). And executives of SOEs have an incentive to please the government by paying taxes generously, with lower incentives to adopt tax avoidance to obtain funds (Bradshaw et al., 2019). In addition, the government-controlled background of SOEs allows them to receive large supportive government subsidies and bank loans, face a more relaxed financing environment and lower financing costs (Liu et al., 2016; Zhang et al., 2019), so SOEs are less likely to be in financial distress. Hering and Poncet (2014) find that China's Sulphur dioxide emissions trading rights pilot policy significantly reduced exports from the pilot provinces, and the effect is more evident on private firms. Especially because better access to financing made it easier for SOEs to use advanced technologies, thus enabling them to stay in business as environmental regulation tightened. In columns 1) and 2) of **Table 4**, we regress model 1) on the sample of non-SOEs and SOEs separately, and the findings show that the effect of carbon emissions trading policy on corporate tax avoidance is mainly present in non-SOEs, while it is not significant in SOEs.

5.1.2 Degree of Financing Constraints

Firms with severe financing constraints have poor access to external financing and higher cost of financing, and are more likely to resort to internal financing such as tax avoidance to save cash flow to alleviate financing constraints when subjected to policy shocks (Law and Mills, 2015; Edwards et al., 2016). We use the SA index, which is commonly used in the literature, as a proxy variable for the degree of a corporate financing constraints (Hadlock and Pierce, 2010). The SA index is calculated using the formula: $SA\ Index = -0.737 \times Asset + 0.043 \times Asset^2 - 0.040\ \times Age$. Where Asset is the logarithm of the corporate total assets and Age is the corporate age. A higher SA index represents a more severe financing constraint. In terms of variable definitions, firms are ranked from the highest to the lowest degree of financing constraint for each industry in each observation year. If a corporate rank is in the top (bottom) 50% of all firms in the industry, the firm is considered the group with a high (low) degree of financing constraint. Columns 3) and 4) of **Table 4** demonstrate the groups with high and low financing constraints, respectively. The coefficients of ETS variables are significantly positive only in the group with a high degree of corporate financing constraints. It indicates that the effect mainly exists in firms facing a high degree of financing constraints, while it is not significant in firms with a low degree of financing constraints.

5.1.3 Degree of Industry Competition

Intuitively, the higher competitive pressure a firm faces, the more likely it will avoid taxes to have more cash for investment to compete in the market. Cai and Liu (2009) examined the effect of competitive market pressure on corporate income tax avoidance. They found that the higher competitive market pressure a firm faces, tax avoidance is more severe. Bulan et al. (2009) pointed out that when market competition becomes fierce, the reduction of corporate profit margins weakens the ability of companies to

TABLE 4 | Heterogeneity analysis.

Dependent variable	DDBTD Non-SOEs (1)	DDBTD SOEs (2)	DDBTD Large financing constraints (3)	DDBTD Small financing constraints (4)	DDBTD High level of market competition (5)	DDBTD Low level of market competition (6)
ETS	0.0119**	0.0052	0.0119**	0.0018	0.0132***	0.0022
	(0.0053)	(0.0038)	(0.0046)	(0.0047)	(0.0050)	(0.0057)
Constant	–0.0633	0.0610	0.0847	–0.0406	–0.0306	–0.0060
	(0.0415)	(0.0563)	(0.0902)	(0.0431)	(0.0444)	(0.0558)
Observations	5,383	3,625	4,544	4,464	3,989	3,876
R-squared	0.0329	0.0383	0.0376	0.0428	0.0302	0.0519
Firm characteristics	Y	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y

*Note: ***, **, and * represent the significance levels at 1, 5, and 10%, respectively. The robust standard error is reported in parentheses.*

create cash flow and releases signals of decline in debt solvency. Therefore, competition will increase the difficulty of external financing for companies. Furthermore, when firms are subject to policy shocks, the increase in economic burden is not entirely borne by shareholders, but it is passed on to customers under certain conditions. Smale et al. (2006) pointed out that firms in carbon trading pilots can pass on the cost of carbon to consumers by raising prices. However, when the market is highly competitive, it is difficult for companies to pass on. Therefore, firms in a competitive market may have a greater incentive to evade taxes. We use the CR10 index to measure the degree of market competition (Hall and Tideman, 1967; Cai and Liu, 2009), which represents the ratio of the ten largest firms in the industry to industry-wide sales (CR10) as a proxy for the degree of competition in the industry. In the definition of the variable, the industry is ranked from the highest to the lowest level of competitive intensity. If a corporate industry is in the top (bottom) 50% of competitive intensity, the firm is considered in the group with a high (low) level of industry competition. Columns 5) and 6) of **Table 4** show the groups with high and low industry competitive intensity, respectively. The findings show that the coefficients of ETS variables are significant in industries with high industry competitive intensity. It indicates that the enhancement effect of environmental regulation on corporate tax avoidance mainly exists in firms with high industry competition and is not significant in firms with low industry competition.

5.2 Mechanism Analysis

5.2.1 Cash Flow Level

The increased intensity of environmental regulations may increase the cost of corporate investment in environmental protection equipment and pollutant treatment improvements, resulting in higher actual product costs, which reduces the competitiveness of corporate products given the same product quality, leading to lower sales or exports of corporate products (Hering and Poncet, 2014), and exacerbating corporate cash flow constraints. Chen et al. (2021) pointed out that China's carbon emissions trading policy pilot reduced corporate output, operating income, main operating costs, and net cash flow. The reduced level of corporate cash flow after implementing carbon emissions trading policy may be one of the reasons for corporate tax avoidance. In this paper, we use the net cash flow generated by the corporate operating activities after adjusting total assets as a measure of the corporate operating cash flow. In column 1) of **Table 5**, we replace the explanatory variable in model 1) with cash flow level. The result shows that operating cash flow is significantly lower for firms in the carbon emissions trading pilot region. Further, in column 2) of **Table 5**, we replace the explanatory variable with the corporate current ratio, calculated by the corporate current assets to current liabilities. In this way, we will examine the changes in the solvency of companies after implementing the carbon emissions trading policy. The result shows that the solvency of firms has declined significantly after the implementation of the trading pilot, which the decline in profitability may cause.

5.2.2 Corporate Innovation Capability

The increase in R&D investment demand of the regulated firms after implementing the carbon trading pilot may be one of the channels for firms to avoid taxes. Existing studies have not reached a unanimous conclusion on the research of carbon emissions trading on corporate green innovation (Shi et al., 2018; Wang et al., 2019; Chen et al., 2021). On the one hand, before the establishment of the carbon emission trading rights system, firms faced a more relaxed carbon emission reduction constraint, the cost of carbon emissions was low, and the incentive to reduce emissions was not high. After implementing the carbon emissions trading pilot, firms were forced into the carbon market aggregate control increased the cost of carbon emissions, prompting firms s to tend to reduce their own emission reduction costs by increasing R&D investment to achieve low-carbon technology transformation (Wang et al., 2019). On the other hand, the reduction of corporate cash flow and expected revenue after implementing the carbon emissions trading policy may reduce corporate R&D investment (Chen et al., 2021). We replace the explained variable in column 3) of **Table 5** with the corporate green innovation measured by the logarithm of the number of corporate green

TABLE 5 | Potential mechanisms.

Dependent variable	Cash	Current ratio	R&D input	Fixed-asset investment	Management expenses	Operating risks
	(1)	(2)	(3)	(4)	(5)	(6)
ETS	–0.0115*	–0.1920*	–0.1541**	0.0007	0.0016	–0.0012
	(0.0066)	(0.1054)	(0.0598)	(0.0039)	(0.0028)	(0.0017)
Constant	1.3653**	2.8029*	–5.3568***	0.2367***	0.2757***	0.0505***
	(0.5784)	(1.6279)	(0.9061)	(0.0523)	(0.0496)	(0.0189)
Observations	8,492	8,996	9,008	8,425	8,996	7,869
R-squared	0.1047	0.4020	0.1697	0.1945	0.1184	0.1286
Firm characteristics	Y	Y	Y	Y	Y	Y
Firm FE	Y	Y	Y	Y	Y	Y
Year FE	Y	Y	Y	Y	Y	Y

*Note: ***, **, and * represent the significance levels at 1, 5, and 10%, respectively. The robust standard error is reported in parentheses.*

patent applications, where a larger number of corporate green patent applications represents a higher level of corporate green innovation. The coefficient of the ETS variable is significantly negative, and the result suggests that the carbon emissions trading policy reduces the level of corporate green innovation. After implementing the carbon emissions trading policy, firms did not enhance their R&D investment, indicating that the increase in R&D investment is not a channel for firms to avoid taxes.

5.2.3 Corporate Capital Investment

To reduce the cost of carbon emissions, emission-controlled firms need to invest a large amount of capital for upgrading production equipment, and corporate tax avoidance may be motivated by corporate capital investment needs. Drawing on Richardson (2006) measure of intra-firm investment, we define intra-firm investment as (cash paid for the purchase of fixed assets, intangible assets, and other long-term assets - net cash recovered from the disposal of fixed assets, intangible assets, and other long-term assets - depreciation) as a proportion of total assets. Column 4) of **Table 5** explores whether carbon emissions trading policy increase firms' internal investment by including the amount of internal investment as an explanatory variable. The conclusion shows that the coefficients of the ETS variables are not significant, indicating that the increased level of corporate tax avoidance caused by the carbon emissions trading policy is not due to an increase in the amount of internal investment by the regulated firms.

5.2.4 Corporate Overhead Costs

The increase in business management costs due to the carbon emissions trading policy may motivate corporate tax avoidance. Tightening environmental regulation may impose new constraints on corporate production and management decisions, prompting them to provide environmentally compatible products and services. When external environmental regulation change, firms need to incorporate various environmental policies and plans into their operational strategies and adjust specific behaviors regarding product design, process technology selection, management techniques, production processes, quality management, and other related business management (Gupta, 1995). After implementing carbon emission policies, companies may implement aggressive carbon reduction plans, initiate environment-related performance measures, and adjust their original organizational frameworks, bringing about a significant increase in corporate management costs. We use the share of corporate overhead costs in operating income as a measure of corporate overhead costs, and try to explore whether the facilitation effect of environmental regulation on corporate tax avoidance is due to the increase in overhead costs by the change in overhead costs of pilot firms. The findings in column 5) of **Table 5** show that the coefficients of the ETS variables do not show statistical significance, indicating that the carbon emissions trading policy did not increase corporate overhead costs. The increase in the degree of corporate tax avoidance after the post-pilot implementation may not be caused by an increase in corporate overhead costs.

5.2.5 Operational Risk

The existing literature suggests that strict environmental regulation can change firms' original operating patterns and impose additional constraints on their production decisions, thus increasing their operational risks (Peng et al., 2021). When companies face the effect of carbon emissions trading policy, they may increase tax avoidance activities for preventive motives to withstand the uncertainties and risks they face. Geng et al. (2021) confirmed that after facing stricter environmental regulation brought about by the "11th Five-Year Plan", companies have increased corporate tax avoidance. We refer to the practice of Dhaliwal et al. (2011) and define the company's operational risk (OR) as the standard deviation of the company's return on total assets in the next 3 years, and use OR as the explained variable to explore the effect of carbon trading emissions on affected companies. The effect of operational risks. The regression results in column 6) of **Table 5** show that the regression coefficients of the EST variables are not significant, indicating that the implementation of carbon trading emission policies has not had a significant effect on corporate operational risks, and the increase in corporate operational risks is not the primary motivation for corporate tax avoidance.

5.3 Effect of Government Subsidies

Carbon trading emission policy brings additional costs for firms, making firms face more financing constraints and lower liquidity

TABLE 6 | Government subsidies and corporate tax avoidance.

Dependent variable	DDBTD (1)	DDBTD (2)	DDBTD (3)
ETS	0.0054	0.0111*	0.0110***
	(0.0052)	(0.0057)	(0.0041)
Subsidy			0.0434**
			(0.0215)
ETS*Subsidy			–0.1165**
			(0.0572)
Constant	0.0035	–0.0618	–0.0243
	(0.0519)	(0.0478)	(0.0318)
Observations	4,267	4,514	8,781
R-squared	0.0384	0.0326	0.0379
Firm characteristics	Y	Y	Y
Firm FE	Y	Y	Y
Year FE	Y	Y	Y

*Note: ***, **, and * represent the significance levels at 1, 5, and 10%, respectively. The robust standard error is reported in parentheses.*

as an important motive for tax avoidance. In contrast, government subsidies can bring direct cash flow to firms and improve their financial liquidity. Government subsidies can reduce a series of sunk costs brought by corporate innovation and R&D and help firms resist the risk and loss of R&D failure, thus reducing the incentive of tax avoidance. In addition to directly supplementing corporate capital, government subsidies can release positive signals to the outside world, attract social resources to gather, alleviate corporate financing difficulties and guide market expectations, further weakening corporate tax avoidance incentives in an environment of economic policy uncertainty. Columns 1) and 2) of **Table 6** distinguish between the subsamples with high and low government subsidies levels. The regressions conclude that the effect of carbon emissions trading policy on corporate tax avoidance is mainly found in firms with low levels of government subsidies. Column 3) of **Table 6** incorporates the interaction term between government subsidies and ETS in an attempt to explore the moderating effect of government subsidies on environmental regulation and corporate tax avoidance, and the findings indicate that the facilitating effect of environmental regulation on corporate tax avoidance is weakened for firms that receive higher government subsidies.

6 CONCLUSION

As ecological improvement becomes a global consensus, market-incentivized environmental regulation tools are increasingly. Environmental regulation triggers adjustments in firm behavior. Based on a quasi-natural experiment of carbon trading emission, this paper explored the effect of market-incentivized environmental regulation on corporate tax avoidance using a sample of industrial firms listed in China. The results show that 1) Market-incentivized environmental regulation significantly increase the level of tax avoidance of firms in the region where the carbon trading rights pilot is implemented. Our findings remain robust after conducting robustness tests such as excluding the confounding effects of contemporaneous policies, reclassifying the control and control groups, replacing the measure of corporate tax avoidance, and including more control variables. 2) Heterogeneity analysis shows that tax avoidance significantly increases for non-state-owned firms, firms with severe financing constraints, and firms in competitive industries after a policy shock. 3) Mechanistic analysis suggests that the decrease of cash flow may be a channel affecting corporate tax avoidance. 4) Government subsidies help mitigate the elevated effect of environmental regulation on corporate tax avoidance. The more government subsidies a company receives, the less tax avoidance it has.

The results of this paper provide insights into the implementation of carbon emissions trading policy. When firms face stricter environmental regulation, they resort to tax avoidance to defray the costs associated with the policy. When assessing the cost of carbon policies, governments should also pay attention to the effect of the policies on the tax avoidance behavior of different firms. Based on the results of this paper, we offer the following suggestions: 1) Strengthen the cooperation between environmental protection departments and other departments. Share data and information with tax authorities to increase enforcement against regulated firms and curb unreasonable tax avoidance. 2) Reducing corporate cash flow is the main motivation for corporate tax avoidance. To cope with the crowding out of corporate cash by emissions cost after implementing carbon emissions trading policy, environmental protection departments should help the private firms and financing constraints serious firms to broaden financing channels. 3) To encourage green R&D investment and low-carbon technology innovation, the government should continue to increase tax incentives such as tax deductions for R&D expenses, and give subsidies to regulated firms through various support policies.

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

CF: Conceptualization, Writing–Original Draft, Writing–Review and Editing. XZ: Investigation, Writing–Original Draft, Writing—Reviewing and Editing. YG: Methodogy, Data Curation, Software, Writing–Original Draft, Writing–Review and Editing. YL: Investigation, Methodology, Data Curation, Writing—Original Draft.

FUNDING

This paper is supported by the Programme of Introducing Talents of Discipline to Universities (No. B20084). We declare all sources of funding received for the research being submitted.

REFERENCES

Abrell, J., Faye, A. N., and Zachmann, G. (2008). *Assessing the Impact of the EU ETS Using Firm Level Data*. Brussels: Bruegel Working Paper.

Allingham, M. G., and Sandmo, A. (1972). Income Tax Evasion: A Theoretical Analysis. *J. Publ. Econ.* 1 (3-4), 323–338. doi:10.1016/0047-2727(72)90010-2

Beck, T., Lin, C., and Ma, Y. (2014). Why Do Firms Evade Taxes? the Role of Information Sharing and Financial Sector Outreach. *J. Finance* 69 (2), 763–817. doi:10.1111/jofi.12123

Blundell, R., and Costa Dias, M. (2020). Evaluation Methods for Non-experimental Data. *Fisc. Stud.* 21 (4), 427–468. doi:10.1111/j.1475-5890.2000.tb00031.x

Bradshaw, M., Liao, G., and Ma, M. (2019). Agency Costs and Tax Planning when the Government Is a Major Shareholder. *J. Account. Econ.* 67 (2/3), 255–277. doi:10.1016/j.jacceco.2018.10.002

Bulan, L., Mayer, C., and Somerville, C. T. (2009). Irreversible Investment, Real Options, and Competition: Evidence from Real Estate Development. *J. Urban Econ.* 65 (3), 237–251. doi:10.1016/j.jue.2008.03.003

Cai, H., and Liu, Q. (2009). Competition and Corporate Tax Avoidance: Evidence from Chinese Industrial Firms. *Econ.J.* 119 (537), 764–795. doi:10.1111/j.1468-0297.2009.02217.x

Cai, X., Lu, Y., Wu, M., and Yu, L. (2016). Does Environmental Regulation Drive Away Inbound Foreign Direct Investment? Evidence from a Quasi-Natural Experiment in China. *J. Develop. Econ.* 123, 73–85. doi:10.1016/j.jdeveco.2016.08.003

Chen, S. X. (2017). The Effect of a Fiscal Squeeze on Tax Enforcement: Evidence from a Natural Experiment in China. *J. Public Econ.* 147, 62–76. doi:10.1016/j.jpubeco.2017.01.001

Chen, Z., Zhang, X., and Chen, F. (2021). Do Carbon Emission Trading Schemes Stimulate Green Innovation in Enterprises? Evidence from China. *Technol. Forecast. Soc. Change* 168, 120744. doi:10.1016/j.techfore.2021.120744

Chetty, R., Looney, A., and Kroft, K. (2009). Salience and Taxation: Theory and Evidence. *Am. Econ. Rev.* 99 (4), 1145–1177. doi:10.1257/aer.99.4.1145

Dang, D., Fang, H., and He, M. (2019). Economic Policy Uncertainty, Tax Quotas and Corporate Tax burden: Evidence from China. *China Econ. Rev.* 56, 101303. doi:10.1016/j.chieco.2019.101303

Desai, M. A., and Dharmapala, D. (2006). Corporate Tax Avoidance and High-Powered Incentives. *J. Financial Econ.* 79 (1), 145–179. doi:10.1016/j.jfineco.2005.02.002

Dhaliwal, D., Lee, H. S., and Neamtiu, M. (2011). The Impact of Operating Leases on Firm Financial and Operating Risk. *J. Account. Auditing Finance* 26 (2), 151–197. doi:10.1177/0148558X11401210

Dong, C., Dong, X., Jiang, Q., Dong, K., and Liu, G. (2018). What Is the Probability of Achieving the Carbon Dioxide Emission Targets of the Paris Agreement? Evidence from the Top Ten Emitters. *Sci. Total Environ.* 622-623, 1294–1303. doi:10.1016/j.scitotenv.2017.12.093

Dong, F., Dai, Y., Zhang, S., Zhang, X., and Long, R. (2019). Can a Carbon Emission Trading Scheme Generate the Porter Effect? Evidence from Pilot Areas in China. *Sci. Total Environ.* 653, 565–577. doi:10.1016/j.scitotenv.2018.10.395

Dong, K., Shahbaz, M., and Zhao, J. (2022). How Do Pollution Fees Affect Environmental Quality in China. *Energy Policy* 160, 112695. doi:10.1016/j.enpol.2021.112695

Dudley, E., and Zhang, N. (2016). Trust and Corporate Cash Holdings. *J. Corporate Finance* 41, 363–387. doi:10.1016/j.jcorpfin.2016.10.010

Edwards, A., Schwab, C., and Shevlin, T. (2016). Financial Constraints and Cash Tax Savings. *Account. Rev.* 91 (3), 859–881. doi:10.2308/accr-51282

Falkinger, J. (1995). Tax Evasion, Consumption of Public Goods and Fairness. *J. Econ. Psychol.* 16 (1), 63–72. doi:10.1016/0167-4870(94)00038-c

Fallan, E., and Fallan, L. (2019). Corporate Tax Behaviour and Environmental Disclosure: Strategic Trade-Offs across Elements of CSR. *Scand. J. Manage.* 35 (3), 101042. doi:10.1016/j.scaman.2019.02.001

Geng, Y., Liu, W., Li, K., and Chen, H. (2021). Environmental Regulation and Corporate Tax Avoidance: A Quasi-Natural Experiment Based on the Eleventh Five-Year Plan in China. *Energ. Econ.* 99, 105312. doi:10.1016/j.eneco.2021.105312

Godfrey, P. C. (2005). The Relationship between Corporate Philanthropy and Shareholder Wealth: A Risk Management Perspective. *Amr* 30 (4), 777–798. doi:10.5465/AMR.2005.18378878

Gray, W., B. (1987). The Cost of Regulation: OSHA, EPA and the Productivity Slowdown. *Am. Econ. Rev.* 77 (5), 998–1006. Available at: http://www.jstor.org/stable/1810223.

Gupta, M. C. (1995). Environmental Management and its Impact on the Operations Function. *Int. Jrnl Op Prod. Mnagemnt* 15 (8), 34–51. doi:10.1108/01443579510094071

Gupta, S., and Newberry, K. (1997). Determinants of the Variability in Corporate Effective Tax Rates: Evidence from Longitudinal Data. *J. Account. Public Pol.* 16 (1), 1–34. doi:10.1016/s0278-4254(96)00055-5

Hadlock, C. J., and Pierce, J. R. (2010). New Evidence on Measuring Financial Constraints: Moving beyond the KZ Index. *Rev. Financ. Stud.* 23 (5), 1909–1940. doi:10.1093/rfs/hhq009

Hall, M., and Tideman, N. (1967). Measures of Concentration. *J. Am. Stat. Assoc.* 62 (317), 162–168. doi:10.1080/01621459.1967.10482897

Hanlon, M., and Heitzman, S. (2010). A Review of Tax Research. *J. Account. Econ.* 50, 127–178. doi:10.1016/j.jacceco.2010.09.002

Hering, L., and Poncet, S. (2014). Environmental Policy and Exports: Evidence from Chinese Cities. *J. Environ. Econ. Manage.* 68 (2), 296–318. doi:10.1016/j.jeem.2014.06.005

Huang, Y. S. (2003). *Selling China: Foreign Direct Investment during the Reform Era*. New York, NY: Cambridge University Press.

Jacobson, L. S., Lalonde, R. J., and Sullivan, D. G. (1993). Earnings Losses of Displaced Workers. *Am. Econ. Rev.* 83, 685–709. doi:10.17848/wp92-11

Jong, T., Couwenberg, O., and Woerdman, E. (2014). Does EU Emissions Trading Bite? an Event Study. *Energy Policy* 69, 510–519. doi:10.1016/j.enpol.2014.03.007

Kanagaretnam, K., Lee, J., Lim, C. Y., and Lobo, G. J. (2018). Cross-Country Evidence on the Role of Independent Media in Constraining Corporate Tax Aggressiveness. *J. Bus. Ethics* 150 (3), 879–902. doi:10.1007/s10551-016-3168-9

Khurana, I. K., and Moser, W. J. (2013). Institutional Shareholders' Investment Horizons and Tax Avoidance. *J. Am. Tax. Assoc.* 35 (1), 111–134. doi:10.2308/atax-50315

Kleven, H., J., Knudsen, M. B., Kreiner, C. T., Pedersen, S., and Saez, E. (2011). Unwilling or Unable to Cheat? Evidence from a Tax Audit Experiment in Denmark. *Econometrica* 79 (3), 651–692. doi:10.3982/ecta9113

Koch, N., and Bassen, A. (2013). Valuing the Carbon Exposure of European Utilities. The Role of Fuel Mix, Permit Allocation and Replacement Investments. *Energ. Econ.* 36, 431–443. doi:10.1016/j.eneco.2012.09.019

Kubick, T. R., Lynch, D. P., Mayberry, M. A., and Omer, T. C. (2015). Product Market Power and Tax Avoidance: Market Leaders, Mimicking Strategies, and Stock Returns. *Account. Rev.* 90 (2), 675–702. doi:10.2308/accr-50883

Law, K. K. F., and Mills, L. F. (2015). Taxes and Financial Constraints: Evidence from Linguistic Cues. *J. Account. Res.* 53 (4), 777–819. doi:10.1111/1475-679x.12081

Li, J., Dong, X., and Dong, K. (2021). Do pollutant Discharge Fees Affect Labor Demand? Evidence from China's Industrial Enterprises. *Appl. Econ.*, 1–19. doi:10.1080/00036846.2021.1963662

Li, P., Lu, Y., and Wang, J. (2016). Does Flattening Government Improve Economic Performance? Evidence from China. *J. Develop. Econ.* 123, 18–37. doi:10.1016/j.jdeveco.2016.07.002

Liao, S., and Pan, Y. (2015). Analysis on the Policy Effect of Replacing Business Tax with Added-Value Tax. *Ijefm* 3 (3), 162–171. doi:10.11648/j.ijefm.20150303.13

Liu, M., Zhou, C., Lu, F., and Hu, X. (2021). Impact of the Implementation of Carbon Emission Trading on Corporate Financial Performance: Evidence from Listed Companies in China. *PLoS One* 16, e0253460. doi:10.1371/journal.pone.0253460

Liu, Q., Luo, J., and Tian, G. G. (2016). Managerial Professional Connections versus Political Connections: Evidence from Firms' Access to Informal Financing Resources. *J. Corporate Finance* 41, 179–200. doi:10.1016/j.jcorpfin.2016.09.003

Mills, L. F., Nutter, S. E., and Schwab, C. M. (2013). The Effect of Political Sensitivity and Bargaining Power on Taxes: Evidence from Federal Contractors. *Account. Rev.* 88 (3), 977–1005. doi:10.2308/accr-50368

Oestreich, A. M., and Tsiakas, I. (2015). Carbon Emissions and Stock Returns: Evidence from the EU Emissions Trading Scheme. *J. Banking Finance* 58, 294–308. doi:10.1016/j.jbankfin.2015.05.005

Olsen, K. J., and Stekelberg, J. (2016). CEO Narcissism and Corporate Tax Sheltering. *J. Am. Tax. Assoc.* 38 (1), 1–22. doi:10.2308/atax-51251

Peng, J., Xie, R., Ma, C., and Fu, Y. (2021). Market-based Environmental Regulation and Total Factor Productivity: Evidence from Chinese Enterprises. *Econ. Model.* 95, 394–407. doi:10.1016/j.econmod.2020.03.006

Peng, S., Chang, Y., and Zhang, J. (2015). Consideration of Some Key Issues of Carbon Market Development in China. *Chin. J. Popul. Resour. Environ.* 13 (1), 10–15. doi:10.1080/10042857.2015.1005344

Pomeranz, D., and Vila-Belda, J. (2019). Taking State-Capacity Research to the Field: Insights from Collaborations with Tax Authorities. *Annu. Rev. Econ.* 11 (1), 755–781. doi:10.1146/annurev-economics-080218-030312

Porter, M. E., and Linde, C. v. d. (1995). Toward a New Conception of the Environment-Competitiveness Relationship. *J. Econ. Perspect.* 9 (4), 97–118. doi:10.1257/jep.9.4.97

Rego, S. O. (2003). Tax-Avoidance Activities of U.S. Multinational Corporations*. *Contemp. Account. Res.* 20 (4), 805–833. doi:10.1506/vann-b7ub-gmfa-9e6w

Richardson, G., Taylor, G., and Lanis, R. (2013). The Impact of Board of Director Oversight Characteristics on Corporate Tax Aggressiveness: An Empirical Analysis. *J. Account. Public Pol.* 32 (3), 68–88. doi:10.1016/j.jaccpubpol.2013.02.004

Richardson, G., Wang, B., and Zhang, X. (2016). Ownership Structure and Corporate Tax Avoidance: Evidence from Publicly Listed Private Firms in China. *J. Contemp. Account. Econ.* 12 (2), 141–158. doi:10.1016/j.jcae.2016.06.003

Richardson, S. (2006). Over-Investment of Free Cash Flow. *Rev. Acc. Stud.* 11 (2-3), 159–189. doi:10.1007/s11142-006-9012-1

Sari, D., Tjen, C., and Tjen, C. (2016). Corporate Social Responsibility Disclosure, Environmental Performance, and Tax Aggressiveness. *Irjbs* 9 (2), 93–104. doi:10.21632/irjbs.9.2.93-104

Shao, S., Wang, C., Guo, Y., Xie, B.-C., Tian, Z., and Chen, S. (2021). Heterogeneous Performances and Consequences of China's Industrial Environmental Governance: Clean Production vs. End-Of-Pipe Treatment. *J. Environ. Plann. Manage.*, 1–26. doi:10.1080/09640568.2021.1980377

Shen, J., Wei, Y. D., and Yang, Z. (2017). The Impact of Environmental Regulations on the Location of Pollution-Intensive Industries in China. *J. Clean. Prod.* 148, 785–794. doi:10.1016/j.jclepro.2017.02.050

Shi, B., Feng, C., Qiu, M., and Ekeland, A. (2018). Innovation Suppression and Migration Effect: The Unintentional Consequences of Environmental Regulation. *China Econ. Rev.* 49 (1-23), 1–23. doi:10.1016/j.chieco.2017.12.007

Smale, R., Hartley, M., Hepburn, C., Ward, J., and Grubb, M. (2006). The Impact of CO2emissions Trading on Firm Profits and Market Prices. *Clim. Pol.* 6 (1), 31–48. doi:10.1080/14693062.2006.9685587

Stickney, C. P., and McGee, V. E. (1982). Effective Corporate Tax Rates the Effect of Size, Capital Intensity, Leverage, and Other Factors. *J. Account. Public Pol.* 1 (2), 125–152. doi:10.1016/S0278-4254(82)80004-5

Wang, H., Chen, Z., Wu, X., and Nie, X. (2019). Can a Carbon Trading System Promote the Transformation of a Low-Carbon Economy under the Framework of the porter Hypothesis? -Empirical Analysis Based on the PSM-DID Method. *Energy Policy* 129, 930–938. doi:10.1016/j.enpol.2019.03.007

Wang, L., Cui, L., Weng, S., and Liu, C. (2021). Promoting Industrial Structure Advancement through an Emission Trading Scheme: Lessons from China's Pilot Practice. *Comput. Ind. Eng.* 157, 107339. doi:10.1016/j.cie.2021.107339

Wang, S., Wang, H., Wang, J., and Yang, F. (2020). Does Environmental Information Disclosure Contribute to Improve Firm Financial Performance? an Examination of the Underlying Mechanism. *Sci. Total Environ.* 714, 136855. doi:10.1016/j.scitotenv.2020.136855

Wilson, R. J. (2009). An Examination of Corporate Tax Shelter Participants. *Rev* 84, 969–999. doi:10.2308/accr.2009.84.3.969

Xuan, D., Ma, X., and Shang, Y. (2020). Can China's Policy of Carbon Emission Trading Promote Carbon Emission Reduction. *J. Clean. Prod.* 270, 122383. doi:10.1016/j.jclepro.2020.122383

Ye, B., and Lin, L. (2020). Environmental Regulation and Responses of Local Governments. *China Econ. Rev.* 60, 101421. doi:10.1016/j.chieco.2020.101421

Yu, H., Liao, L., Qu, S., Fang, D., Luo, L., and Xiong, G. (2021). Environmental Regulation and Corporate Tax Avoidance : A Quasi-Natural Experiments Study Based on China's New Environmental protection Law. *J. Environ. Manage.* 296, 113160. doi:10.1016/j.jenvman.2021.113160

Zhang, H., Duan, M., and Deng, Z. (2019). Have China's Pilot Emissions Trading Schemes Promoted Carbon Emission Reductions?- the Evidence from Industrial Sub-sectors at the Provincial Level. *J. Clean. Prod.* 234 (10), 912–924. doi:10.1016/j.jclepro.2019.06.247

Zhao, X., and Sun, B. (2016). The Influence of Chinese Environmental Regulation on Corporation Innovation and Competitiveness. *J. Clean. Prod.* 112 (2), 1528–1536. doi:10.1016/j.jclepro.2015.05.029

Zheng, Y., Sun, X., Zhang, C., Wang, D., and Mao, J. (2021). Can Emission Trading Scheme Improve Carbon Emission Performance? Evidence from China. *Front. Energ. Res.* 9, 759572. doi:10.3389/fenrg.2021.759572

Zimmerman, J. L. (1983). Taxes and Firm Size. *J. Account. Econ.* 5, 119–149. doi:10.1016/0165-4101(83)90008-3

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: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors, and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 11 January 2022
doi: 10.3389/fenrg.2021.820596

The Impacts of FDI Inflows on Carbon Emissions: Economic Development and Regulatory Quality as Moderators

Yanyan Huang[1], Fuzhong Chen[2]*, Huini Wei[2], Jian Xiang[2], Zhexiao Xu[2] and Rabia Akram[3]

[1]Institute of Economic Development and Reform, Huaqiao University, Xiamen, China, [2]School of International Trade and Economics, University of International Business and Economics, Beijing, China, [3]School of Business, Guilin University of Electronic Technology, Guilin, China

With the accelerated development of the global economy, environmental issues have gradually become prominent, which in turn hinders further high-quality economic development. As one of the important driving factors, cross-border flowing foreign direct investment (FDI) has played a vital role in promoting economic development, but has also caused environmental degradation in most host countries. Utilizing panel data for the G20 economies from 1996 to 2018, the purpose of this study is to investigate the impacts of FDI inflows on carbon emissions, and further explore the influence channels through the moderating effects of economic development and regulatory quality. To produce more robust and accurate results in this study, the approach of the feasible generalized least squares (FGLS) is utilized. Meanwhile, this study also specifies the heteroscedasticity and correlated errors due to the large differences and serial correlations among the G20 economies. The results indicate that FDI inflows are positively associated with carbon emissions, as well as both economic development and regulatory quality negatively contribute to the impacts of FDI inflows on carbon emissions. It implies that although FDI inflows tend to increase the emissions of carbon dioxide, they are more likely to mitigate carbon emissions in countries with higher levels of economic development and regulatory quality. Therefore, the findings are informative for policymakers to formulate effective policies to help mitigate carbon emissions and eliminate environmental degradation.

Keywords: foreign direct investment, carbon emissions, economic development, regulatory quality, moderating effects

OPEN ACCESS

Edited by:
Xiaohang Ren,
Central South University, China

Reviewed by:
Taimoor Hassan,
Nanjing University of Science and Technology, China
Yasir Khan,
Anhui Polytechnic University, China

***Correspondence:**
Fuzhong Chen
uibesitechen@126.com

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *23 November 2021*
Accepted: *13 December 2021*
Published: *11 January 2022*

Citation:
Huang Y, Chen F, Wei H, Xiang J, Xu Z and Akram R (2022) The Impacts of FDI Inflows on Carbon Emissions: Economic Development and Regulatory Quality as Moderators. Front. Energy Res. 9:820596. doi: 10.3389/fenrg.2021.820596

INTRODUCTION

In recent decades, the development of the world economy has been facing a relatively serious issue, that is, climate change caused by carbon emissions. A large number of international organizations have made significant efforts to address it. In 1992, the United Nations Conference on Environment and Development signed the United Nations Framework Convention on Climate Change (UNFCCC) to decrease the concentration of greenhouse gases in the atmosphere. In 1997, under the UNFCCC framework, the Kyoto Protocol was signed, and is considered a law to stabilize the amount of greenhouse gases in the atmosphere. Among the six greenhouse gases (GHG) that cause climate change, carbon emissions have the largest impact, accounting for 80% of the total emissions (Ahmad and Wyckoff, 2003). The link between global temperatures and greenhouse gas concentrations, especially carbon dioxide, has been true throughout Earth's history (Lacis et al., 2010). Therefore, reducing carbon emissions has become an effective way to deal with climate change.

According to data from the World in Data based on the Global Carbon Project, before the mid-20th century, the growth of carbon emissions was relatively slow. In 1950, the world emitted just over 5 billion tones of carbon—about the level of the US, or half of China's annual emissions today (Aller et al., 2020). By 1990, the figure for carbon emissions had quadrupled to 22 billion tonnes. Carbon emissions have continued to grow rapidly, and the world now emits more than 36 billion tonnes a year. Moreover, along with the substantial increase in the world's total carbon emissions, there is a notable change. In the first half of the 20th Century, global carbon emissions were dominated by Europe and the United States, accounting for over 90% in 1900 and even more than 85% of emissions by 1950 each year. However, in the second half of the 20th century, the main share of the world's total carbon emissions came from other regions of the world, especially Asia as a whole, of which China accounted for the highest carbon emissions. Meanwhile, the current carbon emissions in the United States and Europe are slightly less than one-third of the total global emissions. In view of this increasingly serious problem, it is generally recognized that to alleviate the serious impact of climate change, countries around the world urgently need to identify the potential drivers of carbon emissions and take effective countermeasures.

With the acceleration of economic globalization, the flow of international capital has become more frequent, especially foreign direct investment (FDI), which not only promotes the economic growth of host countries but also brings about a rapid increase in carbon emissions. As one of the most important international investment activities, inflowing FDI has played a vital role in economic and environmental development, which has always been a hot topic in previous studies. The increase in FDI inflows may be associated with global climate change. Hence, many prior studies have paid attention to investigating the impacts of FDI inflows on carbon emissions. However, many existing studies have claimed conflicting links between FDI inflows and environmental contamination. On the one hand, as the Pollution Haven Hypothesis suggests, FDI inflows may exacerbate environmental degradation. The hypothesis states that companies in pollution-intensive industries are most likely based in countries or regions with relatively low environmental standards, which may lead to excessive or suboptimal levels of pollution. Several studies provide evidence to support the pollution-haven effect and find that FDI inflows aggravate carbon emissions (Cole, 2004; Cole et al., 2011; Kheder and Zugravu, 2012; Rahman et al., 2019). On the other hand, FDI inflows can benefit their host countries by transferring innovative technologies, promoting financial development, and improving management (Nair-Reichert and Weinhold, 2001; Bose and Kohli, 2018), which allow companies to adopt environmentally friendly products and technologies that help mitigate carbon emissions and enhance environmental quality (Wheeler, 2001; Zeng and Eastin, 2012; Ahmad et al., 2019). Thus, the pollution halo effect is demonstrated. Additionally, several studies indicate a nonlinear relationship between FDI inflows and carbon emissions (Shahbaz et al., 2015; Alshubiri and Elheddad, 2019). FDI inflows may enhance carbon emissions initially, but after a threshold point, the increase in FDI inflows will bring about a decrease in carbon emissions.

Nevertheless, FDI inflows do not independently affect carbon emissions. There are other determinants of carbon emissions such as economic development and regulatory quality. Firstly, a great body of literature has examined the relationship between economic development and pollution emissions. While empirical testing of the Environmental Kuznets Curve (EKC) hypothesis continues to increase, generally pointing out an inverted U-shaped nexus between income and environmental pollution (Dutt, 2009; Apergis, 2016), a portion of researchers have questioned the validity of this theory (Aslanidis and Iranzo, 2009; Al-Mulali et al., 2015; Özokcu and Özdemir, 2017). Secondly, economies with higher regulatory quality are more likely to have stricter environmental policies and follow the regulations of related international environmental agreements. Moreover, these economies prefer to force the firms to comply with the control procedures of pollution emissions (Welsch, 2004). By contrast, under economies with weaker regulatory quality, environmental policies are less likely to be stringent for firms (Damania et al., 2003), and governments potentially make sub-optimal decisions concerning pollution emissions. Consequently, the actual carbon emissions are higher than the optimal levels for any income level.

The association between FDI inflows and carbon emissions is a matter of controversy in the literature. The same is true of the indirect effects from economic development and regulator quality on carbon emissions. A variety of studies have focused on the direct association between FDI inflows and carbon emissions, but there may also be indirect effects of FDI inflows on carbon emissions. Therefore, this study introduces economic development and regulatory quality as moderators in investigating the influence mechanism of FDI inflows on carbon emissions. Depending on the literature that has been surveyed in this field, this study expects the moderating effects of economic development and regulatory quality in the association between FDI inflows and carbon emissions. This study is well-positioned to inform policymakers to formulate effective policies to help mitigate carbon emissions.

Using panel data of the G20 economies from 1996 to 2018, the purpose of this study is to examine the impacts of FDI inflows on carbon emissions, and the moderating effects of economic development and regulatory quality are investigated. The rest of this study is structured as follows. *Literature Review* highlights the conceptual framework and reviews related literature. *Methodology and Data* presents the hypotheses and methodology and statistically describes the data. *Empirical Results* discusses empirical results. Further Discussions examine the moderating effects of economic development and regulatory quality in carbon emissions. Conclusions and

Implications summarize and put forward policy recommendations.

LITERATURE REVIEW

Previous Research on the FDI Inflows and Carbon Emissions

Over the past decade, there has been an increasing amount of literature on the roles of FDI inflows in carbon emissions. However, the impacts of FDI inflows on carbon emissions have long been a matter of debate. Recent research results on this topic mainly incorporate the following three categories.

Firstly, several previous studies have examined the direct impacts of FDI inflows on carbon emissions and put forward the pollution haven hypothesis, which suggests that FDI inflows are associated with a higher level of carbon emissions. On the one hand, to maximize profits, developed countries tend to invest in developing countries with less stringent environmental regulations or lower environmental taxes, which leads to the transfer of polluting industries to these regions (Aller et al., 2020). As a result, carbon emissions in host countries increase with the expansion of FDI-led economic activities (Grimes and Kentor, 2003; Mahadevan and Sun, 2020). By using data from 66 developing countries, Grimes and Kentor (2003) suggested that FDI inflows significantly accelerate the growth of carbon emissions in less developed countries. On the other hand, less developed countries are more inclined to adopt lax regimes to attract foreign investments to achieve economic development (Bommer, 1995). Cole et al. (2006) used data from 33 countries to examine the nexus between FDI inflows and the stringency of environmental policies. The results showed that in countries with high levels of corruption, local carbon emissions increase as multinationals may lobby local governments for lax environmental policies.

Secondly, many prior studies have put forward a contradictory hypothesis—the pollution halo hypothesis, indicating that FDI inflows can bring cleaner and more efficient technologies to the host country which are positive to significantly mitigate carbon emissions (Melane-Lavado et al., 2018; Wang et al., 2021). Zhu et al. (2016) suggested that the impacts of FDI inflows on emissions are negative and become significant at higher quantiles in Indonesia, Malaysia, Philippines, Singapore, and Thailand. Furthermore, Acharyya (2009) argued that FDI inflows have a large beneficial effect on carbon emissions by increasing output in a long run in the case of India.

Thirdly, some studies have drawn comprehensive conclusions. Using panel data from 32 OECD countries, Alshubiri and Elheddad (2019) claimed a non-linear relationship between FDI inflows and carbon emissions. At the left end of the inflection point, FDI inflows are positively correlated with carbon emissions, while at the right end of the inflection point, FDI inflows are negatively associated with carbon emissions. Shahbaz et al. (2015) utilized data from 99 countries and empirical results suggested that the impacts of FDI inflows on carbon emissions are heterogeneous due to differences in national income. Moreover, there is an inverted U-shaped association between FDI inflows and carbon emissions in middle-income countries. In high-income countries, however, FDI inflows can mitigate carbon emissions, while in low-income countries, the relationship is the opposite (Shahbaz et al., 2015).

Prior Studies on Other Factors Influencing Carbon Emissions

In addition to FDI inflows, other determinants of carbon emissions have been documented in many previous studies. For instance, quite a few studies explore the relationship between economic development and carbon emissions. In some of them, the EKC hypothesis is widely recognized, claiming an inverted U-shaped association between income and environmental pollution. When a country's economy is underdeveloped, the country may choose to sacrifice the environment (i.e., increased carbon emissions) to achieve economic growth. But when the country reaches a higher level of income, the cost of environmental governance will decrease, which will make the public pay more attention to environmental quality, and thereby promote the country to choose a more environmentally friendly way (Grossman and Krueger, 1995; Harbaugh et al., 2002; Musah et al., 2021; Ren et al., 2021). Grossman and Krueger (1992) summarized three impacts of economic development on the environment as follows. The first is the scale effect. It indicates that an increase in economic activity without technological innovation is associated with more requirements on natural resources, leading to more waste and carbon emissions. In this case, the boom in economic activity negatively contributes to the environment. The second is the composition effect. It implies that wealth accumulation occurs with shifts in the structure of production institutions. In industrial societies, environmental degradation is exacerbated when the economic structure shifts from rural to urban, but is reversed with the structural shift from energy-intensive industries to technological—and knowledge—based services. The third is the technological effect. Such effect suggests that when nations are rich enough so that they can afford expenses on research and development, new technology will replace the obsolete and ensure environmental quality. Furthermore, several prior studies also provide empirical evidence. Panayotou et al. (2000) examined the relationship between carbon emissions and per capita income by using panel data from 17 developed countries for a period from 1870 to 1994 and time-series data for the United Kingdom and the United States. They claimed that the environmental Kuznets curve always exists regardless of the data type. Moreover, the environmental Kuznets curve still exists after adding variables such as population density and export trade. While the empirical testing of the EKC hypothesis continues, several studies have presented confusing results (Shafik, 1994). For instance, using data from 1960 to 1996 in 100 countries, Azomahou et al. (2005) employed a nonparametric panel approach and revealed that economic development always leads to an increase in carbon emissions in both rich and poor countries. Lee et al. (2009) argued that the environmental Kuznets curve does not apply to all countries. They used the data of 89 countries from 1960 to 2000 to obtain an N-shaped curve for all countries. After grouping all samples for regression, the results indicate that middle-income countries, the United States, and Europe present an inverted U-shape, while high-income countries, low-income countries, Africa, Asia, and Oceania countries do not show an environmental Kuznets curve.

Besides, regulatory quality is also considered to be one of the important factors affecting carbon emissions. Perera and Lee (2013) indicated that the improvement of institutional quality has boosted economic activity in low-income countries in Asia, and the increase in economic activity may cause a significant increase in carbon emissions. Moreover, the quality of the regulations determines the strictness of a country's environmental regulatory system. Ibrahim and Law (2015) argued that countries with loose environmental regulations due to international trade tend to specialize in the production of pollution-intensive products, which will inevitably cause the host country to increase carbon emissions. The poor regulatory quality may also mitigate pollution indirectly through the reduction in income per capita. Welsch (2004), Cole (2007) claimed that the overall effects of regulatory quality captured by corruption levels are insignificant, except for high-income economies, where the total effect of regulatory quality on emissions is found to be negative and significant. On the other hand, the improvement of regulatory quality can improve the allocation of resources, and Porter's hypothesis believed that strict environmental regulations promote innovation of enterprises, decrease production costs, and eliminate the negative impact on the environment (Herrera-Echeverri et al., 2014; Dong et al., 2021). Therefore, the quality of the regulations has a double-edged sword effect on carbon emissions. There are empirical results that can provide a more comprehensive conclusion. On the one hand, the improvement of regulatory quality effectively promotes the increase of economic activities, which causes an increase in carbon emissions. On the other hand, the improvement of regulatory quality will affect the impact mechanism of FDI inflows on carbon emissions, which significantly mitigates carbon emissions.

In addition to these two factors, many others also affect the impacts of FDI inflows on carbon emissions, such as financial development, urbanization, and tourism (Tamazian et al., 2009; Lee and Brahmasrene, 2013; Sadorsky, 2014; Aller et al., 2020; Paramati et al., 2021). Moreover, Salman et al. (2019) employed a panel quantile regression to investigate the effects of imports and exports of seven of the ASEAN countries on carbon emissions, and the results show that imports and exports have a positive effect on carbon emissions, while population size negatively contributes to carbon emissions. Similarly, Dong et al. (2020) examined the effects of GDP on carbon emissions and indicated that the proportion of industrial added value to GDP negatively contributes to carbon emissions. Pao et al. (2011) also investigated the effect of the real output on carbon emissions in Russia and suggested a negative association. Besides, gross fixed capital formation is regarded as an important part of factors that decrease carbon emissions (Mitić et al., 2020).

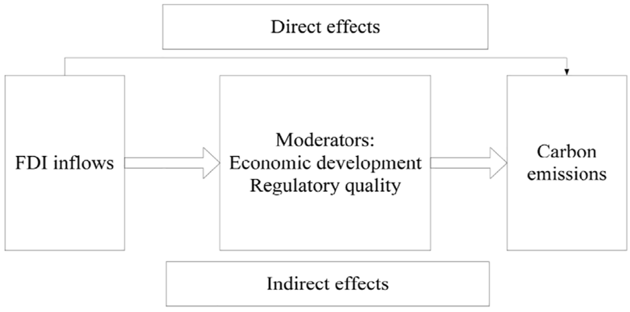


FIGURE 1 | Theoretical framework.

Literature Gap

Despite the impacts of FDI inflows on carbon emissions that have been documented in an increasing number of studies, certain research gaps remain. Firstly, despite the fact of researchers' intense focus on the deterioration of environmental quality and significant attention to the impacts of FDI inflows on carbon emissions, the related consequences are inconclusive. Secondly, in addition to the direct impacts, little literature has focused on examining the indirect effects of FDI inflows on carbon emissions, especially investigating the influence channels. Unlike previous research, this study aims to investigate the impacts of FDI inflows on carbon emissions through novel channels with the moderators of economic development and regulator quality.

METHODOLOGY AND DATA

Hypotheses

In recent years, many researchers have focused on the impacts of FDI inflows on carbon emissions, but they have not concluded a consistent insight. Moreover, little research has investigated the influence channels of the impacts of FDI inflows on carbon emissions. Therefore, this study will examine the moderating effects of economic development and regulatory quality in carbon emissions, which may provide a new explanation for the differential impact of FDI inflows on carbon emissions. **Figure 1** presents the theoretical framework of this study.

Concerning the direct impacts of FDI inflows on carbon emissions, Shahbaz et al. (2019) explored the effects of FDI inflows on carbon emissions in the United States, and the results show that FDI inflows increase carbon emissions. Although the United States is a developed country, FDI inflows have not reduced carbon dioxide emissions as expected by the EKC hypothesis. Similarly, Lau et al. (2014b) reached the same conclusion by using the panel data from Malaysia. Furthermore, Kaya et al. (2017) indicated that FDI inflows are negatively associated with carbon emissions in the short term, but they will promote Turkey's carbon emissions in the long run. Kivyiro and Arminen (2014) claimed FDI inflows appear to increase carbon emissions in six Sub-Saharan African countries. All these aforementioned studies support the pollution haven hypothesis. In this study, the G20 economies are employed as samples to explore the impacts of FDI inflows on carbon emissions. Furthermore, most economies have a large economic size and a relatively high of level industrial development. Thus, this study puts forward the following hypothesis:

Hypothesis 1. (H1). Given economic resources and other control variables, FDI inflows significantly and positively contribute to carbon emissions.

According to previous research, the EKC hypothesis is widely recognized, countries with a higher level of economic development pay more attention to environmental protection and improving environmental quality, and hence, richer countries have fewer carbon emissions. However, some studies challenged this hypothesis. Luo et al. (2016) examined the EKC hypothesis for carbon emissions in G20 countries, while the empirical results show that for developing countries, it is in line with the EKC hypothesis, but for developed countries, there is a negative association between economic development and carbon emissions. Besides, Narayan and Narayan (2010) examined the EKC hypothesis for 43 developing countries, and the results reveal that carbon emissions have fallen with economic growth in the long run. Furthermore, Narayan et al. (2016) extended the prior research sample to 118 countries and suggested that in 49 countries, with the national income growth, carbon emissions decline. Concerning the G20 economies, most have a high level of economic development. In this study, a further investigation is conducted to examine the impacts of FDI inflows on carbon emissions moderated by economic development. Thus, the hypothesis is proposed as follows:

Hypothesis 2. (H2). Economic development weakens the impacts of FDI inflows on carbon emissions, and that is, the higher level of economic development, the more likely FDI inflows to mitigate carbon emissions.

Simultaneously, Lau et al. (2014a) explored the effects of regulatory quality on carbon emissions and claimed that regulatory quality is negatively associated with carbon emissions. Besides, Ali et al. (2019) empirically supported the negative effect of regulatory quality on carbon emissions by using the dynamic panel GMM estimations. Also, other empirical results show approximately consistent conclusions (Wawrzyniak and Doryń, 2020). Moreover, Adedoyin et al. (2019) used balanced panel data over the period 1990–2014 from BRICS countries to investigate the nexus between regulatory quality and carbon emissions, indicating a positive and statistically significant association. Although a hypothesis is developed regarding the enhancing effects of FDI inflows on carbon emissions, this study does not expect that such a moderating effect may occur for carbon emissions. Nevertheless, the quality of regulations may mitigate the effects of FDI inflows on carbon emissions. Hence, this study further investigates the impacts of FDI inflows on carbon emissions moderated by regulatory quality. Thus, this paper proposes the following hypothesis:

Hypothesis 3. (H3). Regulatory quality negatively contributes to the effects of FDI inflows on carbon emissions, and that is, the higher quality level of regulations, the greater the possibility that FDI inflows decrease carbon emissions.

Model Specification

The purpose of this study is to investigate the impacts of FDI inflows on carbon emissions. Following the specifications of Chen et al. (2019), Chen et al. (2021b), the baseline model is specified as follows:

$$lnce_{it} = \alpha_0 + \alpha_1 fdipc_{it} + \sum_{j=1}^{k} \beta_j CV_{j,it} + \nu_i + \sigma_t + \varepsilon_{it} \quad (1)$$

In **Eq. 1**, *lnce* represents the dependent variable of carbon emissions, which is measured by the emissions of carbon dioxide. The independent variable of FDI inflows is denoted by *fdipc*, which is measured by the net inflows of FDI. α_0 and α_1 are the coefficients of the constant term and FDI inflows, respectively. β_j indicates the coefficient of the control variable (CV_j), and k is the number of the control variables. To produce more accurate estimates, this study incorporates all country dummies (ν_i) and year dummies (σ_t). Additionally, the disturbance term is denoted by ε_{it}. Following the specifications of Aller et al. (2020), Ali et al. (2021), the control variables (CV) incorporate the exports of goods and services (*lnexpt*), imports of goods and services (*lnimpt*), economic size (*lnrgdp*), industrial added values (*lnindv*), gross fixed capital formation (*lngcapt*), and population (*lnpop*). To be more specific, the economic size is measured by deflated GDP. Except for FDI inflows, all variables are taken in the natural logarithm forms.

In addition to an investigation of the direct impacts of FDI inflows on carbon emissions, this study also further examines the moderating effects of economic development and regulatory quality. Following the approaches of Ehigiamusoe et al. (2020), Zheng et al. (2021), the moderated regressions are specified as follows:

$$lnce_{it} = \alpha_0 + \alpha_1 fdipc_{it} + \phi edvp_{it} + \theta edvp_{it} * fdipc_{it} + \sum_{j=1}^{k}\beta_j CV_{j,it} + \nu_i + \sigma_t + \varepsilon_{it} \quad (2)$$

$$lnce_{it} = \alpha_0 + \alpha_1 fdipc_{it} + \delta rq_{it} + \gamma rq_{it} * fdipc_{it} + \sum_{j=1}^{k}\beta_j CV_{j,it} + \nu_i + \sigma_t + \varepsilon_{it} \quad (3)$$

In **Eq. 2**, *edvp* indicates the economic development, which is measured by the growth rate of GDP per capita. Also, ϕ is the coefficient of economic development. The moderating effects are specified by the interactive term (*edvp**fdipc*) of economic development and FDI inflows, and its coefficient is denoted by θ. In **Eq. 3**, this study also constructs an interactive term (*rq**fdipc*) of regulatory quality (*rq*) and FDI inflows, whose coefficient is represented by γ. Moreover, δ stands for the coefficient of regulatory quality. In terms of H2 and H3, the signs of the coefficients specific to θ and γ are expected to be statistically

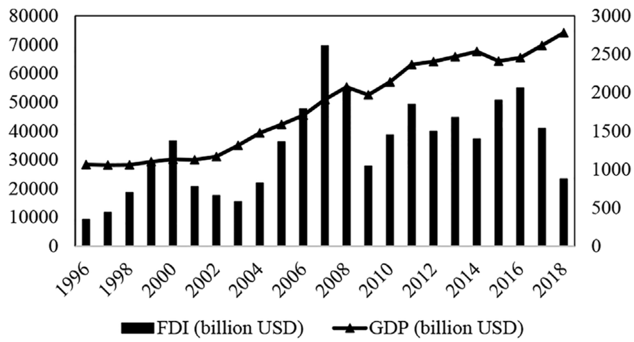


FIGURE 2 | The changing trends of FDI and GDP in G20 economies from 1996 to 2018.

negative, suggesting that economic development and regulatory quality mitigate the impacts of FDI inflows on carbon emissions.

Data Description

The panel data is collected from the World Development Indicators (WDI) and Worldwide Governance Indicators (WGI), both of the data of WDI and WGI come from the World Bank Database. In detail, the data of FDI inflows and related control variables are from WDI, and that of regulatory quality are from the WGI, respectively. To make the sample more representative, the economies of the G20 are incorporated in this study. In terms of the statistics from the World Bank, the GDP of the G20 economies accounts for more than 85% of the world's total economy, and its population exceeds two-thirds of the world's total population (See **Figure 2**). Hence, the panel data utilized in this study are strongly balanced.

To make the economies comparable, this study also includes EU member countries in the sample like other non-EU member economies. Specifically, the sample consists of 27 EU countries and 16 non-EU countries. Accordingly, France, Germany, and Italy are both EU and G20 members. Therefore, there are 43 sample countries. Moreover, the research data is from 1996 to 2018, since most of the variables used in this study have substantial missing values in 2019 and 2020. Concerning the variable of regulatory quality, the data in 1997, 1999, and 2001 are missing, which are imputed using the mean of the data in 1996 and 1998, the mean of the data in 1998 and 2000, and the mean of the data in 2000 and 2002, respectively. Moreover, the missing values of related variables in specific, such as Mexico and Canada, are filled in with the mean of the data of two consecutive years. Thus, the sample size is 989, and the panel data used in this study are balanced with 43 countries (N) and 23 years (T).

Table 1 presents the results of the statistical description. For the dependent variable of carbon emissions, the mean value is 11.7969, and the minimum and maximum values are 7.2079 and 16.1490, respectively. Simultaneously, the standard deviations of carbon emissions overall and between economies are 1.7587 and 1.7712, respectively. This implies that the differentials of carbon emissions between the G20 economies are even larger than that of all the sampling countries. Concerning the independent variable of FDI inflows, the mean, minimum and maximum values are 7.0310, −47.5108, and 366.8067, respectively. Moreover, the standard deviation is as high as 25.7191, indicating significant differences in FDI inflows among the G20 economies. Hence, it is necessary to consider the heteroscedasticity of the dependent and independent variables.

For the control variables, exports of goods and services range from 21.6049 to 28.6094 with a standard deviation of 1.4883, and the minimum and maximum values of imports of goods and services are 21.8062 and 28.7752 with a standard deviation of 1.4542. This implies that the trade between the G20 economies is frequent, and the gap between their exports is relatively large, as is the case for imports. The control variable of economic size is measured by real GDP. Its mean value is 17.4004 with minimum and maximum values of 13.1425 and 21.3932, which shows the huge gap in economic scale between the G20 economies. The standard deviation of industrial added values is 1.8508, and its minimum and maximum values are 20.6929 and 29.3376, respectively. The standard deviation of the gross fixed capital

TABLE 1 | Descriptive statistics of panel data.

Variables		Mean	Std. Dev	Min	Max
lnce	overall	11.7969	1.7587	7.2079	16.1490
	between		1.7712	7.7353	15.6199
	within		0.1605	11.1125	12.3781
fdipc	overall	7.0310	25.7191	−47.5108	366.8067
	between		13.9382	0.2350	67.1513
	within		21.7146	−82.4367	306.6864
lnexpt	overall	25.4308	1.4883	21.6049	28.6094
	between		1.3853	22.8018	28.0458
	within		0.5820	23.7428	26.6345
lnimpt	overall	25.4200	1.4542	21.8062	28.7752
	between		1.3513	22.9521	28.3107
	within		0.5739	23.7589	26.6828
lnrgdp	overall	17.4004	1.7471	13.1425	21.3932
	between		1.7333	13.6521	21.1639
	within		0.3386	15.5111	19.6197
lnindv	overall	25.0518	1.8508	20.6929	29.3376
	between		1.8148	21.0114	28.6434
	within		0.4534	23.6298	26.3104
lngcapt	overall	24.9108	1.8130	20.1206	29.4144
	between		1.7549	21.1207	28.6703
	within		0.5251	22.5094	26.3940
lnpop	overall	16.7955	1.8448	12.8477	21.0545
	between		1.8645	12.9310	20.9953
	within		0.0644	16.5128	17.0842
edvp	overall	0.0251	0.0366	−0.1435	0.2400
	between		0.0165	0.0035	0.0840
	within		0.0327	−0.1688	0.2214
rq	overall	0.9062	0.6961	−1.0743	2.0980
	between		0.6809	−0.4441	1.8456
	within		0.1770	0.2483	1.9212

Notes: The number of observations is 989, as well as the N and T, are 43 and 23, respectively.

TABLE 2 | Results of regressions on carbon emissions.

Variables	(1)	(2)	(3)	(4)
fdipc			0.0002***	0.0003***
			(0.0001)	(0.0000)
lnexpt	−0.3140***	−0.1753***	−0.3124***	−0.1682***
	(0.0103)	(0.0078)	(0.0102)	(0.0085)
lnimpt	0.0557***	0.3288***	0.0531***	0.3230***
	(0.0124)	(0.0098)	(0.0124)	(0.0105)
lnrgdp	−0.0159***	−0.0755***	−0.0157***	−0.0757***
	(0.0027)	(0.0023)	(0.0027)	(0.0021)
lnindv	0.5029***	0.2808***	0.5041***	0.2801***
	(0.0124)	(0.0089)	(0.0124)	(0.0068)
lngcapt	−0.0875***	−0.0906***	−0.0878***	−0.0867***
	(0.0098)	(0.0075)	(0.0097)	(0.0079)
lnpop	1.1027***	0.9687***	1.1033***	0.9568***
	(0.0129)	(0.0113)	(0.0130)	(0.0112)
Constant	−10.3700***	−11.8700***	−10.3791***	−11.7585***
	(0.2180)	(0.2324)	(0.2186)	(0.2364)
Country dummies	Yes	Yes	Yes	Yes
Year dummies	No	Yes	No	Yes
N	989	989	989	989
Prob. > Chi^2	0.0000	0.0000	0.0000	0.0000

*Notes: The data in parentheses are heteroskedastic and correlated errors. Moreover, *, ** and *** denote 10, 5, and 1% significance level, respectively.*

formation and population are 1.8130 and 1.8448, suggesting significant differences in the G20 economies. For the moderating variables, the average growth rate of GDP per capita is 2.51%, and minimum and maximum values are −14.35 and 24.00%. Additionally, the mean value of regulatory quality is 0.9062 with a standard deviation of 0.6961. Therefore, regardless of the control variables and moderating variables of the G20 economies, there are significant differences among countries, which means that the heteroscedasticity needs to be considered as well.

EMPIRICAL RESULTS

Results of Baseline Estimations

Utilizing the panel data over the period of 1996–2018 for the G20 economies, this study aims to investigate the impacts of FDI inflows on carbon emissions as well as the moderating effects of economic development and regulatory quality. To produce more robust estimates, whether to utilize the regressions of the pooled ordinary least squares (POLS), random-effect (RE), and fixed-effect (FE) are verified in detail. For the selection of estimation approaches of the POLS and FE regression, an F test specific to all the intercept terms is employed. The result displays that F (42, 939) = 229.4500, and thereby rejects the null hypothesis at a significance of 1%. Hence, compared with the POLS regression, FE regression is more appropriate in this study. Simultaneously, concerning the selection of regression methods of the FE and RE regression, a Hausman test is utilized, and the result suggests that Chi^2 (6) = 40.3300 with a *p*-value of 0.0000, indicating that the RE regression is inadequate in this study. Thus, this study utilizes the approach of the FE regression to evaluate the impacts of FDI inflows on carbon emissions. Furthermore, the serial correlation of the panel data in this study is checked by using the Wooldridge test. The result shows that F (1, 42) = 103.1460, and the null hypothesis of no first-order autocorrelation is statistically rejected at a significance of 1%. In addition to the heteroscedasticity, the heteroskedastic and correlated errors need to be specified. Additionally, to produce more accurate estimation results, the approach of the feasible generalized least squares (FGLS) is utilized in all estimates.

Table 2 displays the results of baseline estimations. In Columns (1) and (2), all control variables are entered. Due to significant differences among the G20 economies, the country dummies are added in all estimates. In Columns (1) and (3), the year dummies are excluded. To eliminate the estimation bias, this study includes year dummies in subsequent estimates. According to the estimation results, the coefficients of the exports of goods and services (*lnexpt*) are significantly negative, which implies that the more a country exports, the less carbon it emits. In terms of Melitz (2003), only countries with higher technological levels and productivity can be more competitive in the international trade market and can export more goods. The results show a statistically positive association between the imports of goods and services (*lnimpt*) and carbon emissions, which is consistent with Ali et al. (2021). Moreover, the results display that the real GDP (*lnrgdp*) and gross fixed capital formation (*lngcapt*) are positive to decrease carbon emissions. Although there are some developing countries in the G20 economies, most of them have a high level of income. The larger the economic size of a country as well as the more fixed capital investment, the more it can improve production technology and environmental regulations, and thereby mitigate carbon emissions, which is as expected in the EKC hypothesis (Aller et al., 2020). Similar to the impacts of exports on carbon emissions, the results also indicate a significantly positive nexus of industrial added value (*lnindv*) and population (*lnpop*) specific to carbon emissions. The provision of industrial products requires more energy consumption, which in turn needs to emit more carbon. Similarly, the larger the population, the more energy is consumed, and thereby the more carbon dioxide is produced, which is consistent with Chen et al. (2021a).

In Columns (3) and (4) of **Table 2**, the independent variable of FDI inflows (*fdipc*) is incorporated. In terms of the estimation results, the coefficients of FDI inflows are significant and positive, indicating that FDI inflows contribute to the increase of carbon emissions. FDI inflows have attracted international investment from multinational companies and big polluting companies, and it also increases carbon emissions (Acharyya, 2009). Concerning most G20 economies, they have a large population and complete infrastructure, which can provide sufficient labor and a mature investment environment for FDI inflows. Compared with countries with small economies, the G20 economies have created more than 85% of the world's GDP and also emit a large amount of carbon dioxide. Simultaneously, in terms of statistics from the World Bank, FDI flowing into the G20 economies accounted for more than 60% in 2019. Thus, the results are as hypothesized in H1.

Robustness Check

To produce more robust and unbiased estimation results, a comprehensive robustness check is performed. Firstly, the

TABLE 3 | Results of robustness check.

Variables	(1)	(2)	(3)	(4)
L.*lnce*				0.9194***
				(0.0573)
L2.*lnce*				0.0811
				(0.0568)
fdipc	0.0003**	0.0003**	0.0004***	0.0001***
	(0.0002)	(0.0001)	(0.0000)	(0.0000)
lnexpt	−0.0952**	−0.4287***	0.0103	−0.0641
	(0.0483)	(0.0637)	(0.0086)	(0.0459)
lnimpt	0.3166***	0.5848***	0.0379***	0.1816***
	(0.0579)	(0.0797)	(0.0094)	(0.0443)
lnrgdp	−0.0488***	0.2773***	0.0419***	−0.0204
	(0.0130)	(0.0799)	(0.0044)	(0.0318)
lnindv	0.3204***	0.3283***	0.0811***	0.0319
	(0.0453)	(0.0604)	(0.0063)	(0.0472)
lngcapt	−0.1262***	−0.3359***	−0.0065	−0.0050
	(0.0370)	(0.0525)	(0.0049)	(0.0477)
lnpop	1.4672***	0.5437***	0.2647***	0.9189***
	(0.0696)	(0.1387)	(0.0211)	(0.2538)
Constant	−26.2053***	−6.1919***	2.4548***	0.0225
	(1.5983)	(1.9812)	(0.3413)	(0.0551)
Country dummies	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes
N	989	549	667	903
adj. R^2	0.9961	0.9540		
Prob. > Chi^2			0.0000	0.0000

*Notes: *, ** and *** denote 10, 5, and 1% significance level, respectively. In Columns (1) and (2), the approaches of the LSDV regression and panel data with the FE regression are utilized, respectively, and the data in parentheses are standard errors. In Column (3) the method of the panel-data linear regression by using the FGLS is performed and the data in parentheses are heteroskedastic and correlated errors. In Column (4), the dynamic GMM estimation is used, and the data in paratheses are robust standard errors.*

alternative regression approach of the least squares dummy variable (LSDV) is utilized. The second method is to re-estimate the model with samples of higher than average GDP per capita. Since the approach of the FGLS is only available for the balanced panel data, this study employs the method of the panel data with the FE regression. Thirdly, this study re-estimates the model with sampling countries from the EU. In Columns (1) to (3) of **Table 3**, the results of the first three methods to check the estimation robustness are presented, respectively. The results indicate that the coefficients of FDI inflows remain statistically positive, and most of the control variables are also as expected.

Additionally, this study utilizes the approach of the dynamic generalized method of moments (GMM) estimation to eliminate the estimation bias caused by the endogeneity between FDI inflows and carbon emissions. This study enters the first- and second-order lag terms of the dependent variable of FDI inflows in Column (4). To verify whether the GMM estimator is consistent, the Arellano–Bond test is utilized, and the null hypothesis is that there is no second-order autocorrelation of the disturbance term. The results indicate that the statistic $z = -1.1700$ and the p-value is 0.2430, which means that the null hypothesis can not be statistically rejected. Thus, the GMM estimator used in this study is consistent. Moreover, this study also conducts a Sargan test to verify whether there are excessive instrumental variables. The null hypothesis of the Sargan test is that the instrumental variables are appropriate. The results reveal that the Chi^2 (808) = 847.2000, and the p-value is 0.1640, which implies that the null hypothesis can not be rejected. Furthermore, the difference GMM is utilized in this study, and the results are reported in Column (4) of **Table 3**. The results show that FDI inflows still make a positive contribution to carbon emissions, and the signs of most control variables remain unchanged. Therefore, the results of the robustness check are still consistent with H1.

FURTHER DISCUSSIONS

To examine the influence channels of FDI inflows on carbon emissions, this study firstly investigates the moderating effect of economic development. Columns (1) to (3) of **Table 4** present the moderated regression results of economic development. The results indicate that all the three coefficients of FDI inflows are positive at a significance of 1%. In Column (2), the variable of economic development (*edvp*) is incorporated. The results show that the higher level of economic development, the lower the carbon emissions. The results are consistent with the EKC hypothesis. In addition to the specification of Column (2), this study incorporates the interactive term of economic development and FDI inflows (*edvp*fdipc*) in Column (3). The results suggest that the coefficient of the interactive term is significantly negative, which implies that economic development mitigates the impacts of FDI inflows on carbon emissions. In terms of the EKC hypothesis, there is an inverted U-shaped association between income and environmental pollution, as is the case for economic development and carbon emissions. If a country reaches a high economic development level, it will pay more attention to sustainable and green development, and thereby introducing environmentally friendly FDI and decreasing carbon emissions. Thus, the results are as hypothesized in H2.

To further investigate the moderating effects of regulatory quality specific to the impacts of FDI inflows on carbon emissions, this study constructs an interactive term of regulatory quality and FDI inflows (*rq*fdipc*), which is entered in Column (5) of **Table 4**. Meanwhile, the variable f regulatory quality (*rq*) is included in Columns (4) and (5). The results show that the coefficients of FDI inflows are positive, with a significance of 1%. The results are consistent with those of Hassan et al. (2021), in which regulatory quality with lower political risk is considered to be positive to mitigate carbon emissions. As mentioned in H3, regulatory quality is statistically and negatively associated with carbon emissions. Furthermore, the coefficient of the interactive term in Column (5) is significantly negative, which reveals that a higher quality level of regulations, the greater the possibility that FDI inflows decrease carbon emissions. With the improvement of regulatory quality, more attention has been paid to reducing the negative impact on the environment when introducing FDI, and thereby reducing carbon emissions. Thus, H3 is well verified.

TABLE 4 | Results of moderating effects from economic development and regulatory quality.

	(1)	(2)	(3)	(4)	(5)
fdipc	0.0003***	0.0003***	0.0004***	0.0003***	0.0008***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0001)
edvp		−0.0871***	−0.0701***		
		(0.0248)	(0.0260)		
*edvp*fdipc*			−0.0011***		
			(0.0004)		
rq				−0.0832***	−0.0871***
				(0.0041)	(0.0043)
*rq*fdipc*					−0.0004***
					(0.0001)
lnexpt	−0.1682***	−0.1623***	−0.1614***	−0.1997***	−0.1908***
	(0.0085)	(0.0098)	(0.0096)	(0.0083)	(0.0079)
lnimpt	0.3230***	0.3221***	0.3211***	0.3613***	0.3561***
	(0.0105)	(0.0111)	(0.0109)	(0.0076)	(0.0109)
lnrgdp	−0.0757***	−0.0779***	−0.0777***	−0.0589***	−0.0604***
	(0.0021)	(0.0023)	(0.0024)	(0.0019)	(0.0024)
lnindv	0.2801***	0.2754***	0.2764***	0.2821***	0.2768***
	(0.0068)	(0.0071)	(0.0071)	(0.0087)	(0.0084)
lngcapt	−0.0867***	−0.0826***	−0.0834***	−0.0879***	−0.0781***
	(0.0079)	(0.0083)	(0.0082)	(0.0058)	(0.0076)
lnpop	0.9568***	0.9531***	0.9525***	0.9496***	0.9397***
	(0.0112)	(0.0119)	(0.0118)	(0.0113)	(0.0115)
Constant	−11.7585***	−11.7698***	−11.7637***	−12.0783***	−12.0837***
	(0.2364)	(0.2436)	(0.2433)	(0.2195)	(0.2417)
Country dummies	Yes	Yes	Yes	Yes	Yes
Year dummies	Yes	Yes	Yes	Yes	Yes
N	989	989	989	989	989
Prob. > Chi^2	0.0000	0.0000	0.0000	0.0000	0.0000

*Notes: The data in parentheses are heteroskedastic and correlated errors. Moreover, *, ** and *** denote 10, 5 and 1% significance level, respectively.*

CONCLUSION AND IMPLICATIONS

With the rapid development of the world economy, the issue of climate change has become the limitation of further sustainable economic growth. Economic globalization has promoted the cross-border flows of international capital, and FDI inflows have played a vital role in the economic activities of various countries, as well as carbon emissions. With the promotion of sustainable development strategies, increasingly more countries are beginning to pay attention to environmental protection, especially developed countries who are active to construct the friendly nexus between economic development and environmental sustainability. In this context, many economies have formulated a series of measures to regulate FDI activities, reduce pollutant emissions, and thereby achieve the goal of environmental protection. In this study, panel data of the G20 economies from 1996 to 2018 are utilized to investigate the direct impacts of FDI inflows on carbon emissions. Simultaneously, the influence channels that the moderating effects of economic development and regulatory quality are explored. To produce more robust and accurate estimates, this study performs regressions by utilizing the approach of the FGLS and specifies the heteroskedastic and correlated errors. The results indicate that FDI inflows positively contribute to carbon emissions, which implies that with the increasing inflows of FDI, the G20 economies emit more carbon dioxide. Concerning the influence channels, the results suggest that both economic development and regulatory quality mitigate the impacts of FDI inflows on carbon emissions. It implies that with a higher development level of the G20 economies, FDI inflows are more likely to decrease carbon emissions. Simultaneously, with a higher quality level of regulations in the G20 economies, the inflows of FDI positively decrease carbon emissions.

The findings of this study identify vital policy implications in enhancing FDI inflows, accelerating economic development, and improving regulatory quality to decrease carbon emissions and further eliminate environmental degradation. Meanwhile, the policy recommendations of this study also have important insights on the emission of pollutants other than carbon dioxide. First, countries are recommended to develop a sustainable economy. Although FDI inflows have been demonstrated to be positive to economic growth, they may degrade the environment, thereby reducing the quality of economic development. In this study, FDI inflows are positively associated with carbon emissions. However, for the high development level of the G20 economies, FDI inflows, in turn, decrease their carbon emissions. Therefore, it is crucial for a country to pay more attention to the quality of economic development, which helps mitigate carbon emissions caused by inflows of FDI. Second, policymakers are encouraged to formulate effective measures to improve the quality of regulations specific to pollution emissions. In light of the empirical results, although FDI inflows are positive to increase carbon emissions, regulatory quality negatively mitigates the impacts of FDI inflows on carbon emissions. Hence, it is crucial for a country to enhance environmental regulations when introducing FDI to develop its economy.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

YH contributed to conceptualization. YH and FC contributed to data curation and writing. HW contributed to formal analysis. YH and FC contributed to funding acquisition. JX contributed to methodology. ZX and RA contributed to proofreading and editing. All authors contributed to the article and approved the submitted version.

FUNDING

The authors acknowledge the financial support of Huaqiao University's Academic Project Supported by the Fundamental Research Funds for the Central Universities (20SKGC-QT01).

REFERENCES

Acharyya, J. (2009). FDI, Growth and the Environment: Evidence from India on CO2 Emission during the Last Two Decades. *J. Econ. Dev.* 34 (1), 43–58. doi:10.35866/caujed.2009.34.1.003

Adedoyin, F. F., Gumede, M. I., Bekun, F. V., Etokakpan, M. U., and Balsalobre-Lorente, D. (2019). Modelling Coal Rent, Economic Growth and CO2 Emissions: Does Regulatory Quality Matter in BRICS Economies? *Sci. Total Environ.* 710, 136284. doi:10.1016/j.scitotenv.2019.136284

Ahmad, M., Ul Haq, Z., Khan, Z., Khattak, S. I., Ur Rahman, Z., and Khan, S. (2019). Does the Inflow of Remittances Cause Environmental Degradation? Empirical Evidence from China. *Econ. Research-Ekonomska Istraživanja* 32 (1), 2099–2121. doi:10.1080/1331677X.2019.1642783

Ahmad, N., and Wyckoff, A. (2003). Carbon Dioxide Emissions Embodied in International Trade of Goods. *OECD Sci. Tech. Industry Working Pap.* 25 (4), 1–22. doi:10.1787/18151965

Al-Mulali, U., Ozturk, I., and Lean, H. H. (2015). The Influence of Economic Growth, Urbanization, Trade Openness, Financial Development, and Renewable Energy on Pollution in Europe. *Nat. Hazards* 79 (1), 621–644. doi:10.1007/s11069-015-1865-9

Ali, H. S., Zeqiraj, V., Lin, W. L., Law, S. H., Yusop, Z., Bare, U. A. A., et al. (2019). Does Quality Institutions Promote Environmental Quality? *Environ. Sci. Pollut. Res.* 26, 10446–10456. doi:10.1007/s11356-019-04670-9

Ali, S., Dogan, E., Chen, F., and Khan, Z. (2021). International Trade and Environmental Performance in Top Ten-emitters Countries: The Role of Eco-innovation and Renewable Energy Consumption. *Sust. Dev.* 29 (2), 378–387. doi:10.1002/sd.2153

Aller, C., Ductor, L., and Grechyna, D. (2021). Robust Determinants of CO2 Emissions. *Energ. Econ.* 96, 105154. doi:10.1016/j.eneco.2021.105154

Alshubiri, F., and Elheddad, M. (2019). Foreign Finance, Economic Growth and CO2 Emissions Nexus in OECD Countries. *Ijccsm* 12 (2), 161–181. doi:10.1108/IJCCSM-12-2018-0082

Apergis, N. (2016). Environmental Kuznets Curves: New Evidence on Both Panel and Country-Level CO2 Emissions. *Energ. Econ.* 54 (2), 263–271. doi:10.1016/j.eneco.2015.12.007

Aslanidis, N., and Iranzo, S. (2009). Environment and Development: Is There a Kuznets Curve for CO2emissions? *Appl. Econ.* 41 (6), 803–810. doi:10.1080/00036840601018994

Azomahou, T., Laisney, F., and Nguyen Van, P. (2006). Economic Development and CO2 Emissions: A Nonparametric Panel Approach. *J. Public Econ.* 90 (6), 1347–1363. doi:10.1016/j.jpubeco.2005.09.005

Ben Kheder, S., and Zugravu, N. (2012). Environmental Regulation and French Firms Location Abroad: An Economic Geography Model in an International Comparative Study. *Ecol. Econ.* 77, 48–61. doi:10.1016/j.ecolecon.2011.10.005

Bommer, R. (1999). Environmental Policy and Industrial Competitiveness: The Pollution-Haven Hypothesis Reconsidered. *Rev. Int. Econ.* 7 (2), 342–355. doi:10.1111/1467-9396.00168

Bose, S., and Kohli, B. (2018). Study of FDI Trends and Patterns in BRICS Economies during the Period 1990-2015. *Emerging Economy Stud.* 4 (1), 78–101. doi:10.1177/2394901518769225

Chen, F., Hussain, M., Khan, J. A., Mir, G. M., and Khan, Z. (2021a). Voluntary Disclosure of Greenhouse Gas Emissions by Cities under Carbon Disclosure Project: A Sustainable Development Approach. *Sust. Dev.* 29 (4), 719–727. doi:10.1002/sd.2169

Chen, F., Jiang, G., and Kitila, G. M. (2021b). Trade Openness and CO2 Emissions: The Heterogeneous and Mediating Effects for the Belt and Road Countries. *Sustainability* 13 (4), 1958. doi:10.3390/su13041958

Chen, F., Jiang, G., and Wang, W. (2019). Institutional Quality and its Impact on the Facilitation of Foreign Direct Investment: Empirical Evidence from the Belt and Road Countries. *Jcefts* 12 (3), 167–188. doi:10.1108/JCEFTS-07-2019-0041

Cole, M. A. (2007). Corruption, Income and the Environment: An Empirical Analysis. *Ecol. Econ.* 62 (3), 637–647. doi:10.1016/j.ecolecon.2006.08.003

Cole, M. A., Elliott, R. J. R., and Fredriksson, P. G. (2006). Endogenous Pollution Havens: Does FDI Influence Environmental Regulations? *Scand. J. Econ.* 108, 157–178. doi:10.1111/j.1467-9442.2006.00439.x

Cole, M. A., Elliott, R. J. R., and Zhang, J. (2011). Growth, Foreign Direct Investment, and the Environment: Evidence from Chinese Cities. *J. Reginal Sci.* 51 (1), 121–138. doi:10.1111/j.1467-9787.2010.00674.x

Cole, M. A. (2004). Trade, the Pollution haven Hypothesis and the Environmental Kuznets Curve: Examining the Linkages. *Ecol. Econ.* 48 (1), 71–81. doi:10.1016/j.ecolecon.2003.09.007

Damania, R., Fredriksson, P. G., and List, J. A. (2003). Trade Liberalization, Corruption, and Environmental Policy Formation: Theory and Evidence. *J. Environ. Econ. Manag.* 46 (3), 490–512. doi:10.1016/S0095-0696(03)00025-1

Dong, B., Ma, X., Zhang, Z., Zhang, H., Chen, R., Song, Y., et al. (2020). Carbon Emissions, the Industrial Structure and Economic Growth: Evidence from Heterogeneous Industries in China. *Environ. Pollut.* 262, 114322. doi:10.1016/j.envpol.2020.114322

Dong, K., Ren, X., and Zhao, J. (2021). How Does Low-Carbon Energy Transition Alleviate Energy Poverty in China? A Nonparametric Panel Causality Analysis. *Energ. Econ.* 103, 105620. doi:10.1016/j.eneco.2021.105620

Dutt, K. (2009). Governance, Institutions and the Environment-Income Relationship: A Cross-Country Study. *Environ. Dev. Sustain.* 11 (4), 705–723. doi:10.1007/s10668-007-9138-8

Ehigiamusoe, K. U., Lean, H. H., and Smyth, R. (2020). The Moderating Role of Energy Consumption in the Carbon Emissions-Income Nexus in Middle-Income Countries. *Appl. Energ.* 261, 114215. doi:10.1016/j.apenergy.2019.114215

Grimes, P., and Kentor, J. (2003). Exporting the Greenhouse: Foreign Capital Penetration and CO2 Emissions 1980–1996. *Jwsr* 9 (2), 261–275. doi:10.5195/jwsr.2003.244

Grossman, G., and Krueger, A. (1992). *Environmental Impacts of a North American Free Trade Agreement*. NBER Working Paper No. 3914. Cambridge: National Bureau Of Economic Research. doi:10.3386/w3914

Grossman, G. M., and Krueger, A. B. (1995). Economic Growth and the Environment. *Q. J. Econ.* 110 (2), 353–377. doi:10.2307/2118443

Harbaugh, W. T., Levinson, A., and Wilson, D. M. (2002). Reexamining the Empirical Evidence for an Environmental Kuznets Curve. *Rev. Econ. Stat.* 84 (3), 541–551. doi:10.1162/003465302320259538

Hassan, T., Song, H., and Kirikkaleli, D. (2021). International Trade and Consumption-Based Carbon Emissions: Evaluating the Role of Composite Risk for RCEP Economies. *Environ. Sci. Pollut. Res.*, 1–13. doi:10.1007/s11356-021-15617-4

Herrera-Echeverri, H., Haar, J., and Estévez-Bretón, J. B. (2014). Foreign Direct Investment, Institutional Quality, Economic freedom and Entrepreneurship in Emerging Markets. *J. Business Res.* 67 (9), 1921–1932. doi:10.1016/j.jbusres.2013.11.020

Ibrahim, M. H., and Law, S. H. (2015). Institutional Quality and CO2Emission-Trade Relations: Evidence from Sub-saharan Africa. *South Afr. J. Econ.* 84 (2), 323–340. doi:10.1111/saje.12095

Kaya, G., Özgür Kayalica, M., Kumaş, M., and Ulengin, B. (2017). The Role of Foreign Direct Investment and Trade on Carbon Emissions in Turkey. *Environ. Econ.* 8 (1), 8–17. doi:10.21511/ee.08(1).2017.01

Kivyiro, P., and Arminen, H. (2014). Carbon Dioxide Emissions, Energy Consumption, Economic Growth, and Foreign Direct Investment: Causality Analysis for Sub-saharan Africa. *Energy* 74, 595–606. doi:10.1016/j.energy.2014.07.025

Lacis, A. A., Schmidt, G. A., Rind, D., and Ruedy, R. A. (2010). Atmospheric CO2: Principal Control Knob Governing Earth's Temperature. *Science* 330 (6002), 356–359. doi:10.1126/science.1190653

Lau, L.-S., Choong, C.-K., and Eng, Y.-K. (2014a). Carbon Dioxide Emission, Institutional Quality, and Economic Growth: Empirical Evidence in Malaysia. *Renew. Energ.* 68, 276–281. doi:10.1016/j.renene.2014.02.013

Lau, L.-S., Choong, C.-K., and Eng, Y.-K. (2014b). Investigation of the Environmental Kuznets Curve for Carbon Emissions in Malaysia: Do Foreign Direct Investment and Trade Matter? *Energy Policy* 68, 490–497. doi:10.1016/j.enpol.2014.01.002

Lee, C.-C., Chiu, Y.-B., and Sun, C.-H. (2009). Does One Size Fit All? A Reexamination of the Environmental Kuznets Curve Using the Dynamic Panel Data Approach. *Rev. Agr Econ.* 31 (4), 751–778. doi:10.1111/j.1467-9353.2009.01465.x

Lee, J. W., and Brahmasrene, T. (2013). Investigating the Influence of Tourism on Economic Growth and Carbon Emissions: Evidence from Panel Analysis of the European Union. *Tourism Manag.* 38, 69–76. doi:10.1016/j.tourman.2013.02.016

Luo, G., Weng, J.-H., Zhang, Q., and Hao, Y. (2016). A Reexamination of the Existence of Environmental Kuznets Curve for CO2 Emissions: Evidence from G20 Countries. *Nat. Hazards* 85, 1023–1042. doi:10.1007/s11069-016-2618-0

Mahadevan, R., and Sun, Y. (2020). Effects of Foreign Direct Investment on Carbon Emissions: Evidence from China and its Belt and Road Countries. *J. Environ. Manage.* 276, 111321. doi:10.1016/j.jenvman.2020.111321

Melane-Lavado, A., Álvarez-Herranz, A., and González-González, I. (2018). Foreign Direct Investment as a Way to Guide the Innovative Process towards Sustainability. *J. Clean. Prod.* 172, 3578–3590. doi:10.1016/j.jclepro.2017.03.131

Melitz, M. J. (2003). The Impact of Trade on Intra-industry Reallocations and Aggregate Industry Productivity. *Econometrica* 71 (6), 1695–1725. doi:10.1111/1468-0262.00467

Mitić, P., Kostić, A., Petrović, E., and Cvetanovic, S. (2020). The Relationship between CO2 Emissions, Industry, Services and Gross Fixed Capital Formation in the Balkan Countries. *Ee* 31 (4), 425–436. doi:10.5755/j01.ee.31.4.24833

Musah, M., Kong, Y., and Vo, X. V. (2021). Predictors of Carbon Emissions: An Empirical Evidence from NAFTA Countries. *Environ. Sci. Pollut. Res.* 28, 11205–11223. doi:10.1007/s11356-020-11197-x

Nair-Reichert, U., and Weinhold, D. (2001). Causality Tests for Cross-Country Panels: A New Look at FDI and Economic Growth in Developing Countries. *Oxford Bull. Econ. Stat.* 63 (2), 153–171. doi:10.1111/1468-0084.00214

Narayan, P. K., and Narayan, S. (2010). Carbon Dioxide Emissions and Economic Growth: Panel Data Evidence from Developing Countries. *Energy Policy* 38 (1), 661–666. doi:10.1016/j.enpol.2009.09.005

Narayan, P. K., Saboori, B., and Soleymani, A. (2016). Economic Growth and Carbon Emissions. *Econ. Model.* 53, 388–397. doi:10.1016/j.econmod.2015.10.027

Özokcu, S., and Özdemir, Ö. (2017). Economic Growth, Energy, and Environmental Kuznets Curve. *Renew. Sust. Energ. Rev.* 72, 639–647. doi:10.1016/j.rser.2017.01.059

Panayotou, T., Peterson, A., and Sachs, J. (2000). *Is the Environmental Kuznets Curve Driven by Structural Change? what Extended Time Series May Imply for Developing Countries*. CAER II Discussion Paper 80. Cambridge, USA: Harvard Institute for International Development. doi:10.7916/D8CV4QJF

Pao, H.-T., Yu, H.-C., and Yang, Y.-H. (2011). Modeling the CO2 Emissions, Energy Use, and Economic Growth in Russia. *Energy* 36 (8), 5094–5100. doi:10.1016/j.energy.2011.06.004

Paramati, S. R., Mo, D., and Huang, R. (2021). The Role of Financial Deepening and green Technology on Carbon Emissions: Evidence from Major OECD Economies. *Finance Res. Lett.* 41, 101794. doi:10.1016/j.frl.2020.101794

Perera, L. D. H., and Lee, G. H. Y. (2013). Have Economic Growth and Institutional Quality Contributed to Poverty and Inequality Reduction in Asia? *J. Asian Econ.* 27, 71–86. doi:10.1016/j.asieco.2013.06.002

Rahman, Z. U., Chongbo, W., and Ahmad, M. (2019). An (A)symmetric Analysis of the Pollution haven Hypothesis in the Context of Pakistan: A Non-linear Approach. *Carbon Manag.* 10 (3), 227–239. doi:10.1080/17583004.2019.1577179

Ren, X., Cheng, C., Wang, Z., and Yan, C. (2021). Spillover and Dynamic Effects of Energy Transition and Economic Growth on Carbon Dioxide Emissions for the European Union: A Dynamic Spatial Panel Model. *Sust. Dev.* 29, 228–242. doi:10.1002/sd.2144

Sadorsky, P. (2014). The Effect of Urbanization on CO2 Emissions in Emerging Economies. *Energ. Econ.* 41, 147–153. doi:10.1016/j.eneco.2013.11.007

Salman, M., Long, X., Dauda, L., Mensah, C. N., and Muhammad, S. (2019). Different Impacts of export and Import on Carbon Emissions across 7 ASEAN Countries: A Panel Quantile Regression Approach. *Sci. Total Environ.* 686, 1019–1029. doi:10.1016/j.scitotenv.2019.06.019

Shafik, N. (1994). Economic Development and Environmental Quality: An Econometric Analysis. *Oxford Econ. Pap.* 46 (Suppl. ment_1), 757–773. doi:10.1093/oep/46.Supplement_1.757

Shahbaz, M., Gozgor, G., Adom, P. K., and Hammoudeh, S. (2019). The Technical Decomposition of Carbon Emissions and the Concerns about FDI and Trade Openness Effects in the United States. *Int. Econ.* 159, 56–73. doi:10.1016/j.inteco.2019.05.001

Shahbaz, M., Nasreen, S., Abbas, F., and Anis, O. (2015). Does Foreign Direct Investment Impede Environmental Quality in High-, Middle-, and Low-Income Countries? *Energ. Econ.* 51, 275–287. doi:10.1016/j.eneco.2015.06.014

Tamazian, A., Chousa, J. P., and Vadlamannati, K. C. (2009). Does Higher Economic and Financial Development lead to Environmental Degradation: Evidence from BRIC Countries. *Energy Policy* 37 (1), 246–253. doi:10.1016/j.enpol.2008.08.025

Wang, Y., Liao, M., Wang, Y., Xu, L., and Malik, A. (2021). The Impact of Foreign Direct Investment on China's Carbon Emissions through Energy Intensity and Emissions Trading System. *Energ. Econ.* 97, 105212. doi:10.1016/j.eneco.2021.105212

Wawrzyniak, D., and Doryń, W. (2020). Does the Quality of Institutions Modify the Economic Growth-Carbon Dioxide Emissions Nexus? Evidence from a Group of Emerging and Developing Countries. *Econ. Research-Ekonomska Istraživanja* 33 (1), 124–144. doi:10.1080/1331677X.2019.1708770

Welsch, H. (2004). Corruption, Growth, and the Environment: A Cross-Country Analysis. *Envir. Dev. Econ.* 9 (5), 663–693. doi:10.1017/S1355770X04001500

Wheeler, D. (1999). Racing to the Bottom? Foreign Investment and Air Pollution in Developing Countries. *J. Environ. Dev.* 10 (3), 225–245. doi:10.1596/1813-9450-2524

Zeng, K., and Eastin, J. (2012). Do developing Countries Invest up? the Environmental Effects of Foreign Direct Investment from Less-Developed Countries. *World Dev.* 40 (11), 2221–2233. doi:10.1016/j.worlddev.2012.03.008

Zheng, S., Wang, R., Mak, T. M. W., Hsu, S.-C., and Tsang, D. C. W. (2021). How Energy Service Companies Moderate the Impact of Industrialization and Urbanization on Carbon Emissions in China? *Sci. Total Environ.* 751, 141610. doi:10.1016/j.scitotenv.2020.141610

Zhu, H., Duan, L., Guo, Y., and Yu, K. (2016). The Effects of FDI, Economic Growth and Energy Consumption on Carbon Emissions in ASEAN-5: Evidence from Panel Quantile Regression. *Econ. Model.* 58, 237–248. doi:10.1016/j.econmod.2016.05.003

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: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 21 January 2022
doi: 10.3389/fenrg.2021.821677

The Effect of China's Pilot Low-Carbon City Initiative on Enterprise Labor Structure

Xiaoyang Sun[1], *Yuhua Zheng*[2]*, *Chenyu Zhang*[2], *Xuelian Li*[2] *and Baosheng Wang*[2]

[1]*School of Economics and Management, China University of Labor Relations, Beijing, China,* [2]*Business School, Beijing Technology and Business University, Beijing, China*

Based on the background of China's pilot low-carbon city initiative in 2010, 2012, and 2017, this article captures the exogenous change of enterprise labor structure based on A-share listed companies from 2007 to 2019 in Shenzhen and Shanghai Stock exchanges. With the integration of macro data on the city level and micro data on the enterprise level, adopting the time-varying difference-in-differences (DID) model, we found that 1) China's pilot low-carbon city initiative can significantly promote the upgrading of enterprise labor structure; 2) China's pilot low-carbon city initiative can significantly increase R&D investment of listed companies, suggesting that R&D investment is a channel for the impact of China's pilot low-carbon city initiative on enterprise labor structure in the pilot cities; 3) the heterogeneity analysis shows that the labor structure of the state-owned listed companies has been optimized significantly, while the labor structure of the non–state-owned listed companies is not significant. Meanwhile, the labor structure of the listed companies under high-quality government control has been optimized significantly, while the labor structure of the listed companies under low-quality government control is not significant. Overall, our study shows that the pilot low-carbon city initiative has played a governance role in China and optimized enterprise labor structure.

Keywords: China, low-carbon city, labor structure, R&D investment, difference-in-differences

OPEN ACCESS

Edited by:
Kangyin Dong,
University of International Business and Economics, China

Reviewed by:
Minghao Zhuang,
China Agricultural University, China
Liu Guixian,
Tsinghua University, China
Suli Hao,
China University of Mining and Technology-Beijing, China

***Correspondence:**
Yuhua Zheng
zhengyuhua@btbu.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *24 November 2021*
Accepted: *22 December 2021*
Published: *21 January 2022*

Citation:
Sun X, Zheng Y, Zhang C, Li X and Wang B (2022) The Effect of China's Pilot Low-Carbon City Initiative on Enterprise Labor Structure. Front. Energy Res. 9:821677. doi: 10.3389/fenrg.2021.821677

INTRODUCTION

Global warming, as a result of excessive emissions of greenhouse gases, destroys the balance of the ecosystem, which in turn poses a great threat to human survival. Multiple countries have acted to cope with global climate change. The term "low carbon economy" first appeared in the field of economics (Kinzig and Kammen, 1998), and subsequently in official documents. In 2015, China announced the goal for peak carbon dioxide emissions by 2030 under the framework of the Paris Agreement (United Nations, 2015). In 2018, the Intergovernmental Panel on Climate Change (IPCC) issued a special report on the impacts of global warming of 1.5°C (IPCC, 2018), and that China will make a significant contribution to limiting the global temperature increase by 1.5°C compared with pre-industrial levels, responding to the agreement, and that China will promote low-carbon economic construction and incorporate the response to climate change into the national economic and social development plans. In 2021, "Carbon Peak" and "Carbon Neutral" were first included in the Chinese Government Work Report (The State Council, 2021), which fully demonstrates the Chinese government's determination to play its part as a major and responsible country.

TABLE 1 | List of pilot low-carbon cities.

Batch province	The first batch (July 2010)	The second batch (December 2012)	The third batch (January 2017)
Beijing		Beijing	
Tianjin	Tianjin		
Shanghai		Shanghai	
Chongqing	Chongqing		
Guangdong	Guangdong, Shenzhen	Guangzhou	Zhongshan
Liaoning	Liaoning		Shenyang, Dalian, Chaoyang
Hubei	Hubei	Wuhan	Changyang Tujia Autonomous County
Shaanxi	Shaanxi	Yan'An	Ankang
Yunnan	Yunnan	Kunming	Yuxi, Simao District (Pu'er City)
Fujian	Xiamen	Nanping	Sanming
Zhejiang	Hangzhou	Ningbo, Wenzhou	Jiaxing, Jinhua, Quzhou
Jiangxi	Nanchang	Jingdezhen, Ganzhou	Gongqingcheng, Ji'an, Fuzhou
Guizhou	Guiyang	Zunyi	
Hebei	Baoding	Shijiazhuang, Qinhuangdao	
Hainan		Hainan	Sanya, Qiongzhong Li and Miao Autonomous County
Shanxi		Jincheng	
Inner Mongolia		Hulunbuir	Wuhai
Jilin		Jilin	
Heilongjiang		Daxing'anling Prefecture	Xunke County
Jiangsu		Suzhou, Huai'an, Zhenjiang	Nanjing, Changzhou
Anhui		Chizhou	Hefei, Huaibei, Huangshan, Liu'an, Xuancheng
Shandong		Qingdao	Jinan, Yantai, Weifang
Henan		Jiyuan	
Guangxi		Guilin	Liuzhou
Sichuan		Guangyuan	Chengdu
Gansu		Jinchang	Lanzhou, Dunhuang
Xinjiang		Urumqi	Changji, Yining, Hetian
Hunan			Changsha, Zhuzhou, Xiangtan, Chenzhou
Tibet			Lhasa
Qinghai			Xining
Ningxia			Yinchuan, Wuzhong
Xinjiang Production and Construction Corps			Alar

China has implemented various carbon reduction policies and made efforts to continuously explore new paths for fulfilling China's commitment to the world. At the practical level, China has explored a series of policies, such as emission trading scheme (ETS) pilot policy, pilot low-carbon city initiative, carbon tax, etc. In the past 10 years, the National Development and Reform Commission of China has successively identified three batches of pilot areas in 2010, 2012, and 2017 (National Development and Reform Commission, 2010; National Development and Reform Commission, 2012; National Development and Reform Commission, 2017), including four municipalities, 71 prefecture-level cities, and 12 non-municipal districts (**Table 1**). The pilot areas actively explore low-carbon development paths in line with the actual condition.

Furthermore, environmental regulation also exerts a subtle influence on the labor structure. In July 2021, the Ministry of Education of the People's Republic of China issued the Action Plan for Carbon Neutralization and Technological Innovation in Higher Educational Institutions (The Chinese Ministry of Education, 2021), calling on colleges and universities to accelerate the construction of the carbon-neutral technological innovation system and talent training system, to focus on improving the ability of technological innovation and innovative talent training. As we all know, enterprises play an important role in urban construction and shoulder an important mission of promoting the construction of a low-carbon city. A series of decisions made by enterprises to reduce carbon emissions are actually fulfilled by their workforce. Therefore, low-carbon development inevitably leads to a higher demand for talents.

After nearly 10 years of exploration and development, at the macro-level, achievements have been made in the adjustment of industrial structure, optimization of energy mix, and the awakening of public awareness. Zheng et al. (2021b) previously research the impact of China's ETS pilot policy on enterprises, and prove that China's ETS pilot policy can significantly improve the carbon emission performance of listed companies in the pilot provinces. Meanwhile, Zheng et al. (2021b) also find that innovation is a channel for the impact of China's ETS pilot policy on carbon emission performance in the pilot provinces. Therefore, we continue to study the effect of the pilot low-carbon city initiative at the microlevel. What effect does the pilot low-carbon city initiative have on local enterprises? Does it have an impact on the upgrading of labor force structure? Is it a positive or negative effect? What mechanisms are in place to make an impact? Researchers have not drawn a clear and general conclusion on these questions yet. The study takes the release of the pilot low-carbon city initiative as a quasi-natural experiment and employs the time-varying difference-in-differences (DID) to discuss the impact of low-carbon development of cities on enterprise labor structure. The study aims to respond to the above questions theoretically and tries to shed light on if and how the low-carbon city initiative can shape Chinese corporates' future development trajectory.

We present three main contributions in this article. 1) This article discusses the impact of China's pilot low-carbon city initiative on enterprise labor structure from a micro perspective, aiming to complement the literature in this area. 2) The study also has a certain empirical contribution. Based on China's pilot low-carbon city initiative launched in 2010, 2012, and 2017 as a quasi-natural experiment, this article uses the time-varying DID model to evaluate the impact of this initiative on enterprise labor structure. Furthermore, we set up various robustness tests to increase the validity of the conclusions. 3) The research also has certain policy implications. In recent years, China's economy has encountered mounting downward pressure. In this case, how to stabilize employment has become a focus of discussion from all walks of life. Based on the data of A-share listed companies in China, we found that the pilot low-carbon city initiative can effectively optimize the employment behavior of enterprises, which provides some empirical evidence for the government to optimize the labor structure through the pilot low-carbon city initiative. Furthermore, considering that the effect of China's pilot low-carbon city initiative is heterogeneous among different enterprises, the government should formulate different policies to comprehensively optimize the employment demand of enterprises in different regions, hence achieving the employment goal of emission reduction policies.

This article is structured as follows: Section "Literature Review and Research Gap" organizes the literature on the effect of pilot low-carbon city initiative, the effects of carbon policy and environmental regulation on labor, the relationship between pilot low-carbon city initiative and enterprise innovation, the relationship between enterprise innovation and labor structure, and then summarizes the research gap. Section "Theoretical Analysis and Hypotheses Development" provides the theoretical basis and hypotheses. Section "Research Design" presents the sample, model, variable, and descriptive statistics. Section "Empirical Results" presents the empirical results and discussions. Section "Conclusion" concludes the article and addresses the policy implications.

LITERATURE REVIEW AND RESEARCH GAP

Research on Effects of Pilot Low-Carbon City Initiative

In recent years, a large number of domestic and foreign scholars have continued to study the factors influencing CO_2 emissions (Li et al., 2017; Wen and Yan, 2018; Li and Hu, 2020; Dong et al., 2020b) and have focused on China's carbon reduction policies and approaches (Hunter et al., 2019; Jiang and Kang, 2019; Dong et al., 2020a). The effect of pilot low-carbon city initiative has received a lot of attention. Related studies go from the national level, regional level, industry level, and gradually to the enterprise level. Most of the studies have focused on the national and regional levels, while relatively few studies have focused on the industry and enterprise levels.

On the national level, Khanna et al. (2014) adopt an ex ante comparative assessment of the low-carbon development plans and supporting measures and find that a lack of explicit definition for the low-carbon city, complexity and confusion resulting from several parallel programs, and insufficient supporting policies and market-based instruments, are the major factors in hindering the development of the low-carbon city. Li et al. (2018) set several indicators to analyze the progress of the implementation of low-carbon policies from the initial two batches and document that more constraints and incentives should be integrated into China's pilot low-carbon city initiative, a policy evaluation system should be establish, and good practices should be summarized to promote further development of policies. Qu and Liu (2017) establish a low-carbon development indicators system based on the driving force–pressure–state–impact–response model, which can quantify the level of low-carbon development, find that only five pilot cities' low-carbon development levels were positive, and present that measures, including legislation, economic means, improvement of renewable energy-saving technology, and low-carbon transportation can improve the low-carbon development level. Zheng et al. (2021a) research the positive impact of China's pilot low-carbon city initiative on the upgrading of the industrial structure, finding that technological innovation and reduction of high-carbon industries are the development path to promote the upgrading of the industrial structure. Under strong environmental law enforcement, the policies have a significant role in promoting the rationalization of the industrial structure. Using the logarithmic mean Divisia index method to decompose the factors of carbon emissions, Shen et al. (2018) find that industrial structure is the main factor in reducing carbon emissions and economic output is the top factor in increasing carbon emissions, based on analyzing various factors of carbon emissions. Yu and Zhang (2021) establish the general non-convex metafrontier data envelopment analysis model to measure the carbon emission efficiency. The analysis shows that China's pilot low-carbon city initiative increases the carbon emission efficiency by 1.7%, providing support for the implementation of China's pilot low-carbon city initiative.

On the regional level, Feng et al. (2021) study the impact of China's pilot low-carbon city initiative on carbon intensity on the city level and find that China's pilot low-carbon city initiative can increase carbon intensity in the short term. But after 3 years, the increase in carbon intensity decreases. Fu et al. (2021) analyze the effectiveness of China's pilot low-carbon city initiative on carbon emission reduction from the perspective of cost and benefit. The study shows that China's pilot low-carbon city initiative will not have a significant benefit on carbon emission reduction in the short term, but should evaluate its effectiveness from a long-term perspective, and points out that R&D investment is an effective path to improve efficiency. From the perspective of local government policy implementation, Guo et al. (2021) show that local governments' lack of motivation for the implementation of China's pilot low-carbon city initiative makes the effect of China's pilot low-carbon city initiative fail in meeting the national expectations. Song et al. (2021) sort out and evaluate the policy innovations on the city level related to low-carbon pilot city development. They find that only one-third of cities implemented policy innovations, and nearly half of the cities are not applied policy innovations. Hong et al. (2021) show that China's pilot low-carbon city initiative can effectively reduce local energy intensity, especially for eastern cities, high economic development cities, and non-old industrial base cities. Its main mechanism is through technological innovation, not the optimization of the industrial structure. Wang et al. (2015) summarize the main low-carbon–related policies and use Zhejiang as an example to focus on key policy tools to understand the implementation of policies and provide advanced experience for reducing carbon emissions and reaching carbon peaks as soon as possible. Taking Shanghai as an example, Yang and Li (2018) establish a low-carbon economic development level evaluation model to analyze the city's low-carbon level and future development trends. In the end, it is discovered that although Shanghai is in a low-carbon economy and continues to develop, its investment in low-carbon construction and low-carbon technology is still relatively insufficient.

On the industry level, Tang et al. (2018) find that the pilot policy reduces land shifts in energy-intensive industries, but this effect diminishes rapidly over time. The role of the local secretary, namely the *de facto* "first-in-command" official of the local government, is also analyzed.

On the enterprise level, Chen et al. (2021) find that China's pilot low-carbon city initiative has a significant effect on the total factor productivity. Through analysis, it is pointed out that promoting technological innovation and optimizing resource allocation efficiency are important ways to improve total factor productivity, so as to achieve a win–win situation of reducing carbon emissions and high-quality development of enterprises.

Research on Effects of Carbon Policy and Environmental Regulation on Labor

The existing researches on the effects of carbon policy and environmental regulation on labor can be summarized in four levels, the national level, regional level, industry level, and enterprise level. Scholars have done a lot of research on the policy effects on labor demand, and they are gradually starting to focus on the enterprise level.

On the national level, Yamazaki (2017) examines the employment impact of British Columbia's revenue-neutral carbon tax and find that the British Columbia (BC) carbon tax generates an overall positive effect on the employment of labor. Zhong et al. (2021), using Cobb–Douglas production function and Dynamic Spatial Durbin Modeling, find that the proportion of high-skilled labor in China will increase with the intensification of environmental regulation while that of the low-skilled labor will show a U-shaped curve of first declining and then rebounding. The results confirm that the proportions of high-skilled and low-skilled labor are influenced by the intensity of environmental regulations.

On the regional level, based on the generalized method of moments estimator, Cao et al. (2017) adopt a mediating model to examine the impact of environmental regulation in resource-based provinces in China on enterprise labor. It is found that the implementation of the environmental regulation in resource-based areas has direct positive impacts on labor and has positively mediating effect on labor by inducing industrial upgrades. Therefore, these findings provide policy suggestions to help the labor to adapt to the job changes brought about by technological innovation, by increasing the education of the labor force and improving the skills of the labor force.

On the industry level, Carbone et al. (2020), based on a computable general equilibrium model and quasi-natural experimental econometric model, compare ex ante estimates with ex post estimates of the employment effect of the BC carbon tax and find that carbon tax has a significant impact on the sectoral labor levels, and that sectoral labor levels with the highest carbon intensity decrease, while those with the lowest carbon intensity increase.

On the enterprise level, Anger and Oberndorfer (2008) take a large number of German enterprises covered by the European Union Emissions Trading System (EU ETS) as samples for quantitative analysis and research the relationship between the relative allowance allocation in the EU ETS and both the performance and labor force of the German enterprises. It is found that, within the first phase of EU ETS, the relative allowance allocation has no significant influence on the performance and labor force of the regulated German enterprises. Hanoteau and Talbot (2019), based on the DID model, find that the implementation of the Quebec carbon emission trading system (QC ETS) reduces greenhouse gas emissions but the regulated plants first and foremost scales down their investment activities to adapt to the implementation of the policy, resulting in labor demand reduction, and its employment effect is in contrast to the findings of similar studies on the early stages of EU ETS and BC carbon tax. The results promote the QC ETS to develop the ability to induce facilities to improve technology and innovation activities. Yu and Li (2021) research China's carbon emission trading pilot policy on labor demand from the perspective of micro enterprises and find that there are scale, substitution, and spatial spillover effects in the effect of carbon trading policy on the labor employment market, which refers to the fact that carbon emission trading policies increase labor demand by increasing enterprise production, promote enterprises to invest in environmental governance thus reducing labor demand, and force local enterprises to use clean technology thus improving the demand for labor. Using "China's sulfur dioxide (SO_2) emissions trading program" as a quasi-natural experiment, based on the DID model, Ren et al. (2020) find that the labor demand of regulated firms is significantly increased by the emissions trading program, and this positive employment effect is driven by scaling up production. Based on the moderating effect model, Li and Zhu (2019) present that the direct impact of environmental regulation on enterprise labor employment and technological innovation is significantly positive. Furthermore, the effect of environmental regulation on the relationship between technological innovation and enterprise labor employment is negative, and there is significant heterogeneity that the negative impact of the environmental regulation on the employment creation of technological innovation in enterprises is smaller in private enterprises, clean industries, and high-tech industries.

Research on Pilot Low-Carbon City Initiative and Enterprise Innovation

Ma et al. (2021) analyze that China's pilot low-carbon city initiative has a positive effect on green technological innovation from multiple dimensions, especially in the eastern cities and the high carbon enterprises. Further studies show that tax breaks and the government subsidies are significant financial tools. Reducing financing difficulties of enterprises can effectively promote green technology innovation of enterprises. Xu and Cui (2020) demonstrate that China's pilot low-carbon city initiative promoted green technology innovation of enterprises. Further research find that command-and-control policy tools can effectively promote green technology innovation in pilot areas. Huang et al. (2021) find that environmental regulations promoted enterprises to increase R&D expenditure continuously, demonstrating the impact of environmental regulations on innovation activities. Based on Porter hypothesis, Xiong et al. (2020) find that China's pilot low-carbon city initiative has a significant effect on improving the level of green technology innovation of the high-carbon enterprises in the pilot city, especially in the green utility-model patents of enterprises. Zhong et al. (2020) find that China's pilot low-carbon city initiative induces green innovation among local firms, significantly increasing the absolute and relative levels of green innovation among firms, while further heterogeneity analysis is done. Li et al. (2019) confirm that the implementation of China's pilot low-carbon city initiative not only enhances the technological innovation capability of enterprises but also reduces the gap between the technological innovation levels of enterprises in cities of different grades.

Research on Enterprise Innovation and Labor Structure

Luo and Guo (2021) adopt the method of multidimensional fixed effect estimation and find that enterprise innovation input, through the effect of labor costs and labor productivity, has a two-way effect on employee employment. On the one hand, enterprise innovation input inhibits the employment of production personnel. On the other hand, it stimulates the employment of non–direct production personnel, including salesmen, technicians, managers. Zeng and Zhu (2014) find that the labor structure of R&D plays a key role in the development of high-tech industries and that enterprises should pay attention to the optimal allocation of the labor force and capital investment to promote their long-term development. Based on the current situation of labor allocation in China's knowledge-intensive service industry, Li et al. (2021) find that there is a labor mismatch in China's knowledge-intensive service industry and further find that the mismatch of labor allocation inhibits the innovation performance of knowledge-intensive service enterprises, and heterogeneity exists in this inhibition.

Literature Gap

From the previous literature review, it can be found that a large number of scholars have studied the application effect of carbon emission reduction policies, such as the ETS pilot policy, pilot low-carbon city initiative, carbon tax, environmental regulation, etc. However, most scholars focus on the macro level, such as country, city, and industry. Limited literature focuses on enterprise at the microlevel, which is mainly limited to the impact on enterprise technological innovation, and there is relatively limited research on the integration with enterprise labor structure. A few scholars have studied the impact of R&D investment on the enterprise labor structure. Overall, the research on the impact and path of China's pilot low-carbon city initiative on enterprise labor structure is still relatively insufficient. This article will supplement research on the application effect of China's pilot low-carbon city initiative at the microlevel.

THEORETICAL ANALYSIS AND HYPOTHESES DEVELOPMENT

Basic Hypothesis

In the recent years, China's environmental pollution has been increasingly concerning the public, and it has become the inevitable choice of the Chinese government to intensify environmental regulations. Environmental regulations mean carbon emission trading, carbon tax, technical standards, etc., and forcing enterprises to redistribute resources such as labor and capital to reduce enterprise pollution (Ambec et al., 2013). Previous researches suggest that intensifying environmental regulations generate "compliance cost effect" and "innovation offset effect," which carries a double dividend of reducing pollution emissions and promoting employment for society (Yu and Li, 2021; Zhong et al., 2021).

As a comprehensive environmental policy under the interaction of the central and local governments, China's pilot low-carbon city initiative brings more preferential policies to the pilot areas, mainly in tax relief, financial subsidies, and talent incentives (Cao et al., 2017), which are the critical factors to promote the upgrading of enterprise labor structure. Furthermore, it has been shown that the pilot low-carbon city initiative promotes enterprises to increase R&D investment, and R&D investment can optimize enterprise labor structure (Yamazaki, 2017; Guo et al., 2018; Carbone et al., 2020; Huang et al., 2021). Thus, the following hypothesis 1 is proposed:

Hypothesis 1. China's pilot low-carbon city initiative can promote the upgrading of enterprise labor structure.

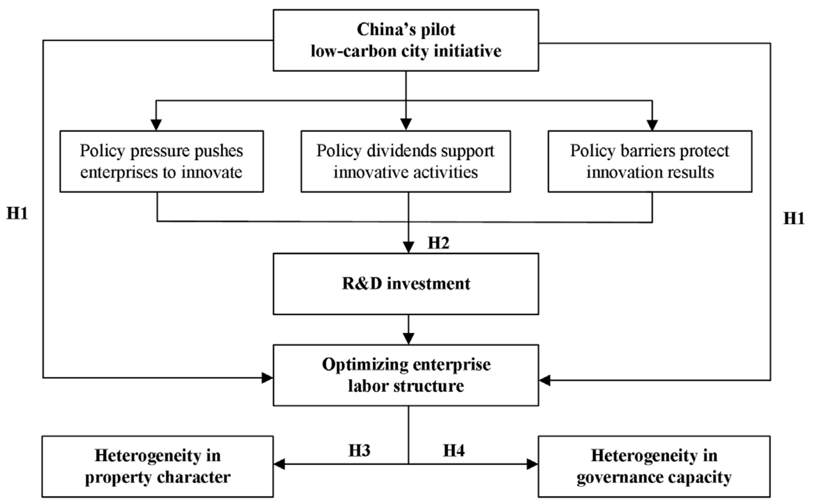


FIGURE 1 | Logical framework.

Mediation Hypothesis

Because enterprise innovation is characterized by high investment, long payback periods, and unstable earnings (Bansal and Hunter, 2003), it is difficult for enterprises to have the motivation to implement this highly risky business decision in the absence of external incentives (Borghesi et al., 2015).

There are three reasons that R&D investment can be used as mediating variable between the pilot low-carbon city initiative and the upgrading of enterprise labor structure: 1) the external pressures forcing enterprises to innovate have risen sharply. The pilot low-carbon city initiative, as a legal pressure, has also increased the pressure on enterprises to innovate and progress (Chen et al., 2017; Liao et al., 2018). In the game between increased carbon emission costs and reduced human resource costs, due to policy pressure, more enterprises tend to choose the latter, which will reduce the policy default cost by improving the enterprise labor structure and production technology. 2) Policy dividends to support innovation activities have been increased. The pilot low-carbon city initiative gives pilot cities tax incentives, talents motivation mechanism, and other multiple policy dividends, which play a key role in stimulating enterprises' innovation (Hall and Reenen, 2000; Lu and Li, 2021), thereby improving the overall quality of enterprise labor. 3) Policy barriers to protect innovation achievements have been strengthened. The low-carbon pilot city policy has given stronger protection to intellectual property rights in such high-tech sectors as clean energy, carbon emission reduction, etc., ensuring that the enterprises' innovation achievements can be smoothly transformed into internal income, breaking the illusion of stealing the intellectual property achievements of others (He et al., 2021; Zhuang et al., 2021) and in effectively increasing the demand and salary payments for technical talents. As a result, the enterprise labor structure is effectively improved. Based on the above discussions, we propose the following hypothesis 2:

Hypothesis 2. China's pilot low-carbon city initiative can promote the upgrading of enterprise labor structure through increasing R&D investment.

Heterogeneity Hypothesis

Property Character

Depending on whether the ultimate controller is the government or not, enterprises in China are divided into state-owned enterprises and non–state-owned enterprises, and they have great difference in policy implementation, corporate governance, and the role they play in the market.

Firstly, the property character of state-owned enterprises leads them to bear many non-market burdens, such as strategic policy burdens and social policy burdens (Lin and Liu., 2001), which makes enterprises subject to greater government regulations and interventions and urges them to implement policies more vigorously and strictly. In addition, the government and state-owned enterprises hold a relationship of mutual assistance with Chinese characteristics—state-owned enterprises bear the policy burden and the government gives them preferential policies (Liao and Shen., 2014). Therefore, state-owned enterprises located in low-carbon cities will respond more strongly to the policy requirements of carbon emission reduction than non–state-owned enterprises and thereby having a higher demand for high-tech talents.

Secondly, state-owned enterprises are the backbone of national economic development and the pillar of socialism with Chinese characteristics, and the important strategic position makes state-owned enterprises have inherent political advantages, have easier access to policy and financial support (Li and Li., 2014; Li et al., 2016), and be frequently ahead of ordinary private enterprises in terms of enterprise strength, etc. Strong overall enterprise competitiveness and abundant funds provide support for state-owned enterprises to recruit talents.

Finally, state-owned enterprises face many challenges. Besides their own hard power such as production efficiency, the relationship between enterprises and society also forces them

TABLE 2 | Variable definition.

Variable	Definition and unites	Measurement
LDLJG	Labor structure (%)	The number of staff with bachelor degree and above/total number
DTShidian	Pilot low-carbon city initiative	Assigning it to 1 after the implementation, while assigning it to 0 before the implementation
Growth	Profit growth rate (%)	(Total profit of this year – total profit of the previous year)/total profit of the previous year
Size	Company size (-)	Ln (assets)
Lev	Leverage level (%)	Liabilities/total assets
ROA	Return on assets (%)	Net profit after tax/total assets
WXZCZB	Proportion of intangible assets (%)	Intangible assets/total assets
ZBLDB	Proportion of capital and labor (%)	Net value of fixed assets/number of employees
TOP1	Proportion of the largest shareholder (%)	Proportion of shares held by the shareholder with the most capital
Board	Board size (-)	Number of directors
Indd	Proportion of independent directors (%)	Number of independent directors/number of directors
GDP Growth	GDP growth rate (%)	(Total GDP of this year – total GDP of the previous year)/total GDP of the previous year

TABLE 3 | Descriptive statistics of variables.

Variable	Obs	Mean	SD	Min	Max	1st	5th	25th	50th	75th	95th	99th
LDLJG	22421	0.268	0.205	0.0214	0.874	0.0214	0.0467	0.113	0.203	0.370	0.715	0.874
DTShidian	22421	0.222	0.416	0	1	0	0	0	0	0	1	1
Growth	22421	0.220	0.584	−0.609	4.297	−0.609	−0.293	−0.0192	0.119	0.294	0.921	4.297
Size	22421	22.11	1.430	19.37	27.08	19.37	20.22	21.10	21.89	22.85	24.84	27.08
Lev	22421	0.454	0.222	0.0532	0.979	0.0532	0.110	0.276	0.448	0.618	0.829	0.979
ROA	22421	0.0351	0.0621	−0.273	0.200	−0.273	−0.0577	0.0125	0.0340	0.0633	0.125	0.200
WXZCZB	22421	0.0468	0.0546	0	0.338	0	0.000314	0.0143	0.0325	0.0577	0.145	0.338
ZBLDB	22421	0.533	0.900	0.0111	6.201	0.0111	0.0391	0.136	0.263	0.515	1.911	6.201
TOP1	22421	0.349	0.151	0.0850	0.746	0.0850	0.136	0.230	0.329	0.453	0.625	0.746
Board	22421	8.813	1.833	5	15	5	6	8	9	9	12	15
Indd	22421	0.372	0.0530	0.300	0.571	0.300	0.333	0.333	0.333	0.429	0.455	0.571
GDP Growth	22421	0.108	0.0495	0.00294	0.239	0.00294	0.0507	0.0783	0.0986	0.123	0.215	0.239

to pay more attention to the development of soft power, including corporate image and public reputation, etc. (Duan, 2014). Compared with non–state-owned enterprises, state-owned enterprises have more urgent needs for social image, and they are required to establish a good image in front of the public, respond to the policy vigorously, and show leadership for other private enterprises, which urges them to continuously introduce talents and optimize the labor structure. Based on the above comprehensive analysis, research hypothesis 3 can be put forward:

Hypothesis 3. Compared with non–state-owned enterprises, the labor structure of state-owned enterprises will be better optimized through China's pilot low-carbon city initiative.

Governance Capacity

As the main body of implementing China's pilot low-carbon city initiative, the governance capacity of the local governments has a significant impact on the efficiency and effectiveness of policy implementation. According to China's marketization index (Wang et al., 2021), this article divides governments into high-quality governments and low-quality governments. First of all, governments with stronger governance capacity will interpret policies more accurately and correctly to understand policy requirements. Implementing policies with policy requirements as the standard is better at preventing mistakes (Feng, 2021); secondly, the government's competence relies on their capacities to regulate various economic entities within their region. The stronger the governance capacity, the better the regulation and institutional environment, and lesser the enterprises' rent-seeking behavior by establishing political affiliation (Wan and Chen, 2010). Based on the above comprehensive analysis, the research hypothesis 4 can be put forward:

Hypothesis 4. Compared with low-quality governments, the labor structure of listed companies under high-quality government control will be better optimized through China's pilot low-carbon city initiative.

Logical Framework

The logical relationship between the above theoretical analysis and research hypotheses are presented in **Figure 1**. Based on three aspects of policy effects, China's pilot low-carbon city initiative increases R&D investment and thereby has an impact on the micro–enterprise labor structure. Furthermore, analyzing the heterogeneity in property character and government governance capacity, we discuss differences of policy implementation effect, not only between state-owned and non–state-owned enterprises but also between high-quality and low-quality governments.

TABLE 4 | The impact of China's pilot low-carbon city initiative on enterprise labor structure.

	(1)	(2)	(3)	(4)	(5)	(6)
	LDLJG	LDLJG	LDLJG	LDLJG	LDLJG	LDLJG
	Basic regression	Basic regression	State-owned	Non–state-owned	High-quality	Low-quality
DTShidian	0.020***	0.020***	0.016**	0.013	0.021***	0.014
	(3.14)	(3.27)	(1.99)	(1.58)	(2.87)	(1.36)
Size		0.004	0.000	0.008**	0.004	0.003
		(1.53)	(0.12)	(2.20)	(1.06)	(0.65)
Lev		−0.024	0.006	−0.061***	−0.007	−0.045**
		(−1.60)	(0.25)	(−3.22)	(−0.38)	(−2.00)
ROA		0.134***	0.184***	0.103**	0.213***	0.020
		(3.85)	(3.27)	(2.45)	(4.65)	(0.38)
Growth		0.015***	0.015***	0.015***	0.016***	0.013***
		(5.50)	(3.82)	(4.22)	(4.44)	(3.26)
WXZCZB		−0.413***	−0.360***	−0.404***	−0.416***	−0.389***
		(−9.14)	(−5.32)	(−6.67)	(−7.64)	(−5.96)
ZBLDB		0.029***	0.035***	0.014*	0.032***	0.025***
		(8.47)	(8.82)	(1.95)	(7.75)	(4.47)
TOP1		−0.076***	0.035	−0.147***	−0.077***	−0.053*
		(−3.94)	(1.13)	(−6.34)	(−3.24)	(−1.76)
Board		−0.001	−0.002	0.002	0.001	−0.003
		(−0.59)	(−0.97)	(0.59)	(0.48)	(−1.24)
Indd		0.042	0.026	0.101	0.085	0.018
		(0.87)	(0.39)	(1.47)	(1.44)	(0.23)
GDP Growth		0.072	0.115*	−0.020	0.143	0.091
		(1.55)	(1.93)	(−0.28)	(1.60)	(1.52)
_cons	0.175***	0.095	0.100	0.058	0.070	0.148
	(6.48)	(1.58)	(1.13)	(0.65)	(0.87)	(1.43)
Year	Yes	Yes	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes	Yes	Yes
Obs	22421	22421	9388.000	13033	13798	8623.000
Adj. R^2	0.347	0.378	0.400	0.402	0.346	0.441

Standard errors are in parentheses. The _cons represents the intercept term.
, **, and * denote significance at the 10, 5, and 1% levels, respectively.*

RESEARCH DESIGN

Sample Selection

Our sample is composed of A-share listed companies on the Shanghai Stock Exchange and Shenzhen Stock Exchange in 293 prefecture-level cities in China from the China Stock Market and Accounting Research system over the period from 2007 to 2019. The city-level data comes from the China City Statistical Yearbook.

Since China's pilot low-carbon city initiatives were implemented in July 2010, December 2012, and January 2017 respectively, the years 2011, 2013, and 2017 will be taken as the time points for external policy shocks. Listed companies registered in the pilot cities are set as the experimental group, and listed companies registered in the non–pilot cities are set as the control group. In order to ensure the validity of the data processing results, this article screens the samples as follows, before the analysis: 1) exclude non-municipalities and non–prefecture-level cities; 2) exclude financial listed companies; 3) exclude ST or *ST companies; and 4) exclude companies with incomplete data or abnormal financial data. Based on winsorizing continuous variables on 1% quantile, 22,421 unbalanced panel data are constructed finally.

Model

The DID model is the most widely used measure for estimating treatment effects and is originally proposed by medical scientist Snow (1855) in his study of the cholera epidemic in London and is introduced into economics by Obenauer and Nienburg (1915) in their study of the effects of the minimum wage method. In estimating treatment effects, the synthetic control method is used if the experimental group has only one treated subject. If the experimental group has more than one treated object, the DID method is used. If the treated time is the same point in time, the traditional DID is used; if the treated time is different, the time-varying DID is used.

The implementation of China's pilot low-carbon city initiative is equivalent to a "quasi-natural experiment." Firstly, the initiative is equal to an exogenous event for the enterprises located in the pilot city and is not determined by the enterprises' characteristics, thereby meeting the external conditions of a quasi-natural experiment (Pan and Dong, 2021). Secondly, the construction of the low-carbon pilot city not only produces a certain efficiency in attracting talents but also provides necessary financial support. From this perspective, it also meets the relevant requirements between the explanatory and explained variables, providing the feasibility for using the DID quantitative model. Due to different regions implementing the pilot low-carbon city initiative at

TABLE 5 | The impact of China's pilot low-carbon city initiative on innovation.

	(1)	(2)
	R&D	R&D
	R&D/sales revenue	R&D/total assets
DTShidian	0.002**	0.493**
	(2.22)	(2.18)
Size	−0.002***	0.670***
	(−4.39)	(7.75)
Lev	−0.042***	−4.957***
	(−14.85)	(−10.10)
ROA	−0.018**	4.028***
	(−2.42)	(3.80)
Growth	−0.001***	−0.315***
	(−3.30)	(−3.45)
WXZCZB	−0.004	1.226
	(−0.52)	(0.73)
ZBLDB	−0.001**	−0.492***
	(−2.57)	(−3.97)
TOP1	−0.017***	0.440
	(−5.27)	(−0.74)
Board	0.000	0.052
	(0.40)	(0.95)
Indd	0.019**	0.964
	(2.31)	(0.66)
GDP Growth	0.014	−5.902***
	(1.40)	(−2.66)
_cons	0.048***	−10.111***
	(5.36)	(−5.19)
Year	Yes	Yes
Industry	Yes	Yes
Province	Yes	Yes
Obs	22421	22421
Adj. R^2	0.392	0.506

Note: Standard errors are in parentheses.
, **, and * denote significance at the 10, 5, and 1% levels, respectively.*

different times, this article chooses the time-varying DID method to identify the impact of China's pilot low-carbon city initiative on the enterprise labor structure.

This article regards the impact of China's pilot low-carbon city initiative in 2011, 2013, and 2017 as a quasi-natural experiment and uses the time-varying DID model to compare the enterprise labor structure and the R&D investment of listed companies in the experimental and control groups before and after the implementation of the policy, so as to present the policy effect more intuitively. Therefore, the benchmark panel time-varying DID model is constructed as follows:

$$Y = \beta_0 + \beta_1 Treat \times T + \sum Control + year + industry + province + \varepsilon \quad (1)$$

Enterprise labor structure and R&D investment are used as the explained variables, denoted by LDLJG and R&D (Ting et al., 2021), respectively. $Treat$ is a regional dummy variable that equals 1 if the city is in the experimental group; otherwise, it is 0. T equals 1 if the pilot low-carbon city initiative is implemented; otherwise, it is 0. The interaction term, the core explanatory variable, is denoted by $Treat \times T$, and it tests whether China's pilot low-carbon city initiative can bring double dividends of the enterprise labor structure and R&D investment. $Control$ represents the control variables, including macro and micro control variables. $year$, $industry$, and $province$ represent the time fixed, industry fixed, and province fixed effects, respectively. ε is the error term.

Variable Definitions and Measurement

Explained Variable

The existing literatures have not yet provided a unified measure for measuring the labor structure of enterprises. In this article, we refer to the research results of Zhu and Li (2018) and consider bachelor's degree and above as higher education and construct the index "The number of staff with bachelor degree and above/ total number of workers" to portray the optimization level of the labor structure (LDLJG).

Explanatory Variable

Whether or not to implement China's pilot low-carbon city initiative is used as a policy dumb variable, and the experimental and control groups are divided by regions. The experimental group contains the municipalities and prefectures in **Table 1**, which are equal to 1, while the control group contains the other municipalities and prefectures, which are equal to 0. We define the next year of the first and second batches and the year of the third batch of the pilot low-carbon city initiative as the event year. The event year and subsequent years are equal to 1, and the years before the event year are equal to 0. Above all, if the enterprise registration place belongs to the experimental group city and the time is after the event year, it is regarded as the group adopting China's pilot low-carbon city initiative, which is equal to 1.

Control Variable

Considering that the explained variable is the micro data of enterprises while the policy dummy variable has macro characteristics, on the basis of previous research results (He and Tian, 2013; Bel and Joseph, 2018; Tang et al., 2018; Huang et al., 2019; Hu et al., 2020; Wen et al., 2020; Liu and Sun, 2021; Lv and Bai, 2021; Ting et al., 2021; Yu et al., 2021), this article selects control variables from macro (city) and micro (enterprise) dimensions. Here are control variables of enterprises: "Growth" represents the profitability rate of the company; "Size" represents the company size; "Lev" represents leverage level of the company; "ROA" represents the return on assets; "WXZCZB" represents proportion of intangible assets; "ZBLDB" represents proportion of capital and labor; "TOP1" represents proportion of the largest shareholder; "Board" represents the size of the board; and "Indd" represents proportion of independent directors. As a macro control variable, "GDP Growth" represents GDP growth rate of cities in the experimental and control groups.

In summary, the detailed variable definitions are presented in **Table 2**.

Descriptive Statistics

Table 3 reporting the descriptive statistics of the variables shows that the mean value of the enterprise labor structure is 0.268 and

TABLE 6 | Robustness test results.

	(1)	(2)	(3)	(4)
	LDLJG	LDLJG	LDLJG	LDLJG
	Regarding the policy year as the event year	Regarding postgraduate degree or above as a higher degree	Adopting PSM model	Excluding samples from the four municipalities
DTShidian	0.020***	0.008***	0.020***	0.022***
	(3.49)	(4.62)	(3.12)	(3.35)
Size	0.004	0.001	0.003	0.007**
	(1.54)	(1.46)	(0.75)	(2.30)
Lev	−0.024	−0.007*	−0.015	−0.033**
	(−1.61)	(−1.72)	(−0.85)	(−2.08)
ROA	0.134***	0.024**	0.155***	0.070*
	(3.86)	(2.51)	(3.46)	(1.86)
Growth	0.015***	0.003***	0.008**	0.016***
	(5.48)	(4.11)	(2.26)	(5.26)
WXZCZB	−0.413***	−0.058***	−0.381***	−0.347***
	(−9.13)	(−4.75)	(−7.18)	(−7.26)
ZBLDB	0.029***	0.005***	0.037***	0.027***
	(8.47)	(3.43)	(9.81)	(6.76)
TOP1	−0.076***	−0.009*	−0.056**	−0.064***
	(−3.96)	(−1.66)	(−2.15)	(−3.10)
Board	−0.001	−0.001	−0.002	0.001
	(−0.59)	(−0.98)	(−0.90)	(0.49)
Indd	0.042	−0.017	−0.042	0.027
	(0.87)	(−1.27)	(−0.67)	(0.53)
GDP Growth	0.083*	−0.008	0.082	−0.010
	(1.77)	(−0.52)	(1.06)	(−0.19)
_cons	0.092	0.014	0.138*	−0.019
	(1.52)	(0.70)	(1.80)	(−0.24)
Year	Yes	Yes	Yes	Yes
Industry	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
Obs.	22421	22421	8711	17933
Adj. R^2	0.378	0.200	0.355	0.329

Standard errors are in parentheses
, **, and * denote significance at the 10, 5, and 1% levels, respectively.*

the standard deviation is 0.205, indicating that the labor structure of the surveyed companies has relatively small differences. The mean value of DTShidian is 0.222, indicating that 22.2 percent of companies in the sample interval are regulated by China's pilot low-carbon city initiative. Basic statistics of control variables are varied within a reasonable range.

EMPIRICAL RESULTS

Basic Analysis of the DID Regression Results

Based on the benchmark regression analysis, we apply the time-varying DID method to investigate the average treatment effect of enterprise labor structure of listed companies in the pilot cities. The results for the enterprise labor structure as the explained variables are reported in **Table 4**.

The basic regression results in the first and second columns show that the coefficient of $Treat \times T$ is significantly positive at the 1% level ($\beta_1 = 0.020$, $p < 0.01$), indicating that no matter whether control variables are added or not, China's pilot low-carbon city initiative significantly promotes the upgrading of enterprise labor structure, which is consistent with Hypothesis 1.

Based on the basic regression analysis, heterogeneity analysis is also conducted. On the basis of distinguishing corporate property rights by the standards of state-owned companies and non–state-owned companies, we evaluate the similarities and differences in the labor structure optimization from different enterprises with different property rights by China's pilot low-carbon city initiative. The third and fourth columns of **Table 4** show that the labor structure of state-owned listed companies has been optimized significantly, but not of non–state-owned listed companies, which is consistent with Hypothesis 3.

Otherwise, according to China's marketization index (Wang et al., 2021), municipal governments can be divided into high-quality and low-quality governments, then we should assess the different impacts of China's pilot low-carbon city initiative on the different types of governments. The fifth and sixth columns of **Table 4** show that the labor structure of listed companies under high-quality government control has been optimized significantly, but not under low-quality government control, which is consistent with Hypothesis 4. It can be seen that the stronger the governance capacity of municipal government, the more obvious the effect of the pilot low-carbon city initiative.

Mechanism Analysis

Enterprise's R&D investment (R&D), as the mediating variable, is measured by two indicators. The first indicator is "R&D to sales revenue" and the other is "R&D to total assets." The test results of **Eq. 1** for R&D investment as the explained variable are reported in **Table 5**.

The regression results in the first and second columns show that the two coefficients of $Treat \times T$ are both significantly positive at the 5% level ($\beta_1 = 0.002$, $p < 0.05$; $\beta_1 = 0.493$, $p < 0.05$), indicating that China's pilot low-carbon city initiative can significantly increase R&D investment of listed companies, suggesting that R&D investment is a channel for the impact of China's pilot low-carbon city initiative on enterprise labor structure in the pilot cities, which is consistent with Hypothesis 2.

Robustness Tests

Through the basic regression analysis, it is known that China's pilot low-carbon city initiative significantly promotes the upgrading of enterprise labor structure. In order to reduce the error of time-varying DID estimation and ensure the reliability of the conclusion, we use four different methods to conduct the robustness tests. The results are shown in **Table 6**.

Method 1: Regarding the policy year as the event year. Three batches of pilot low-carbon city initiatives were promulgated in 2010, 2012, and 2017, respectively. The first column of **Table 6** shows the regression results. It can be seen intuitively that the coefficient of $Treat \times T$ is significantly positive at the 1% level ($\beta_1 = 0.020$, $p < 0.01$), indicating that China's pilot low-carbon city initiative can significantly promote the upgrading of enterprise labor structure.

Method 2: Regarding postgraduate degree or above as a higher degree. On the basis of measuring the variable LDLJG by "Number of employees with postgraduate degree or above/total number of employees," the second column of **Table 6** shows the regression results. It can be seen intuitively that the coefficient of $Treat \times T$ is significantly positive at the 1% level ($\beta_1 = 0.008$, $p < 0.01$), indicating that China's pilot low-carbon city initiative can significantly promote the upgrading of enterprise labor structure.

Method 3: Adopting propensity score matching (PSM) model. To reduce systematic errors and estimation bias in the time-varying DID method, based on the principle that the company size and leverage level are as similar as possible to the experimental group before the policy occurs, we match the experimental group with a more similar control group in the non-pilot region. The third column of **Table 6** shows the regression results. It can be seen intuitively that the coefficient of $Treat \times T$ is significantly positive at the 1% level ($\beta_1 = 0.020$, $p < 0.01$), indicating that China's pilot low-carbon city initiative can significantly promote the upgrading of enterprise labor structure.

Method 4: Excluding samples from the four municipalities. The fourth column of **Table 6** shows the regression results. It can be seen intuitively that the coefficient of $Treat \times T$ is significantly positive at the 1% level ($\beta_1 = 0.022$, $p < 0.01$), indicating that China's pilot low-carbon city initiative can significantly promote the upgrading of enterprise labor structure.

In **Table 6**, we find that the estimated coefficients of $Treat \times T$ are still significant, which indicates that the conclusion is robust.

CONCLUSION

In this study, using panel data based on municipalities and prefecture-level cities in the pilot low-carbon cities and A-share listed companies in Shanghai and Shenzhen from 2007 to 2019, we explore whether China's pilot low-carbon city initiative can significantly promote the upgrading of enterprise labor structure by using the time-varying DID model. Our study finds that: 1) China's pilot low-carbon city initiative can significantly optimize enterprise labor structure. 2) China's pilot low-carbon city initiative can significantly increase R&D investment of listed companies, suggesting that R&D investment is a channel for the impact of China's pilot low-carbon city initiative on enterprise labor structure in the pilot cities. 3) Furthermore, the heterogeneity analysis shows that the labor structure of state-owned listed companies has been optimized significantly, but not of non–state-owned listed companies. Meanwhile, the labor structure of listed companies under high-quality government control has been optimized significantly, but not under low-quality government control.

Based on the above findings, several policy recommendations are provided as follows: 1) The effect of China's pilot low-carbon city initiative is heterogeneous in different regions. The government should formulate differentiated policies to optimize the employment demand of enterprises in different regions, thus achieving the goal of optimizing the labor structure. 2) Under the guidance of the government's dual carbon strategic goals, cities in China should formulate emission reduction plans, improve assessment and incentive mechanisms, and practically implement carbon emission action plans. 3) With the increasing pressure of enterprise emission reduction, technological innovation has become the only way out. Looking ahead, Enterprises should increase R&D investment, optimize labor structure, improve talent quality, strengthen innovation, and seek long-term development. 4) Higher education institutions shoulder the important responsibility of providing talent support for dual carbon strategic goals. They should take social demand as the guide, strengthen social requirement investigation, vigorously develop talent training programs and teaching materials in the field of carbon neutrality, and integrate the concept and practice of carbon neutrality into the talent training system.

DATA AVAILABILITY STATEMENT

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

AUTHOR CONTRIBUTIONS

XS: conceptualization, resources, writing—review, proofreading language, and supervising. YZ: conceptualization, investigation, resources, writing—original draft, writing—review, and editing. CZ: validation, investigation, methodology, software, data curation, writing—original draft, and funding acquisition. XL: literature and data collection. BW: literature and data collection. All authors contributed to the article and approved the submitted version.

FUNDING

We acknowledge financial support from the Fundamental Research Funds for the Central Universities, China (Grant No. 2018100123), the Municipal Social Science Fund of Beijing (Grant No.19GLB015), the National Natural Science Foundation of China (Grant No. 71902006), and the Scientific Research Program of Beijing Municipal Education Commission (Grant No. SM202010011007).

REFERENCES

Ambec, S., Cohen, M. A., Elgie, S., and Lanoie, P. (2013). The porter hypothesis at 20: Can environmental regulation enhance innovation and competitiveness? *Review of Environmental Economics and Policy* 7 (1), 2–22. doi:10.1093/reep/res016

Anger, N., and Oberndorfer, U. (2008). Firm performance and employment in the EU emissions trading scheme: An empirical assessment for Germany. *Energy Policy* 36, 12–22. doi:10.1016/j.enpol.2007.09.007

Bansal, P., and Hunter, T. (2003). Strategic explanations for the early adoption of ISO 14001. *Eournal of Business Ethics* 46 (3), 289–299. doi:10.1023/A:1025536731830

Bel, G., and Joseph, S. (2018). Policy stringency under the European Union Emission trading system and its impact on technological change in the energy sector. *Energy Policy* 117, 434–444. doi:10.1016/j.enpol.2018.03.041

Borghesi, S., Cainelli, G., and Mazzanti, M. (2015). Linking emission trading to environmental innovation: evidence from the Italian manufacturing industry. *Research Policy* 44 (3), 669–683. doi:10.1016/j.respol.2014.10.014

Cao, W., Wang, H., and Ying, H. (2017). The Effect of Environmental Regulation on Employment in Resource-Based Areas of China-An Empirical Research Based on the Mediating Effect Model. *International Journal of Environmental Research and Public Health* 14 (12), 1598. doi:10.3390/ijerph14121598

Carbone, J. C., Rivers, N., Yamazaki, A., and Yonezawa, H. (2020). Comparing applied general equilibrium and econometric estimates of the effect of an environmental policy shock. *Journal of the Association of Environmental and Resource Economists* 7 (4), 687–719. doi:10.1086/708734

Chen, Z., Li, X., and Cao, H. (2017). Research on the influence of institutional pressures on green innovation strategy. *IOP Conf. Ser.: Earth Environ. Sci.* 94, 012162. doi:10.1088/1755-1315/94/1/012162

Chen, H., Guo, W., Feng, X., Wei, W., Liu, H., Feng, Y., and Gong, W. (2021). The impact of low-carbon city pilot policy on the total factor productivity of listed enterprises in china. *Resources, Conservation and Recycling* 169 (2), 105457. doi:10.1016/j.resconrec.2021.105457

Dong, K., Dong, X., and Ren, X. (2020a). Can expanding natural gas infrastructure mitigate CO_2 emissions? Analysis of heterogeneous and mediation effects for China. *Energy Economics* 90, 104830. doi:10.1016/j.eneco.2020.104830

Dong, K., Hochman, G., and Timilsina, G. R. (2020b). Do drivers of CO_2 emission growth alter overtime and by the stage of economic development? *Energy Policy* 140, 111420. doi:10.1016/j.enpol.2020.111420

Duan, P. (2014). Analysis of the existing problems and countermeasures of the image of large state-owned enterprises—A state-owned enterprise as an example. *Modern Communication (Journal of Communication University of China)* 36 (07), 27–33. doi:10.3969/j.issn.1007-8770.2014.07.007

Feng, M. (2021). Innovation degree and implementation difference of local governance policies. *Academia Bimestrie* 2021 (03), 120–127. doi:10.16091/j.cnki.cn32-1308/c.2021.03.014

Feng, T., Lin, Z., Du, H., Qiu, Y., and Zuo, J. (2021). Does low-carbon pilot city program reduce carbon intensity? Evidence from chinese cities. *Research in International Business and Finance* 58 (1), 101450. doi:10.1016/j.ribaf.2021.101450

Fu, Y., He, C., and Luo, L. (2021). Does the low-carbon city policy make a difference? Empirical evidence of the pilot scheme in china with dea and psm-did. *Ecological Indicators* 122, 107238. doi:10.1016/j.ecolind.2020.107238

Guo, S., Song, Q., and Qi, Y. (2021). Innovation or implementation? Local response to low-carbon policy experimentation in China. *Rev Policy Res* 38 (5), 555–569. doi:10.1111/ROPR.12436

Guo, Y., Xia, X., Zhang, S., and Zhang, D. (2018). Environmental Regulation, Government R&D Funding and Green Technology Innovation: Evidence from China Provincial Data. *Sustainability* 10, 940. doi:10.3390/su10040940

Hall, B., and Reenen, J. (2000). How effective are fiscal incentives for R&D? A review of the evidence. *Research Policy* 29 (4), 449–469. doi:10.1016/S0048-7333(99)00085-2

Hanoteau, J., and Talbot, D. (2019). Impacts of the Québec carbon emissions trading scheme on plant-level performance and employment. *Carbon Management* 10 (3), 287–298. doi:10.1080/17583004.2019.1595154

He, J., and Tian, X. (2013). The dark side of analyst coverage: The case of innovation. *Journal of Financial Economics* 109, 856–878. doi:10.1016/j.jfineco.2013.04.001

He, L., Liu, H., and Xu, K. (2021). Impact of intellectual property protection on innovation investment of high-tech enterprises: Mediating role of new technologies and new products. *Science and Technology Management Research* 41 (15), 170–177. doi:10.3969/j.issn.1000-7695.2021.15.022

Hong, M., Chen, S., and Zhang, K. (2021). Impact of the "Low-Carbon City Pilot" Policy on Energy Intensity Based on the Empirical Evidence of Chinese Cities. *Front. Environ. Sci.* 9, 717737. doi:10.3389/fenvs.2021.717737

Hu, J., Pan, X., and Huang, Q. (2020). Quantity or quality? The impacts of environmental regulation on firms' innovation-Quasi-natural experiment based on China's carbon emissions trading pilot. *Technological Forecasting and Social Change* 158, 120122. doi:10.1016/j.techfore.2020.120122

Huang, J., Zhao, J., and Cao, J. (2021). Environmental regulation and corporate R&D investment-evidence from a quasi-natural experiment. *International Review of Economics and Finance* 72, 154–174. doi:10.1016/j.iref.2020.11.018

Huang, Q., Yu, Y., and Zhang, S. (2019). Internet development and productivity growth in manufacturing industry: Internal mechanism and China experiences. *China Industrial Economics* (08), 5–23. doi:10.19581/j.cnki.ciejournal.2019.08.001

Hunter, G. W., Sagoe, G., Vettorato, D., and Ding, J. (2019). Sustainability of low carbon city initiatives in China: A comprehensive literature review. *Sustainability* 11 (16), 4342. doi:10.3390/su11164342

IPCC (2018). Special report on global warming of 1.5°C. Available online at: https://www.ipcc.ch/sr15/ (Accessed October 06, 2018).

Jiang, W., and Kang, W. (2019). A Review on the low-carbon city study: Development and trends. *Chn. J. Urb. Environ.Stud* 07 (2), 1950006. doi:10.1142/S2345748119500064

Khanna, N., Fridley, D., and Hong, L. (2014). China's pilot low-carbon city initiative: A comparative assessment of national goals and local plans. *Sustainable Cities and Society* 12, 110–121. doi:10.1016/j.scs.2014.03.005

Kinzig, A. P., and Kammen, D. M. (1998). National trajectories of carbon emissions: analysis of proposals to foster the transition to low-carbon economies. *Global Environmental Change* 8 (3), 183–208. doi:10.1016/S0959-3780(98)00013-2

Li, D., and Zhu, J. (2019). The role of environmental regulation and technological innovation in the employment of manufacturing enterprises: Evidence from China. *Sustainability* 11, 2982. doi:10.3390/su11102982

Li, H., Wang, J., Yang, X., Wang, Y., and Wu, T. (2018). A holistic overview of the progress of China's low-carbon city pilots. *Sustainable Cities and Society* 42, 289–300. doi:10.1016/j.scs.2018.07.019

Li, L., Wang, J., and Xu, Y. (2019). The influence of pilot policy of low-carbon city on enterprise technology innovation: An empirical research based on difference-in-different model. *Ecological Economy* 35 (11), 48–54. Available online at: https://kns.cnki.net/kcms/detail/detail.aspx?FileName=STJJ201911011&DbName=DKFX2019.

Li, J., Zhang, B., and Shi, J. (2017). Combining a genetic Algorithm and support vector machine to study the f influencing CO_2 emissions in Beijing with scenario snalysis. *Energies* 10, 1520. doi:10.3390/en10101520

Li, W., and Li, Y. (2014). Does industrial policy promote corporate investment. *China Industrial Economics* 13 (5), 122–134. doi:10.19581/j.cnki.ciejournal.2014.05.010

Li, X., Guo, Y., Hou, J., and Liu, J. (2021). Human capital allocation and enterprise innovation performance: An example of China's Knowledge-Intensive service industry. *Research in International Business and Finance* 58, 101429. doi:10.1016/j.ribaf.2021.101429

Li, Y., Holgado, M., and Evans, S. (2016). "Business model innovation in state-owned and private-owned enterprises in China," in *Advances in Production Management Systems. Initiatives for a Sustainable World. APMS 2016. IFIP Advances in Information and Communication Technology*. Editors I. Nääs, O. Vendrametto, J. M. Reis, R. F. Gonçalves, M. T. Silva, G. von Cieminski, and D Kiritsis (Cham: Springer) 488, 528–535. doi:10.1007/978-3-319-51133-7_63

Li, Y., and Hu, H. (2020). Influential Factor Analysis and Projection of Industrial CO2 Emissions in China Based on Extreme Learning Machine Improved by Genetic Algorithm. *Polish Journal of Environmental Studies* 29(3), 2259–2271. doi:10.15244/pjoes/110973

Liao, G., and Shen, H. (2014). Policy burdens of state-owned enterprises: Reason, consequence and governance. *China Industrial Economics* 13, 96–108. doi:10.19581/j.cnki.ciejournal.2014.05.010

Liao, Z., Xu, C.-k., Cheng, H., and Dong, J. (2018). What drives environmental innovation? A content analysis of listed companies in china. *Journal of Cleaner Production* 198, 1567–1573. doi:10.1016/j.jclepro.2018.07.156

Lin, Y., and Liu, P. (2001). Self-generating capacity and SOE reform. *Economic Research Journal* 11, 60–70. Available online at: https://kns.cnki.net/kcms/detail/detail.aspx?FileName=JJYJ200109007&DbName=CJFQ2001.

Liu, Z., and Sun, H. (2021). Assessing the impact of emissions trading scheme on low-carbon technological innovation: Evidence from China. *Environmental Impact Assessment Review* 89, 106589. doi:10.1016/j.eiar.2021.106589

Lu, X., and Li, L. (2021). Influencing factors and the mechanisms of enterprise innovation: A literature review and prospects. *Theories* 32 (07), 55–62. doi:10.16158/j.cnki.51-1312/f.2021.07.006

Luo, R., and Guo, Y. (2021). Enterprise innovation investment, employee demand scale and employee internal composition. *Journal of Shanxi University of Finance and Economics* 43 (4), 47–62. doi:10.13781/j.cnki.1007-9556.2021.04.004

Lv, M., and Bai, M. (2021). Evaluation of China's carbon emission trading policy from corporate innovation. *Finance Research Letters* 39, 101565. doi:10.1016/j.frl.2020.101565

Ma, J., Hu, Q., Shen, W., and Wei, X. (2021). Does the low-carbon city pilot policy promote green technology innovation? Based on green patent data of Chinese A-share listed companies. *Int. J. Environ. Res. Public Health* 18 (7), 3695. doi:10.3390/ijerph18073695

National Development and Reform Commission (2010). Circular of the National Development and Reform Commission on carrying out pilot work of low carbon provinces, regions and cities. Available online at: https://www.ndrc.gov.cn/xxgk/zcfb/tz/201008/t20100810_964674.html (Accessed July 19, 2010).

National Development and Reform Commission (2012). Circular of the National Development and Reform Commission on carrying out pilot work of the second batch of national low carbon provinces, regions and cities. Available online at: https://www.ndrc.gov.cn/xxgk/jianyitianfuwen/qgzxwytafwgk/202107/t20210708_1288699.html?code=&state=123 (Accessed November 26, 2012).

National Development and Reform Commission (2017). Circular of the National Development and Reform Commission on carrying out the third batch of national low carbon cities pilot work. Available online at: https://www.ndrc.gov.cn/xxgk/zcfb/tz/201701/t20170124_962888.html (Accessed January 01, 2020).

Obenauer, M. L., and Nienburg, B. V. D. (1915). Effect of minimum-wage determination in oregon. *Monthly Review of the U.S. Bureau of Labor Statistics* 1 (3), 5–8. doi:10.2307/41823870

Pan, L., and Dong, Z. (2021). Tax incentives and corporate employment: A quasi-natural experiment from payroll tax policy. *Statistical Research* 38 (7), 100–111. doi:10.19343/j.cnki.11-1302/c.2021.07.008

Qu, Y., and Liu, Y. (2017). Evaluating the low-carbon development of urban china. *Environ Dev Sustain* 19 (3), 939–953. doi:10.1007/s10668-016-9777-8

Ren, S., Liu, D., Li, B., Wang, Y., and Chen, X. (2020). Does emissions trading affect labor demand? Evidence from the mining and manufacturing industries in China. *Journal of Environmental Management* 254, 109789. doi:10.1016/j.jenvman.2019.109789

Shen, L., Wu, Y., Lou, Y., Zeng, D., Shuai, C., and Song, X. (2018). What drives the carbon emission in the Chinese cities?-A case of pilot low carbon city of Beijing. *Journal of Cleaner Production* 174, 343–354. doi:10.1016/j.jclepro.2017.10.333

Snow, J. (1855). On the comparative mortality of large towns and rural districts, and the causes by which it is influenced. *Journal of Public Health, and Sanitary Review* 1 (4), 16–24. Available online at: https://www.webofscience.com/wos/alldb/full-record/MEDLINE:30378870 (Accessed January 10, 2010).

Song, Q., Liu, T., and Qi, Y. (2021). Policy innovation in low carbon pilot cities: lessons learned from China. *Urban Climate* 39, 100936. doi:10.1016/J.UCLIM.2021.100936

Tang, P., Yang, S., Shen, J., and Fu, S. (2018). Does China's low-carbon pilot programme really take off? Evidence from land transfer of energy-intensive industry. *Energy Policy* 114, 482–491. doi:10.1016/j.enpol.2017.12.032

The Chinese Ministry of Education (2021). Action plan for carbon neutral scientific and technological innovation in colleges and universities. Available online at: http://www.gov.cn/zhengce/zhengceku/2021-07/29/content_5628172.htm (Accessed July 12, 2021).

The State Council (2021). The Government Work Report. Available online at: http://www.gov.cn/zhengce/2021-10/24/content_5644613.htm (Accessed September 22, 2021).

Ting, H.-I., Wang, M.-C., Yang, J. J., and Tuan, K.-W. (2021). Technical expert CEOs and corporate innovation. *Pacific-Basin Finance Journal* 68, 101603. doi:10.1016/j.pacfin.2021.101603

United Nations (2015). The Paris Agreement. Available online at: https://newsroom.unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (Accessed December 12, 2015).

Wan, H., and Chen, X. (2010). Governance environment rent-seeking and transaction cost: Evidence from the non-productive expenditures of Chinese firms. *China Economic Quarterly* 9 (1), 553–570. doi:10.1382/j.Cnki.ceq.2010.02.018

Wang, X., Hu, L., and Fan, G. (2021). *Marketization index of China's provinces*. Beijing: Social Sciences Academic Press.

Wang, Y., Song, Q., He, J., and Qi, Y. (2015). Developing low-carbon cities through pilots. *Climate Policy* 15, S81–S103. doi:10.1080/14693062.2015.1050347

Wen, L., and Yan, F. (2018). Regional differences and influencing factors in the CO_2 emissions of China's power industry based on the panel data models considering power-consuming efficiency factor. *Environ Dev Sustain* 20, 1987–2007. doi:10.1007/s10668-017-9973-1

Wen, Y., Hu, P., Li, J., Liu, Q., Shi, L., Ewing, J., and Ma, Z. (2020). Does China's carbon emissions trading scheme really work? A case study of the hubei pilot. *Journal of Cleaner Production* 277, 124151. doi:10.1016/j.jclepro.2020.124151

Xiong, G., Shi, D., and Li, M. (2020). The effect of low-carbon pilot cities on the green technology innovation of enterprises. *Science Research Management* 41 (12), 93–102. doi:10.19571/j.cnki.1000-2995.2020.12.008

Xu, J., and Cui, J. (2020). Low-carbon cities and firms' green technological innovation. *China Industrial Economics* 12, 178–196. doi:10.3969/j.issn.1006-480X.2020.12.016

Yamazaki, A. (2017). Jobs and climate policy: Evidence from British Columbia's revenue-neutral carbon tax. *Journal of Environmental Economics and Management* 83, 197–216. doi:10.1016/j.jeem.2017.03.003

Yang, X., and Li, R. (2018). Investigating low-carbon city: Empirical study of Shanghai. *Sustainability* 10 (4), 1054. doi:10.3390/su10041054

Yu, D.-J., and Li, J. (2021). Evaluating the employment effect of china's carbon emission trading policy: Based on the perspective of spatial spillover. *Journal of Cleaner Production* 292 (490), 126052. doi:10.1016/j.jclepro.2021.126052

Yu, P., Cai, Z., and Sun, Y. (2021). Does the emissions trading system in developing countries accelerate carbon leakage through OFDI? Evidence from China. *Energy Economics* 101, 105397. doi:10.1016/j.eneco.2021.105397

Yu, Y., and Zhang, N. (2021). Low-carbon city pilot and carbon emission efficiency: Quasi-experimental evidence from china. *Energy Economics* 96 (2), 105125. doi:10.1016/j.eneco.2021.105125

Zeng, J., and Zhu, H. (2014). "R&D human capital allocation in high-tech industries and its economic effects," in 2014 Seventh International Joint Conference on Computational Sciences and Optimization, Beijing, China, 4-6 July 2014, 218–222. doi:10.1109/CSO.2014.47

Zheng, J., Shao, X., Liu, W., Kong, J., and Zuo, G. (2021a). The impact of the pilot program on industrial structure upgrading in low-carbon cities. *Journal of Cleaner Production* 290, 125868. doi:10.1016/J.JCLEPRO.2021.125868

Zheng, Y., Sun, X., Zhang, C., Wang, D., and Mao, J. (2021b). Can emission trading scheme improve carbon emission performance? Evidence from China. *Front. Energy Res.* 9, 759572. doi:10.3389/fenrg.2021.759572

Zhong, C., Hu, D., and Huang, Y. (2020). Evaluation of Green innovation effect of low carbon pilot policy — An empirical study based on the data of listed firms in China. *Science and Technology Progress and Policy* 37 (19), 113–122. doi:10.6049/kjjbydc.2020050667

Zhong, S., Xiong, Y., and Xiang, G. (2021). Environmental regulation benefits for whom? Heterogeneous effects of the intensity of the environmental regulation on employment in China. *Journal of Environmental Management* 281 (69), 111877. doi:10.1016/j.jenvman.2020.111877

Zhu, Q., and Li, M. (2018). A study on artificial intelligence, technological progress and the optimization countermeasures of labor structure. *Science and Technology Progress and Policy* 35 (6), 36–41. doi:10.6049/kjjbydc.2017090391

Zhuang, Z., Jia, H., and Li, X. (2021). Research on the impact of intellectual property rights protection on firm innovation—Based on the perspective of firm heterogeneity. *Nankai Business Review* 29, 1–22. Available online at: http://kns.cnki.net/kcms/detail/12.1288.f.20210923.1037.002.html.

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.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 02 February 2022
doi: 10.3389/fenrg.2021.821242

Do Green Credit Affect Green Total Factor Productivity? Empirical Evidence from China

Qingqing Hu[1], Xue Li[2] and Yanhong Feng[3]*

[1]School of International Studies, Hunan Institute of Technology, Hengyang, China, [2]School of Economics and Statistics, Guangzhou University, Guangzhou, China, [3]School of Economics, Management and Law, University of South China, Hengyang, China

Understanding the effects of green credit on green total factor productivity (GTFP) is conductive to promoting the sustainable economy development. This paper examines the total effects, influence mechanism, and heterogeneous impacts of green credit on GTFP based on GTFP data of 30 provinces in China from 2008 to 2017. The findings show that, firstly, on the whole, green credit significantly increases GTFP, which is tested by the panel regression model. Secondly, according to the result of the panel quantile model, the increasing effect of green credit on GTFP is strengthened by the improvement of GTFP. Thirdly, green credit has heterogeneous impact on GTFP, which is reflected in economic development with different level, especially for different degrees of environmental regulation. Fourthly, under the full samples, green credit impacts GTFP through green technology innovation, but it has no effect on energy consumption structure. Besides, the influence mechanism is heterogeneous in the variation of sample characteristics. Finally, some significant policy recommendations are provided for policymakers based on these conclusions.

Keywords: green credit, green total factor productivity, heterogeneous effects, mediating effects, green technology innovation

OPEN ACCESS

Edited by:
Xiaohang Ren,
Central South University, China

Reviewed by:
Yan Zheng,
Central South University, China
Zhifeng Liu,
Hainan University, China
Jie Chen,
Yangzhou University, China

****Correspondence:***
Yanhong Feng
1111864008@e.gzhu.edu.cn

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *24 November 2021*
Accepted: *20 December 2021*
Published: *02 February 2022*

Citation:
Hu Q, Li X and Feng Y (2022) Do Green Credit Affect Green Total Factor Productivity? Empirical Evidence from China. Front. Energy Res. 9:821242. doi: 10.3389/fenrg.2021.821242

INTRODUCTION

The United Nations environmental programme points that financing is one of the greatest challenges to promote green economy transformation. In fact, the government-centered financing mode cannot be adapted to the requirements of sustainable development (Ming et al., 2014). However, as an act of the financial institution, it actively supports the financing of environmental protection and energy conservation projects. Green finance can guide social funds to the field of green production and promote green economic transformation through the innovation of financial instruments. Then, for most developing countries, "green credit" still plays a role of the main channel of green project financing, and also the main force to build green financial system. Moreover, GTFP is developed based on the traditional total factor productivity accounting framework, which takes both environmental factors and the impact of energy consumption into consideration (Mohtadi, 1996). Consequently, GTFP is considered as a suitable indication for measuring the sustainable development of a country or region (Li et al., 2020a; Li et al., 2021a). In view of the above analysis, it is of great practical significance to study the impact of green credit on the GTFP.

Existing researches on GTFP mainly focuses on its measurements and influencing factors. Parametric method and non-parametric method are common ways to measure GTFP. Among these measurement methods, Solow residual method and stochastic frontier analysis method are representative methods of parametric methods (Carroll et al., 2011). The most widely used non-parametric method is data envelopment analysis (DEA) (Lin and Chen, 2018; Demirtaş et al., 2020). Then, the influencing factors of GTFP are rich and diverse. In general, the existing studies mainly study the influencing factors of GTFP from the following perspectives: firstly, technological progress or innovation is an important factor. Some researchers examine the relationship between manufacturing GTFP and technological progress, and also prove that technological progress plays a significant role in improving manufacturing GTFP (Shi and Li, 2019). Innovation promotes GTFP; whereas economic policy uncertainty inhibits GTFP based on research of 30 provinces in China from the period 2005 to 2016 (Yuan et al., 2021), as well as the revelatory from its affect on the corporate risk-taking and carbon futures prices (Wen et al., 2021a; Wen et al., 2021b). Base on the research of 285 Chinese cities from 2003 to 2017, green technology progress is conducive to the improvement of urban GTFP (Yu et al., 2021). Besides, the major crisis events and important political and economic events also have certain influence on market, exchange rate and global efficiency (Li et al., 2020b; Hou et al., 2021; Zheng et al., 2021), which effect GTFP indirectly to some extent. Secondly, environmental regulation has a significant positive effect on the GTFP (Liang et al., 2020). Thirdly, appropriate fiscal decentralization can improve GTFP; otherwise, GTFP decreases (Song et al., 2018). In addition, other study indicates that GTFP is negatively influenced by coal intensity and industrial structure (Zhang et al., 2016). In particular, a few scholars analyze the relationship between financial development and GTFP. For example, by examining 40 countries from 1991 to 2014, they find that there is an inverted U-shaped relationship between financial development and GTFP (Li and Liao, 2020). It can be seen that GTFP is affected by different factors with different forms and directions.

However, the existing literature pays less attention to the impact of green credit on GTFP and its heterogeneity directly. Previous studies mainly pay more attention to the role of green credit or green finance in green economic growth or sustainable development. A research believes that green credit is a sustainable financing method, that is, banks provide financing facilities for green projects through credit that can achieve the purpose of guiding sustainable development (Jeucken, 2001). Another research argues that green finance is an innovative move in the development of financial institutions, which can realize the coordinated and healthy development of economy and environment (Scholtens, 2006). Besides, an empirical research verifies that the development of green credit can promote green economic growth (Hu et al., 2011). Actually, green finance can create a win-win situation regarding economic development and the environment through developing a model based on the theory of the environmental Kuznets curve (Zhou et al., 2020). In addition, in view of the coordination between green finance and green economy, some investigations prove that the coordination degree of green finance and the green economy is relatively low and show strong spatial dependence (Liu et al., 2020). From the above, it should be noted that few studies have investigated the relationship between green credit and green economic growth from the perspective of GTFP, and even the heterogeneous influence of green credit on GTFP.

As an important financial means, green credit can guide the capital flow to green and low-carbon areas. Green credit is the main force of ecological civilization construction, which is conducive to curb the blind expansion of high energy consumption and heavy pollution industries (Zhang et al., 2011), and plays an important role in promoting the development of GTFP. In addition, the impact of green credit on GTFP is heterogeneous under different factors. On this basis, taking China as an example, this study of the impact of green credit on GTFP is of great significance to the sustainable development of a country's economy. Here are the main contributions as follows.

Firstly, from the perspective of efficiency, the impact of green credit on green economic development by measuring GTFP is studied for the first time. This is a significant supplement to the previous research in terms of green finance and green economy development. Previous studies pay attention to the relationship between green finance and green economic growth, but the literatures of the impact of green credit on GTFP is relatively scarce. Because efficiency of green development is an important factor of sustainable development, it is significant to explore the impact of green credit on GTFP.

Secondly, the heterogeneous impact of green credit on GTFP is investigated from different perspectives, which also provides new empirical research perspectives and evidences for their relationships. However, the heterogeneous effect of green credit on GTFP has not attracted more attention. On the one hand, the promotion effect is heterogeneous under different GTFP levels. Specifically, with the improvement of the GTFP level, the promotion effect of green credit on GTFP is significantly strengthened. On the other hand, the impact of green credit on GTFP is closely related to the sample characteristics such as different economic development levels, especially environmental regulation degrees.

Thirdly, based on the heterogeneous impact under the characteristics of different samples, the impact mechanism and its heterogeneity are further discussed, which helps to better understand the impact of green credit on GTFP. This paper finds that green credit can impact GTFP through green technology innovation, but has no effect through energy consumption structure on the whole. However, the impact mechanism of green credit on GTFP is heterogeneous under different sample characteristics.

The remainder of this paper is arranged as follows. **Section 2** expounds the research hypothesis and introduces the model and data. **Section 3** studies the total effects and influence mechanism of green credit on GTFP. Then, the heterogeneity of the impact of green credit on GTFP is tested based on the characteristics of different samples in **section 4**. **Section 5** not only discusses the deviation degree of different subsamples from the full sample, but also analyzes the heterogeneity of the impact mechanism of green credit on GTFP under different samples. Lastly, **section 6** concludes our paper with a note on limitation and implications.

HYPOTHESES, METHOD, AND DATA

Hypotheses

Green credit improves GTFP. Credit capital is an important driving force of modern economic development, which supports and guides the development of a real economy. Based on the national environmental protection policy and related industrial policies, green credit is an important part of "Green development," and guided by the core value of social responsibility (He et al., 2019). Through differentiated monetary and financial policies, green credit guides funds to invest in green fields by utilizing credit tilt and interest rate floating, and then forms green investment and provides capital support for green economic growth (Soundarrajan and Vivek, 2016). Meanwhile, by controlling the direction of credit, polluting industrial structures can be eliminated or restructured, and then promote green economic growth. A research theoretically confirms that green credit can promote cleaner production innovation (Li et al., 2018). For the enterprises, green credit provides R&D investment capital for their green technology innovations, which increasingly becomes an important driving force to improve their competitive advantages and green transformation (He et al., 2019). Green credit is the innovation of financial concepts, which reflects the sustainable development of the economy and Society (Xu, 2020). Therefore, green credit has a promoting effect on the promotion of GTFP. Based on the above analysis, the following hypothesis is put forward:

H1: Green credit has a promoting effect on GTFP.

Green credit aims to support regional energy conservation and environmental protection industries. These are capital-intensive and technology-intensive industries with a long output cycle and require a large amount of capital input and capital support (Feng et al., 2020; Huang et al., 2021). Therefore, the full improvement of green credit on GTFP requires a certain amount of capital and technology accumulation. When the certain region's GTFP is low, it means that they don't have good green technology conditions and infrastructure. Hence, it is difficult for green credit to produce effects in a short time, and also has little effect on the improvement of GTFP. With the improvement of GTFP, the enterprises in certain areas have better green technology level and infrastructure, and also have more confidence in green development. Under this condition, green credit further provides financial support for the promotion of green development level. Therefore, enterprises pay more and more attention to green development and adopt environment-friendly technology to carry out green production actively. And then the production efficiency of enterprise is improved greatly due to the Capital and technological advantages, which further improves GTFP in the region further.

H2: The promoting effect is heterogeneous with the change of GTFP level.

Influenced by economic development level and environmental regulation, the impact of green credit on GTFP is heterogeneous. Firstly, the impact of green credit on GTFP is related to the level of economic development. On one hand, economic development brings technological progress, and technological progress is conducive to breaking through the technical bottleneck of the green industry and then promoting green economic development (Meirun et al., 2021). Compared to areas with a low level of economic development, the green economy development level of areas with a high level of economic development is also higher. In this case, the effect of introducing green credit to different economic development level areas is different. Therefore, the difference in economic development level makes different impact of green credit on GTFP.

H3: With different economic development level, the impact of green credit on GTFP is heterogeneous.

In addition, environmental regulation is one of the most effective measures to solve the problem of excessive use of elements and externality of environmental pollution (Li and Wu, 2017). Compared with the low-level environmental regulation areas, the areas with high environmental regulation need to invest more funds and energy for pollution control and emission reduction. In this case, the introduction of green credit can provide financial support for environmental governance. Therefore, with different environmental regulations, the impact of green credit on GTFP is heterogeneous. From the above analysis, the following hypothesis is also provided:

H4: With different environmental regulation degree, the impact of green credit on GTFP is heterogeneous.

Green credit may impact GTFP through two channels of green technology innovation and energy consumption structure. On one hand, green credit guides capital flow to green and low-carbon areas, which has a profound impact on the business decision-making like green technology innovation investment of relevant enterprises (Li et al., 2018). In other words, green credit can improve the green technology innovation due to solving the financing problem for environmental protection enterprises to a certain extent. And then, green technology innovation can significantly promote the improvement of GTFP (Wang et al., 2021). Therefore, green credit may affect GTFP through green technology innovation.

On the other hand, through controlling the scale and direction of credit, green credit transfers funds to green industries such as new energy, energy conservation, and environmental protection, and help enterprises to eliminate with high energy consumption and high pollution (Soundarrajan and Vivek, 2016), which changes the energy consumption structure. In addition, green credit will attract extensive attention from the public. With consideration for their own health, consumers will also require enterprises to reduce the emission of high-carbon pollutants. Hence, it indirectly promotes enterprises to enhance their sense of social responsibility and optimize the energy consumption structure. The increase of the proportion of clean energy is conducive to the reduction of pollutant emissions (Dogan and Seker, 2016; Zoundi, 2017), and then improve energy efficiency. Therefore, green credit may affect GTFP through energy consumption structure. Here are the following hypotheses:

H5a: Green credit influence GTFP through the mediating variable of green technology innovation.

H5b: Green credit impact GTFP through the mediating variable of energy consumption structure.

Methods

Benchmark Panel Regression Model

To test the impact of green credit on GTFP, this paper refers to some existing studies and establishes the following panel benchmark panel regression model (Tuzcuoğlu, 2020; Chen et al., 2021):

$$GTFP_{it} = a_0 + \alpha GC_{it} + \beta Control_{it} + T_t + \varepsilon_{it} \quad (1)$$

Where, the subscripts i and t represent the province and year respectively. GTFP is the explained variable, namely green total factor productivity. GC is the core explanatory variable, namely green credit. Control stands for controlling variables. T is the year fixed effect, and ε_{it} is the stochastic error term. In the model, individual characteristic variables such as the scale of economic development are controlled, therefore, there's no need to add individual fixed effect item. The same is true for the following model Settings.

Panel Quantile Model

In order to further test the heterogeneity of the impact of green credit on GTFP under different levels of GTFP, the panel quantile model which is considered superior to OLS for verification is used (Li et al., 2021b). Compared with ordinary regression methods, quantile regression can make an estimate of explanatory variables at various quantiles in the conditional distribution (Canay, 2011), and it can effectively avoid the heteroscedasticity problem of the data. Therefore, the following panel quantile regression model is established:

$$Q_{\tau_{it}}(GTFP|GC) = a_0 + \alpha^{\tau} GC_{it} + \beta^{\tau} Control_{it} + T_t + \varepsilon_{it}^{\tau} \quad (2)$$

Where $Q_{\tau_{it}}(GTFP|\bullet)$ represents the conditional quantile of GTFP at τ_{it} quantile, $\tau \in (0,1)$. The implication of the rest variables is consistent with Formula **(1)**.

Mediating Effect Model

In addition, in order to analyze the impact mechanism of green credit on GTFP, the mediation effect model for verification is used. Firstly, verify the comprehensive effect of green credit on GTFP, the intermediary variables are temporarily not added to the model, as shown in Formula **(1)**). Secondly, in order to identify whether green credit has an impact on the intermediary variables, the intermediary variables are taken as the explained variables, and the green credit is taken as the core explanatory variable, as the following Formula **(3)**. Finally, Formula **(4)** is constructed which including the explained variables, intermediary variables, core explanatory variables, and control variables, in order to test the mediating effect of intermediary variables in the impact of green credit on GTFP.

$$M_{it} = a_0 + \alpha 1 GC_{it} + \beta Control_{it} + T_t + \varepsilon_{it} \quad (3)$$

$$GTFP_{it} = a_0 + \alpha 2 GC_{it} + \lambda M_{it} + \beta Control_{it} + T_t + \varepsilon_{it} \quad (4)$$

Where M is the intermediary variable, and the implication of the rest variables are consistent with Formula **(1)**.

Based on these formulas, the improved stepwise regression method of causality test is adopted for testing by taking the practice of Wen and Ye (2014) as reference (Wen and Ye, 2014). The specific inspection steps are as follows:

Step 1 is to test the regression coefficient α in formula **(1)**. If α is significant, it continues step 2, otherwise, the test will be stopped.

Step 2 is to test regression coefficient α_1 and λ respectively in formula **(3)** and **(4)**. If α_1 and λ are both significant, it has a mediating effect and continues to step 3. Otherwise, the bootstrap method with high statistical power was used to test the significance of $\alpha_1 * \lambda$. If $\alpha_1 * \lambda$ is significant, it continues step 2, otherwise, the test will be stopped and it means no mediating effect.

Step 3 is to test regression coefficient α_2 in formula **(4)**. If α_2 is significant, it means R&D investment or energy consumption structure has partial mediating effect; Otherwise, it indicates that there is a complete mediating effect.

Variables and Data Source

Measurement of GTFP

This paper measures GTFP index by the DEA method. Compared with Solow residual method and stochastic frontier analysis method, DEA has been widely used in GTFP calculation, which can avoid the deviation caused by setting production function form in advance. Non-radial, non-angular SBM directional distance function and GML index (Oh, 2010) are adopted in this work measuring the GTFP level of each province in China. The basic idea is to treat each province as a decision-making unit, and each unit includes input, desired output, and undesired output. Assuming that each province uses M kinds of inputs $x = (x_1, \cdots, x_m, \cdots, x_M) \in R_M^+$, produces N kinds of expected outputs $y = (y_1, \cdots, y_n, \cdots, y_N) \in R_N^+$, and emissions of J kinds of undesired outputs $b = (b_1, \cdots, b_j, \cdots, b_J) \in R_J^+$. Oh (2010) constructed the global production possibility set (Oh, 2010). Thus, this paper's global production possibility set is shown in Formula **(5)**.

$$P^G(x) = \left\{ (y^t, b^t): \sum_{i=1}^{I} z_i^t y_{in}^t \geq y_{in}^t, \forall n; \sum_{i=1}^{I} z_i^t b_{ij}^t \geq b_{ij}^t, \forall j; \sum_{i=1}^{I} z_i^t x_{im}^t \geq x_{im}^t, \forall m; \sum_{i=1}^{I} z_i^t = 1, \forall i \right\} \quad (5)$$

Where $i = 1, 2, \cdots, I$ denotes the province; $t = 1, 2, \cdots, T$ represents the period. z_i^t represents the weight of each cross-sectional observation value.

Because input and output slack variables have an impact on efficiency, the SBM direction function is applied by considering undesired output (Fukuyama and Weber, 2009). The SBM direction function is shown in Formula **(6)**.

$$\vec{S}_v^G\left(x^{t,i}, y^{t,i}, b^{t,i}, g^x, g^y, g^b\right) = \max_{s^x, s^y, s^b} \frac{\frac{1}{M}\sum_{m=1}^{M}\frac{s_p^x}{g_m^x} + \frac{1}{N+J}\left(\sum_{n=1}^{N}\frac{s_n^y}{g_n^y} + \sum_{j=1}^{J}\frac{s_j^b}{g_j^b}\right)}{2} \quad (6)$$

$$s.t. \sum_{i=1}^{I} z_i^t x_{im}^t + s_m^x = x_{im}^t, \forall m;$$

$$\sum_{i=1}^{I} z_i^t x_{in}^t - s_n^y = y_{i,n}^t, \forall n;$$

TABLE 1 | The selection index of GTFP measurement.

Indicator		Measurement
Input	Labor input	The employment number throughout the year
	Capital input	Perpetual inventory method is applied for the fixed asset stock shown in the price in 2000
	Resources Input	Energy consumption showed in standard coal
Output	Desirable output	GDP in the price in 2000
	Undesirable Output	The emission of COD and SO_2 in industrial wastewater

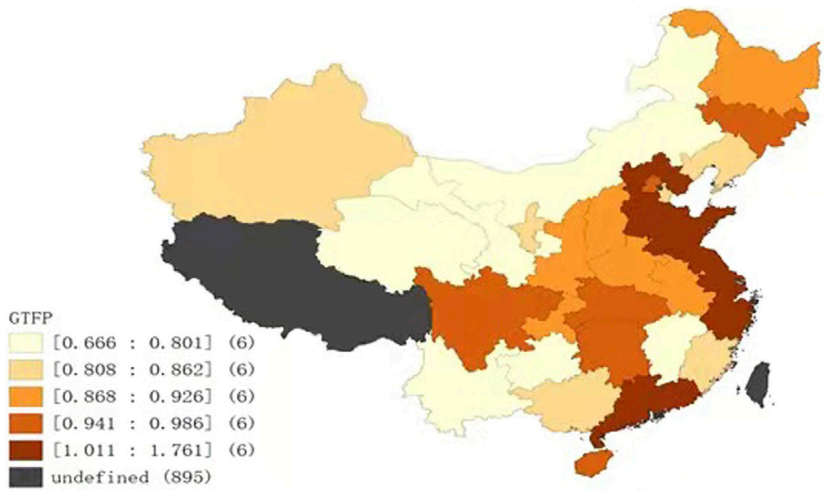


FIGURE 1 | Mean GTFP values from 2008 to 2017.

$$\sum_{i=1}^{I} z_i^t b_{ij}^t + s_j^b = b_{i,j}^t, \forall j;$$

$$\sum_{i=1}^{I} z_i^t = 1, z_i^t \geq 0, \forall i;$$

$$s_m^x \geq 0, \forall m; s_n^y \geq 0, \forall n; s_j^b \geq 0, \forall j$$

Further, according to the research of Oh (2010) (Oh, 2010), the GML index is established as shown in Formula **(7)**.

$$GML_t^{t=1} = \frac{1 + \vec{S}_v^G (x^t, y^t, b^t, g^t)}{1 + \vec{S}_v^G (x^{t+1}, y^{t+1}, b^{t+1}, g^{t+1})} \tag{7}$$

GML represents the growth rate of GTFP relative to the former period. When $GML_t^{t+1} > 1$, it illustrates that from period t to t + 1, the GTFP in this province has increased; when $GML_t^{t+1} < 1$, it illustrates that from period t to t + 1, the GTFP in this province has decreased; when $GML_t^{t+1} = 1$, it illustrates that from period t to t + 1, the GTFP in this province has not changed. Therefore, each province's GTFP can be calculated by Formula **(8)**.

$$GTFP_i^t = GML_i^t \times GTFP_i^{t-1} \tag{8}$$

The measurements of GTFP are including input elements and output elements. Among them, the input elements include labor input, capital input, and resource input; whereas the output elements include desirable outputs and undesirable outputs. The variables involved in GTFP measuring and their measurement methods are shown in **Table 1**. **Figure 1** reports the average distribution of GTFP levels of sample provinces and cities during the investigation period (The figure only shows sample provinces and cities in this research, excluding sea areas, etc.).

Measurement of Other Variables

For the green credit (GC) index, according to Guo et al. (Guo et al., 2019), the proportion of interest expenditure in the six high-energy-consuming industries is adopted for its measurement. However, the proportion of interest expenditure of the six industries is a reverse index to measure the green credit, so this paper measures the green credit by taking 1 to minus the proportion of interest expenditure of the six industries. Six high energy-consuming industries include chemical raw materials and chemical products manufacturing industry, non-metallic mineral products industry, ferrous metal smelting and rolling processing industry, non-ferrous metal smelting and rolling processing industry, petroleum processing coking and nuclear fuel processing industry and power, thermal production and supply industry.

In addition, some relevant variables to control the impact of green credit on GTFP are also introduced. Due to the numerous influencing factors of GTFP, five control variables are added, namely environmental regulation, FDI, GDP, industrial structure,

TABLE 2 | Controlling variables.

Type	Variable name	Variable	Measurement
Control variables	Environmental regulation	ER	Ratio of the investment in industrial pollution of every province to regional GDP.
	Foreign direct investment	FDI	Ratio of the foreign direct investment in the actual use of every province to regional GDP.
	Economic development level	GDP	Ratio of regional GDP per capita to GDP per capita
	Industrial structure	IS	The sum of the proportion of the added value of the three industries accounting for the added value of the primary industry
	Human capital	HC	Average years of education

TABLE 3 | Descriptive statistics of variables.

Variable	Obs	Mean	Std.Dev	Min	Max
GTFP	300	0.9306	0.2413	0.5341	2.1939
GC	300	0.4557	0.1459	0.0940	0.7795
GDP	300	0.0752	0.0369	0.0304	0.2166
IS	300	22.5395	42.7850	3.4814	297.1570
ER	300	0.0015	0.0014	0.0001	0.0110
FDI	300	2.3660	2.1474	0.0401	12.0993
HC	300	9.6832	1.1500	6.9915	13.5149

and human capital into the modeling process based on the existing research (Kong et al., 2021; Yu et al., 2021). The detailed description and calculation methods of the above variables are shown in **Table 2**.

The research targets are 30 provinces in China (except Tibet). Considering the availability of provincial data, the data frequency selected in this paper is annual data, and the time dimension of the selected data is from 2008 to 2017. The data come from the National Bureau of Statistics, the Regional Statistical Yearbook, the China Industrial Statistical Yearbook, the China Science and Technology Statistical Yearbook, and EPS. Some missing data are supplemented by the interpolation method.

Descriptive Statistics

Table 3 reports the description of each variable statistics results. The minimum value of GTFP is 0.534104, the maximum value is 2.193947, and the mean value is 0.930598, indicating that the overall level of GTFP is low. The minimum value of green credit is 0.093954, the maximum value is 0.779496, and the mean value is 0.455714, showing that the overall level of green credit was moderate. In order to clearly understand the GTFP and time change trend of green credit, the GTFP average and green credit average time trend diagram is shown in **Figure 2A**. Moreover, in order to further analyze the heterogeneity between GTFP and the green credit with different sample characteristics, all samples are grouped by 50% quantile of the economic development level, and degree of environmental regulation. The average time trend diagram of GTFP and green credit under different samples are shown in **Figures 2B,C**.

Figure 2 shows the annual mean trend of GTFP and green credit across the country in different subsamples. From **Figure 2A** GTFP shows a trend of the first decline and then rise. To be specific, GTFP shows a downward trend from 2008 to 2014; whereas it begins to increasing after 2014. Overall, the green credit shows a trend of rising. From **Figure 2B**, among the provinces with different economic development levels, the annual mean values of GTFP and green credit in the provinces with lower economic development levels are much higher than those in the provinces with higher levels. It can be seen that the average levels of GTFP and green credit are significantly different in regions with different levels of economic development. **Figure 2C** shows that provinces with higher levels of environmental regulation have higher GTFP and green credit average than in the low-level province. The GTFP gap gradually increases with time. In conclusion, the average levels of GTFP and green credit in regions with different environmental regulation degrees are heterogeneous.

Table 4 is the Pearson correlation matrix, which reports the correlation coefficients among variables. It shows that the correlation coefficient is significantly positive between GTFP and green credit, and also between GTFP and GDP, but significantly negative between GTFP and environment, which suggests that there is a positive correlation connection between GTFP and green credit.

TOTAL EFFECT AND MECHANISM ANALYSIS

Next, the stationarity test and other related preprocessing on the variables are carried out. Then, the panel benchmark regression model is used to test the impact of green credit on GTFP as a whole. Finally, the panel quantile regression model is used to analyze the heterogeneity of the impact of green credit on GTFP with different GTFP levels.

Table 5 reports the stationarity test results of each variable. In this paper, two common methods are used to test the stationarity of data. The first method is the Levin-Lin-Chu unit-root test (Levin et al., 2002); the second one is the standard Augmented Dickey-Fuller *t*-test (Dickey and Fuller, 1981). **Table 5** reports the test results of these two methods, which show that the null hypothesis of the existence of unit roots can be rejected at the significance level of 1%, that is, the variables are considered to be stable.

Benchmark Regression Analysis of GC on GTFP

Table 6 shows the results based on the benchmark panel regression model, i.e. the model parameter estimation results

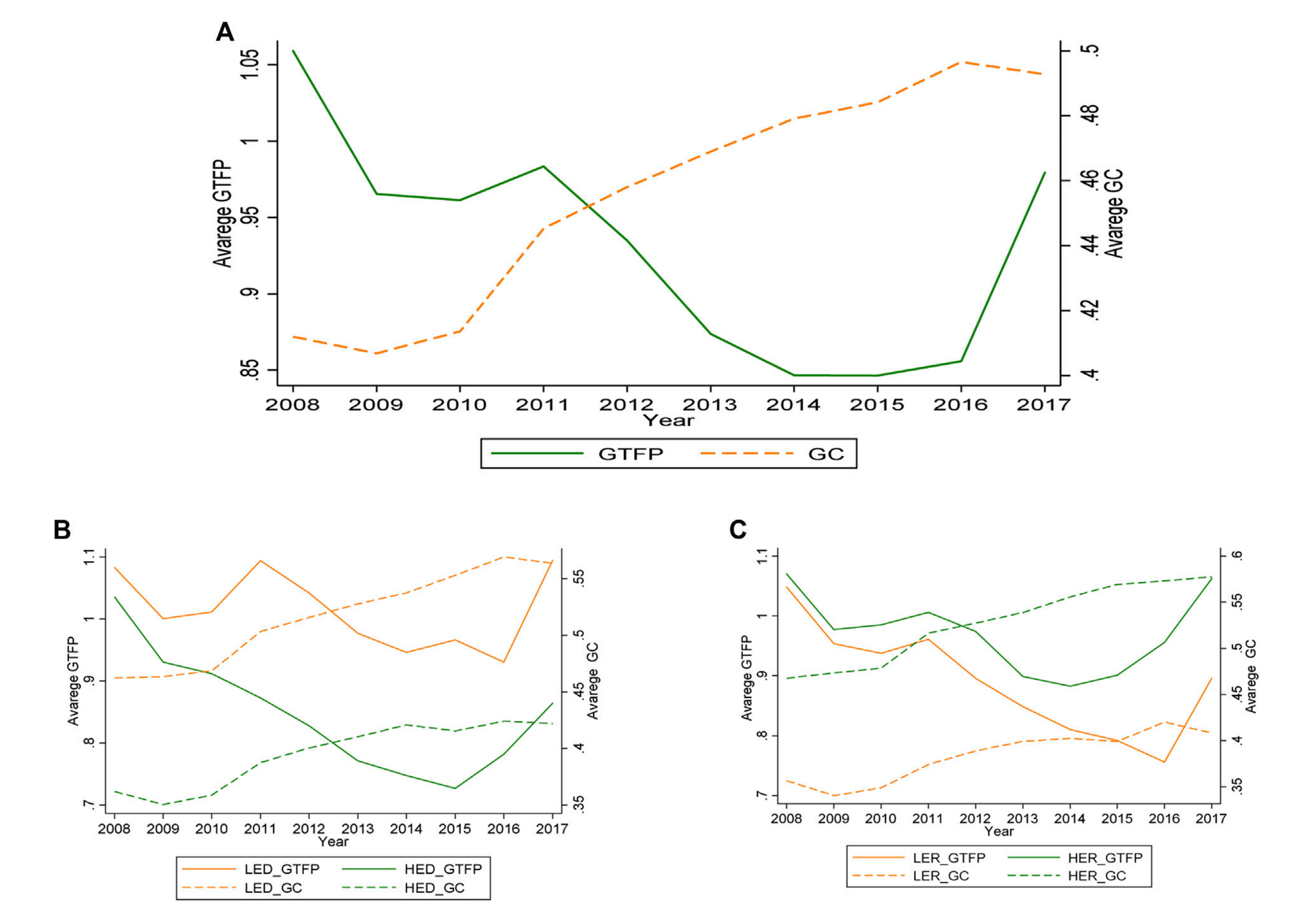


FIGURE 2 | The annual mean time trend of GTFP and GC.

TABLE 4 | Results of the variable correlation coefficient.

	GTFP	GC	GDP	IS	ER	FDI	HC
GTFP	1						
GC	0.4170*	1					
GDP	0.2537*	0.4589*	1				
IS	0.0726	0.2982*	0.7615*	1			
ER	−0.1305*	−0.3242*	−0.2246*	−0.1566*	1		
FDI	0.0555	0.2818*	0.4577*	0.3101*	−0.1844*	1	
HC	0.0733	0.4867*	0.7038*	0.7081*	−0.1868*	0.3544*	1

of Formula **(1)**. As can be seen as below, the improvement of green credit is conducive to the improvement of GTFP. In the column (1) and (2), the baseline regression results without considering control variables show that green credit has a significant promoting effect on the improvement of GTFP, whether control the time effect or not. In order to control the influence of other variables on GTFP, the influence of green credit on GTFP by introducing controlled variables is analyzed. Columns (3) and (4) represent situations that consider control variable without or with time effect, respectively. The regression coefficients of green credit in column (3) and (4) are 0.7436, 0.8047, which are significant at the significance level of 1%. It indicates that the improvement of green credit is conducive to the improvement of GTFP, which proves the Hypothesis 1. On one hand, green credit guides funds to invest in green fields, and then forms green investment and provides capital support for green economic growth (Soundarrajan and Vivek, 2016). On the other hand, by controlling the direction of credit, polluting industrial structures can be eliminated or restructured, and then promote GTFP.

TABLE 5 | The results of Unit root tests.

Variables	LLC	Fisher-ADF
GTFP	−6.4961***	5.2005***
GC	−8.468***	6.8828***
GDP	−9.6355***	10.1498***
IS	−4.4108***	8.6346***
ER	−11.0416***	8.8103***
FDI	−8.6559***	6.5201***
HC	−8.9256***	10.1775***

LLC denotes the Levin-Lin-Chu unit-root test; Fisher-ADF denotes the standard Augmented Dickey–Fuller t-test; ***p < 0.01, **p < 0.05, *p < 0.1.

Robustness Test

Endogeneity Problem

The robustness test results in the column (1)–(4) of **Table 7** indicate that the estimated results are robust. This paper carries out a robustness test from the following three perspectives. Firstly, to alleviate the model of endogenous, the one-period-lagging green credit is introduced as a tool variable, and GMM model are used for estimation (Column (1)). Secondly, considering the lag effect of GTFP, it introduces one-period-lagging GTFP into the fixed panel model for estimation (Column (2)). Thirdly, due to the large time span involved in the sample, the sample time is shortened to 2011–2017, and the panel benchmark regression model is used for estimation (Column (3)). The regression results of the columns (1), (2) and (3) show that green credit has a promoting effect on GTFP significantly. Compared with the regression results in the column (4) in **Table 6**, the sign of the green credit regression coefficient in the robustness test results is same, but there are slight differences in the absolute value and significance of the coefficient, which indicating that the estimation results of the benchmark regression model are robust.

Test of Nonlinear Relationship

In order to test the nonlinear relationship between green credit and GTFP, we take references of the existing studies (Matei, 2020; Li et al., 2021c), and add the green credit squared item (GC2) in the benchmark model. The estimated results are shown in Column (4) in **Table 7**. The regression coefficient of green credit is significant at the level of 1% significantly, whereas the green credit squared item (GC2) is not significant. Hence, it indicates that green credit and GTFP don't have nonlinear relationship, which means that the conclusion of linear benchmark regression is robust.

Multicollinearity Problem

Considering that multicollinearity may lead to the deviation of the estimation results, the variance inflation factor (VIF) of the regression model is calculated to test whether multicollinearity exists in the multivariable model or not. As can be seen from **Table 8**, VIF of all influencing factors is less than 10. In addition, the mean VIF is 2.6, also less than 10. Therefore, it can be considered that there is no multicollinearity between explanatory variables and control variables, which indicates that the results of the benchmark regression model are more reliable.

Influnece Mechanism Test

In this subsection, green technology innovation and energy consumption structure are selected as mediating variables to test the mediating effect of green credit impact on GTFP respectively. In this test, green technology innovation (GTI) is measured by the logarithm of green patent application numbers. Energy consumption structure (ECS) is measured by taking 1 minus the proportion of coal terminal consumption that equivalent to standard coal in energy terminal consumption. The data are from the regional statistical yearbook and China Statistical Yearbook on Science and

TABLE 6 | Benchmark regression results.

Variables	Ming et al. (2014)	Mohtadi, (1996)	Li et al. (2021a)	Li et al. (2020a)
	GTFP	GTFP	GTFP	GTFP
GC	0.6895***	0.8034***	0.7436***	0.8047***
	(0.0871)	(0.0810)	(0.1029)	(0.1009)
GDP			2.6479***	1.4605***
			(0.5930)	(0.5539)
IS			−0.0007	−0.0009***
			(0.0005)	(0.0003)
ER			1.8274	4.8595
			(9.4769)	(6.7352)
FDI			−0.0123*	−0.0177***
			(0.0065)	(0.0037)
HC			−0.0645***	−0.0013
			(0.0170)	(0.0162)
Constant	0.6164***	0.7282***	1.0580***	0.6779***
	(0.0416)	(0.0377)	(0.1443)	(0.1198)
Time fixed effects	no	yes	no	yes
Observations	300	300	300	300
R-squared	0.3048	0.1739	0.2519	0.3356

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

TABLE 7 | Robustness regression results.

Variables	Ming et al. (2014)	Mohtadi, (1996)	Li et al. (2021a)	Li et al. (2020a)
	GTFP	GTFP	GTFP	GTFP
GC	0.8482***	0.2032***	0.9653***	0.8296***
	(0.1065)	(0.0719)	(0.1323)	(0.3103)
GC2				−0.0288
				(0.4056)
L.GTFP		0.8727***		
		(0.1227)		
GDP	1.6674**	0.2823	2.0008**	1.4698***
	(0.7165)	(0.3372)	(0.8261)	(0.5525)
IS	−0.0011**	−0.0004	−0.0014***	−0.0009**
	(0.0005)	(0.0003)	(0.0004)	(0.0004)
ER	5.9165	−1.5450	5.4658	4.9042
	(10.6358)	(4.4765)	(9.1477)	(6.6539)
FDI	−0.0201***	−0.0066**	−0.0260***	−0.0177***
	(0.0067)	(0.0028)	(0.0048)	(0.0036)
HC	0.0006	0.0120	0.0058	−0.0018
	(0.0246)	(0.0094)	(0.0199)	(0.0176)
Constant	0.5475***	0.0150	0.4326***	0.6768***
	(0.1866)	(0.1039)	(0.1524)	(0.1190)
Time effects	YES	YES	YES	yes
Observations	270	270	210	300
R-squared	0.3318	0.7708	0.3575	0.3356

TABLE 8 | Multicollinearity diagnosis.

Variables	VIF	1/VIF
GC	3.34	0.299581
GDP	3.27	0.305773
IS	2.75	0.36364
ER	2.15	0.465856
FDI	1.64	0.610513
HC	1.32	0.755098
Mean VIF	2.23	

Technology. The results of the mediating model (1), (3) and (4) are estimated respectively based on the OLS method, which are shown in **Table 9**.

To begin with, column (1), (2) and (3) in **Table 9** shows the test results of mediating effect of green technology innovation on the impact of green credit on GTFP. More specifically, the estimated value of regression coefficient of green credit on GTFP in column (1), that of green credit on green technology innovation in column (2), and that of green technology innovation on GTFP in column (3) are all significant at 1% significance level. It proves that there is a significant mediating effect of green technology innovation on the impact of green credit on GTFP. This supports Hypothesis 5a. The reason is that green credit is conducive to improving R&D investment, thus it improves the level of green technology innovation, and then affects GTFP.

Next, the mediating effect of energy consumption structure on the impact of green credit on GTFP is also tested. The results are shown in the column (4)–(6) in **Table 9** and in **Table 10**, which indicates that energy consumption structure doesn't play a mediating role in green credit and GTFP again. Hence, Hypothesis 5b cannot be verified. Because of the endowment advantage and price advantage of coal, China's primary energy consumption structure is still dominated by coal. The average observed value of the sample energy consumption structure is 56.9%. In addition, the conception of green development proposed in China is late. Hence, for most enterprises, the energy consumption mode transitioning from traditional energy to clean energy in a short time is unbearable. Therefore, it is temporarily impossible for green credit to improve GTFP by changing the energy consumption structure on the whole.

HETEROGENEOUS EFFECTS

Heterogeneity Analysis with Different Level of GTFP

The impact of GC on GTFP may be different with different level of GTFP. Therefore, in this part, the panel quantile regression model is selected to test the heterogeneous effect. **Table 11** shows the parameter estimation results of Formula **(2)** based on the panel quantile regression model. Then, the regression models are estimated with quantiles of 10, 25, 50, 75, and 90%, respectively.

From **Table 11**, the regression coefficients of green credit are 0.5037, 0.5549, 0.6577, 0.7010, and 0.8061, respectively at the 10, 25, 50, 75, and 90% quantiles. They are all significantly positive, and increasing with the quantile. These show that the impact of green credit on GTFP is heterogeneous with different GTFP levels. As the quantile point increases from 10 to 90%, the regression coefficient of green credit increases from 0.5037 to 0.8061. This shows that the promotion of GTFP by green credit is strengthened with the increase of GTFP level. Thus, hypothesis 2 is proved. This is consistent with reality. In the context of the vigorous development of green finance in China, green credit plays a role in promoting economic development, the level of green economy development will be

TABLE 9 | Test of mediating effect of green technology innovation and energy consumption structure.

Variables	Ming et al. (2014)	Mohtadi, (1996)	Li et al. (2021a)	Li et al. (2020a)	Carroll et al. (2011)
	GTFP	**GTI**	**GTFP**	**ECS**	**GTFP**
GC	0.8047***	1.5879***	0.5397***	0.1252***	0.8014***
	(0.1009)	(0.1725)	(0.0732)	(0.0392)	(0.0957)
GTI			0.1669***		
			(0.0400)		
ECS					0.0264
					(0.1908)
GDP	1.4605***	9.3939***	-0.1074	−1.2332***	1.4930**
	(0.5539)	(0.9840)	(0.5306)	(0.2203)	(0.6052)
IS	−0.0009***	−0.0012**	−0.0007**	0.0000	−0.0009***
	(0.0003)	(0.0005)	(0.0003)	(0.0001)	(0.0003)
ER	4.8595	−92.8043***	20.3492**	5.2937*	4.7197
	(6.7352)	(14.2979)	(9.6858)	(3.0835)	(6.5511)
FDI	−0.0177***	0.0023	−0.0181***	−0.0074***	−0.0175***
	(0.0037)	(0.0093)	(0.0041)	(0.0016)	(0.0033)
HC	−0.0013	−0.0987***	0.0152	−0.0150	−0.0009
	(0.0162)	(0.0344)	(0.0154)	(0.0091)	(0.0169)
Constant	0.6779***	2.0434***	0.3368**	0.4495***	0.6660***
	(0.1198)	(0.2656)	(0.1574)	(0.0733)	(0.1655)
Time fixed effect	yes	yes	Yes	yes	yes
Observations	300	300	300	300	300
R-squared	0.3356	0.7319	0.3892	0.4416	0.3357

TABLE 10 | Bootstrap test of the mediating effect of energy consumption structure in the impact of green credit on GTFP.

Indirect effect	Observed Coef	Bootstrap Std. Err	z	P>z	Normal-based [95% Conf. Interval]	
	0.016	**0.025**	**0.650**	**0.515**	**−0.033**	**0.066**
Direct effect	0.727	0.109	6.680	0.000	0.514	0.941

TABLE 11 | Panel quantile regression results.

Variables	10%	25%	50%	75%	90%
GC	0.5037***	0.5549***	0.6577***	0.7010***	0.8061***
	(0.0636)	(0.0534)	(0.0690)	(0.0938)	(0.1799)
GDP	0.0277	−0.0030	1.0740**	2.4301***	3.5600***
	(0.4152)	(0.3486)	(0.4508)	(0.6127)	(1.1750)
IS	0.0003	0.0004	−0.0006*	−0.0006	−0.0018**
	(0.0003)	(0.0003)	(0.0003)	(0.0004)	(0.0009)
ER	−2.7962	−3.7934	−2.2558	−10.8957	−5.4393
	(6.1036)	(5.1240)	(6.6263)	(9.0071)	(17.2732)
FDI	−0.0106***	−0.0132***	−0.0155***	−0.0146**	−0.0157
	(0.0041)	(0.0034)	(0.0044)	(0.0060)	(0.0115)
HC	0.0093	0.0075	0.0018	−0.0471**	−0.0544
	(0.0146)	(0.0123)	(0.0159)	(0.0216)	(0.0414)
Constant	0.7010***	0.7366***	0.7425***	1.1467***	1.1353***
	(0.1095)	(0.0919)	(0.1189)	(0.1616)	(0.3099)
Time fixed effects	YES	YES	YES	YES	YES
Observations	300	300	300	300	300

Standard error in parentheses.
***p < *0.01*, **p < *0.05*, *p < *0.1*.

TABLE 12 | Heterogeneity test based on different characteristics.

Variables	Low level of economic development	High level of economic development	Low degree of environmental regulation	High degree of environmental regulation
GC	0.5528***	0.9085***	0.4462***	1.2250***
	(0.0762)	(0.2206)	(0.1383)	(0.2377)
GDP	−0.2874	1.1874	1.5212**	1.9371
	(1.0933)	(0.7980)	(0.5956)	(1.7926)
IS	−0.0048	−0.0010**	−0.0011***	−0.0039**
	(0.0049)	(0.0005)	(0.0004)	(0.0018)
ER	−12.4257	3.6048	−11.2244	8.6748
	(7.5090)	(9.9269)	(24.8875)	(9.2048)
FDI	−0.0124	−0.0159***	−0.0092*	0.0018
	(0.0109)	(0.0044)	(0.0048)	(0.0134)
HC	0.0085	−0.0099	0.0146	−0.0745*
	(0.0163)	(0.0382)	(0.0189)	(0.0404)
Constant	0.8635***	0.7028*	0.6595***	1.1244***
	(0.1204)	(0.3599)	(0.1712)	(0.2160)
Time fixed effects	YES	YES	YES	YES
Observations	150	150	150	150
R-squared	0.6705	0.2110	0.4116	0.3592

improved (Zheng et al., 2020), which in turn has a positive effect on the level of GTFP. When GTFP is at a low level, it indicates more undesired outputs and environmental problems are relatively serious. At this time, the positive effect of green credit on GTFP needs to neutralize some of the negative effects of undesired output. Therefore, green credit failed to play the best role. When GTFP is at a high level, the level of green economy, resource utilization efficiency, and the environment will be improved. At this time, the promotion of GTFP by green credit can be brought into full play.

Heterogeneity Analysis with Other Different Characteristics

Considering the possible heterogeneity of the impact of green credit on GTFP, this section selects other two factors of the level of economic development and the degree of environmental regulation based on the characteristics of the sample in a subsample test. According to 50% quantile of the level of economic development, the full sample is divided into two subsamples of low level of economic development and high level of economic development. Similarly, low degree of environmental regulation and a high degree of environmental regulation are also divided into two subsamples.

Table 12 reports the parameter estimation results, and the results show that the impact of green credit on GTFP is heterogeneous, which supports Hypothesis 3 and Hypothesis 4.

In the group regression of different economic development levels, the regression coefficients of green credit in areas with low and high levels are 0.5528 and 0.9085, and both have passed the 1% significance level test. At the same time, it also can be found that the promotion effect of green credit on GTFP is greater in areas with high economic development levels, and even exceeds the promotion effect in the full sample. Thus, regions with different levels of economic development, the impact of green credit on GTFP is heterogeneous. Based on the analysis of **Figure 2B**, although the GTFP level and green credit level in areas with low level of economic development are higher than those areas with high levels of economic development, areas with high levels of economic development have a solid economic foundation and greater market space. In areas with a high level of economic development, the introduction of green credit and the original funding base can better provide support for green projects, thereby promoting the further improvement of the level of GTFP.

In the group regression of different levels of environmental regulation, the regression coefficients of green credit in areas with low and high levels of environmental regulation are both have passed the 1% significance level test. At the same time, it can be found that the promotion effect of green credit on GTFP is greater in regions with higher levels of environmental regulation, about 1.5 times than that of the full sample. Therefore, in regions with different levels of environmental regulation, the impact of green credit on GTFP is heterogeneous. Combined with **Figure 2C**, the GTFP levels and green credit levels of regions with high environmental regulation are higher when comparing with regions with low levels of environmental regulation. Regions with a high degree of environmental regulation have a strong awareness of energy conservation and emission reduction (Hong et al., 2020), which in turn improves environmental governance performance, promotes the improvement of GTFP level and further improves the level of green economy development. Therefore, the commercial banking industry is also more willing to issue green credits to areas with a higher degree of environmental regulation for the development of green projects, thereby, it promotes the improvement of the GTFP level in the region.

DISCUSSION

Deviation Degree of Different Subsamples from the Full Sample

Based on **section 4.2**, we further discuss the degree of deviation of different subsamples from the full sample. To analyze combining the full-sample regression results in **Table 6**, the regression coefficient of green credit is 0.8482. Based on this coefficient, the degree of deviation of different subsamples from the full sample can be

TABLE 13 | Test of mediating effect based on different levels of economic development.

Variables	Low level of economic development				High level of economic development			
	GTI	GTFP	ECS	GTFP	GTI	GTFP	ECS	GTFP
GC	3.1266***	0.3532***	0.3382***	0.6596***	1.5234***	0.2084	0.0438	0.8622***
	(0.2915)	(0.0917)	(0.0663)	(0.0824)	(0.2563)	(0.1442)	(0.0626)	(0.2045)
GTI		0.0638***				0.4595***		
		(0.0217)				(0.0983)		
ECS				−0.3157***				1.0568**
				(0.0940)				(0.4776)
Control variables variables	yes	yes	yes	yes	yes	yes	yes	yes
Constant	yes	yes	yes	yes	yes	yes	yes	yes
Time effects	yes	yes	yes	yes	yes	yes	yes	yes
Observations	150	150	150	150	150	150	150	150
R-squared	0.7564	0.6862	0.2777	0.6976	0.8233	0.4009	0.6236	0.2609

Robust standard error in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

TABLE 14 | Test of mediating effect based on different levels of environmental regulation.

Variables	Low degree of environment regulation				High degree of environment regulation			
	GTI	GTFP	ECS	GTFP	GTI	GTFP	ECS	GTFP
GC	0.3819	0.4261***	−0.1831**	0.3911***	2.4312***	0.5242***	0.3347***	1.2390***
	(0.3984)	(0.1348)	(0.0718)	(0.1320)	(0.2532)	(0.1401)	(0.0529)	(0.2725)
GTI		0.0526				0.2882***		
		(0.0338)				(0.0784)		
ECS				−0.3013**				−0.0419
				(0.1398)				(0.3880)
Control variables	yes	yes	yes	yes	yes	yes	yes	yes
Constant	yes	yes	yes	yes	yes	yes	yes	yes
Time effects	yes	yes	yes	yes	yes	yes	yes	yes
Observations	150	150	150	150	150	150	150	150
R-squared	0.6663	0.4152	0.6316	0.4286	0.7246	0.4448	0.4198	0.3592

Robust standard error in parentheses.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

calculated. From the perspective of regions with different levels of economic development, the impact of green credit on GTFP in areas with low economic development levels deviates downward by 34.83%, whereas the impact of green credit on GTFP in areas with high economic development levels deviates upward by 7.11%, which indicating that green credit has an impact on GTFP, and the role of promotion in areas with high levels of economic development is stronger. From the perspective of regions with different environmental regulations, the impact of green credit on GTFP in low-environmentally regulated areas deviates downward by 47.39%, and the impact of green credit on GTFP in high-environmentally regulated areas deviates upward by 44.42%, which indicating the promotion of green credit on GTFP. It shows that the promotion effect of green credit on GTFP is stronger in areas with high environmental regulation. Considering the characteristics of the samples, comparing geographical location, economic development level, and different impacts caused by environmental regulations, it is found that the degree of deviation caused by environmental regulations is greater, indicating that the heterogeneity of the impact of green credit on GTFP is mainly manifested in different levels of environmental regulation.

Heterogeneous Mediating Effect Tests Under Different Samples

Due to the differences in economic development level and environmental regulation, the impact mechanism of green credit on GTFP may be heterogeneous. Therefore, further research of the heterogeneity of influencing mechanism of green credit on GTFP is conducted.

Table 13 reports the test results of mediating effect in different regions with different economic development levels. It can be seen from **Table 13** that the impact mechanism of green credit on GTFP has heterogeneity for regions with different levels of economic development. For low economic development level areas, the mediating effects of green technology innovation and energy consumption structure are significant. For high economic development level area, the mediating effects of green technology innovation is significant, but energy consumption structure is not significant. The reason is that the R&D investment in low-level economic development areas is relatively insufficient, which consumes more traditional energy. Green credit is conducive to increasing R&D investment and improving the energy consumption structure, which has a further impact on GTFP. For the regions with high economic development level, they have a strong economic foundation, high development level, advanced R&D and innovation technology, and low dependence on traditional energy. Therefore, the effect of green credit on GTFP through energy consumption structure is not significant.

Table 14 reports the test results of mediating effect in regions with different levels of environmental regulation. It can be seen from **Table 14** that the impact mechanism of green credit on GTFP is heterogeneous in regions with different levels of environmental regulation. For regions with a low level of environmental regulation, the mediating effect of green technology innovation is not significant, but that of energy consumption structure is significant. While for regions with a high level of environmental regulation, it's the other way around.

CONCLUSION

This paper examines the total effects, influence mechanism, and heterogeneous impacts of green credit on GTFP based on GTFP data of 30 provinces in China from 2008 to 2017. It mainly draws the following conclusions.

First, green credit has a positive effect on GTFP. Specifically, with the gradual improvement of the GTFP level, the promotion effect of green credit on GTFP is also strengthened. As the quantile point increases from 10 to 90%, the regression coefficient of green credit on GTFP increases from 0.5037 to 0.8061.

Second, heterogeneity exists in the effect of green credit on GTFP, which is reflected in different level of economic development, especially for different degrees of environmental regulation. To be specific, the promotion effect of green credit on GTFP in high economic development level areas is significantly greater than that in low economic development areas; whereas the promotion effect of green credit on GTFP in a high degree of environmental regulation areas is far greater than that in a low degree of environmental regulation areas. Moreover, the heterogeneity deviation caused by the degree of environmental regulation is the largest when it is more than 40%. Therefore, the heterogeneity of the impact of green credit on GTFP is mainly reflected in different degrees of environmental regulation.

Thirdly, on the whole, green credit can impact GTFP through green technology innovation, but not through energy consumption structure, and the influence mechanism is heterogeneous in the variation of sample characteristics. From the perspective of different economic development level, green technology innovation plays a significant mediator role in the impact of green credit on GTFP in both areas with low and high levels of economic development. However, the mediating effect of energy consumption structure is only significant in low level economic development areas. From the perspective of the different environmental regulation degree, the mediating effect of green technology innovation is only significant for the regions with a high environmental regulation degree. In contrast, energy consumption structure only plays a significant mediator role in the impact of green credit on GTFP in areas with low degree of environmental regulation.

Based on the above conclusion, the following enlightenment is drawn. First of all, perfecting the green credit policy (with which the benefit of relieving financial stress (Liu et al., 2021) and enhancing the promotion effect of green credit on GTFP through the establishment of high energy consumption industry credit constraint mechanism (Wen et al., 2021c) and green industry credit incentive mechanism. Secondly, green credit should be adjusted dynamically according to the change of GTFP level, and implement differentiation strategy with different GTFP levels, so as to give full play to the importance of green credit in the process of green economic growth. Finally, considering the regional heterogeneity for the green credit policy, such as enlightenments from researches on credit among assets types (Cao et al., 2021), investor sentiment (Wen et al., 2021d), portfolio diversification (Xiao et al., 2021), which guiding the credit funds flow to the green environmental protection industry according to the regional characteristics, and giving full play to the maximum effect of green credit on the growth of GTFP.

Besides, this paper also has the following limitations: first, the measurement method of core explanatory variables is unitary, and green credit can be measured *via* calculating the proportion of green credit line in the total loan line of financial institutions. Second, the mediating effect of green credit on GTFP takes fewer variables into account, and the channels of green credit on GTFP are rich. We can also explore the mediating effect of industrial structure upgrading. The above aspects should be considered in the directions to be explored in the future research.

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

Conceptualization, QH and YF; Data curation, QH and XL; Formal analysis, QH and YF; Investigation, QH and XL; Methodology, YF and XL; Resources, YF; Software, QH and XL; Supervision, QH and YF; Validation, QH, YF, and XL; Writing—original draft, QH, XL, and YF; Writing—review and editing, QH, XL, and YF.

FUNDING

This research was funded by the Education Special Project of National Social Science Fund of China (grant number BIA180197). This research was also funded by the Horizontal Project of Zhongda Health Limited Company in Hunan Province (grant number: HYW-2019-003). This funder had no role in this study design, data collection and analysis, decision to publish, or preparation of the manuscript.

ACKNOWLEDGMENTS

We are grateful for the support of Hunan Institute of Technology and Guangzhou University. We also appreciate all participants who contributed to the data collection and analysis in this study. We would like to thank reviewers for helpful comments.

REFERENCES

Canay, I. A. (2011). A Simple Approach to Quantile Regression for Panel Data. *Econom. J.* 14, 368–386. doi:10.1111/j.1368-423X.2011.00349.x

Cao, J., Wen, F., Stanley, H. E., and Wang, X. (2021). Multilayer Financial Networks and Systemic Importance: Evidence from China. *Int. Rev. Financial Anal.* 78, 101882. doi:10.1016/j.irfa.2021.101882

Carroll, J., Newman, C., and Thorne, F. (2011). A Comparison of Stochastic Frontier Approaches for Estimating Technical Inefficiency and Total Factor Productivity. *Appl. Econ.* 43, 4007–4019. doi:10.1080/00036841003761918

Chen, S., Wang, Y., Albitar, K., and Huang, Z. (2021). Does Ownership Concentration Affect Corporate Environmental Responsibility Engagement? The Mediating Role of Corporate Leverage. *Borsa Istanbul Rev.* 21, S13–S24. doi:10.1016/j.bir.2021.02.001

Dickey, D. A., and Fuller, W. A. (1981). Likelihood Ratio Statistics for Autoregressive Time Series with a Unit Root. *Econometrica* 49, 1057–1072. doi:10.2307/1912517

Dogan, E., and Seker, F. (2016). The Influence of Real Output, Renewable and Non-renewable Energy, Trade and Financial Development on Carbon Emissions in the Top Renewable Energy Countries. *Renew. Sust. Energ. Rev.* 60, 1074–1085. doi:10.1016/j.rser.2016.02.006

Demirtaş, Y. E., Kececi, N. F., and Fidan Keçeci, N. (2020). The Efficiency of Private Pension Companies Using Dynamic Data Envelopment Analysis. *Quantitative Finance Econ.* 4, 204–219. doi:10.3934/qfe.2020009

Feng, Y., Chen, S., and Failler, P. (2020). Productivity Effect Evaluation on Market-type Environmental Regulation: A Case Study of SO2 Emission Trading Pilot in China. *Ijerph* 17, 8027. doi:10.3390/ijerph17218027

Fukuyama, H., and Weber, W. L. (2009). A Directional Slacks-Based Measure of Technical Inefficiency. *Socio-Economic Plann. Sci.* 43, 274–287. doi:10.1016/j.seps.2008.12.001

Guo, Q., Zhou, M., Liu, N., and Wang, Y. (2019). Spatial Effects of Environmental Regulation and Green Credits on Green Technology Innovation Under Low-Carbon Economy Background Conditions. *Ijerph* 16, 3027. doi:10.3390/ijerph16173027

He, L., Zhang, L., Zhong, Z., Wang, D., and Wang, F. (2019). Green Credit, Renewable Energy Investment and Green Economy Development: Empirical Analysis Based on 150 Listed Companies of China. *J. Clean. Prod.* 208, 363–372. doi:10.1016/j.jclepro.2018.10.119

Hong, M., Drakeford, B., Drakeford, B., and Zhang, K. (2020). The Impact of Mandatory CSR Disclosure on Green Innovation: Evidence from China. *Green. Finance* 2, 302–322. doi:10.3934/gf.2020017

Hou, Y., Li, S., and Wen, F. (2021). Time-varying Information Share and Autoregressive Loading Factors: Evidence from S&P 500 Cash and E-Mini Futures Markets. *Rev. Quant Finan Acc.* 57, 91–110. doi:10.1007/s11156-020-00940-7

Hu, M. Z., Li, W., and Zhang, B. (2011). "Analysis of China's Green Credit Policy Towards Green Economic Growth," in 2011 Asia-Pacific Power and Energy Engineering Conference, Wuhan, China, March 25–28, 2011.

Huang, C., Wen, S., Li, M., Wen, F., and Yang, X. (2021). An Empirical Evaluation of the Influential Nodes for Stock Market Network: Chinese A-Shares Case. *Finance Res. Lett.* 38, 101517. doi:10.1016/j.frl.2020.101517

Jeucken, M. (2001). *Sustainable Finance and Banking: The Financial Sector and the Future of the Planet*. London: Earthscan Publications Ltd.

Kong, Q., Shen, C., Li, R., and Wong, Z. (2021). High-speed Railway Opening and Urban Green Productivity in the Post-COVID-19: Evidence from Green Finance. *Glob. Finance J.* 49, 100645. doi:10.1016/j.gfj.2021.100645

Levin, A., Lin, C.-F., and James Chu, C.-S. (2002). Unit Root Tests in Panel Data: Asymptotic and Finite-Sample Properties. *J. Econom.* 108, 1–24. doi:10.1016/s0304-4076(01)00098-7

Li, B., and Wu, S. (2017). Effects of Local and Civil Environmental Regulation on Green Total Factor Productivity in China: A Spatial Durbin Econometric Analysis. *J. Clean. Prod.* 153, 342–353. doi:10.1016/j.jclepro.2016.10.042

Li, T., Li, X., and Li, X. (2020). Does Structural Deceleration Happen in China? Evidence from the Effect of Industrial Structure on Economic Growth Quality. *Natl. Account. Rev.* 2, 155–173. doi:10.3934/nar.2020009

Li, T., Li, X., and Liao, G. (2021). Business Cycles and Energy Intensity. Evidence from Emerging Economies. *Borsa Istanbul Rev.* [Epub ahead of print]. doi:10.1016/j.bir.2021.07.005

Li, T., and Liao, G. (2020). The Heterogeneous Impact of Financial Development on Green Total Factor Productivity. *Front. Energ. Res.* 8, 29. doi:10.3389/fenrg.2020.00029

Li, X., Xu, C., Cheng, B., Duan, J., and Li, Y. (2021). Does Environmental Regulation Improve the Green Total Factor Productivity of Chinese Cities? A Threshold Effect Analysis Based on the Economic Development Level. *Ijerph* 18, 4828. doi:10.3390/ijerph18094828

Li, Z., Ao, Z., and Mo, B. (2021). Revisiting the Valuable Roles of Global Financial Assets for International Stock Markets: Quantile Coherence and Causality-In-Quantiles Approaches. *Mathematics* 9, 1750. doi:10.3390/math9151750

Li, Z., Liao, G., Wang, Z., and Huang, Z. (2018). Green Loan and Subsidy for Promoting Clean Production Innovation. *J. Clean. Prod.* 187, 421–431. doi:10.1016/j.jclepro.2018.03.066

Li, Z., Tian, M., Ouyang, G., and Wen, F. (2020). Relationship Between Investor Sentiment and Earnings News in High- and Low-sentiment Periods. *Int. J. Fin Econ.* 26, 2748–2765. doi:10.1002/ijfe.1931

Liang, Z., Chiu, Y.-h., Li, X., Guo, Q., and Yun, Y. (2020). Study on the Effect of Environmental Regulation on the Green Total Factor Productivity of Logistics Industry from the Perspective of Low Carbon. *Sustainability* 12, 175. doi:10.3390/su12010175

Lin, B., and Chen, Z. (2018). Does Factor Market Distortion Inhibit the Green Total Factor Productivity in China? *J. Clean. Prod.* 197, 25–33. doi:10.1016/j.jclepro.2018.06.094

Liu, J., Zhang, Z., Yan, L., and Wen, F. (2021). Forecasting the Volatility of EUA Futures with Economic Policy Uncertainty Using the GARCH-MIDAS Model. *Financ. Innov.* 7, 76. doi:10.1186/s40854-021-00292-8

Liu, N., Liu, C., Xia, Y., Ren, Y., and Liang, J. (2020). Examining the Coordination Between Green Finance and Green Economy Aiming for Sustainable Development: A Case Study of China. *Sustainability* 12, 3717. doi:10.3390/su12093717

Matei, I. (2020). Is Financial Development Good for Economic Growth? Empirical Insights from Emerging European Countries. *Quantitative Finance Econ.* 4, 653–678. doi:10.3934/QFE.2020030

Meirun, T., Mihardjo, L. W., Haseeb, M., Khan, S. A. R., and Jermsittiparsert, K. (2021). The Dynamics Effect of Green Technology Innovation on Economic Growth and CO2 Emission in Singapore: New Evidence from Bootstrap ARDL Approach. *Environ. Sci. Pollut. Res.* 28, 4184–4194. doi:10.1007/s11356-020-10760-w

Ming, Z., Ximei, L., Yulong, L., and Lilin, P. (2014). Review of Renewable Energy Investment and Financing in China: Status, Mode, Issues and Countermeasures. *Renew. Sust. Energ. Rev.* 31, 23–37. doi:10.1016/j.rser.2013.11.026

Mohtadi, H. (1996). Environment, Growth, and Optimal Policy Design. *J. Public Econ.* 63, 119–140. doi:10.1016/0047-2727(95)01562-0

Oh, D.-h. (2010). A Global Malmquist-Luenberger Productivity Index. *J. Prod. Anal.* 34, 183–197. doi:10.1007/s11123-010-0178-y

Scholtens, B. (2006). Finance as a Driver of Corporate Social Responsibility. *J. Bus Ethics* 68, 19–33. doi:10.1007/s10551-006-9037-1

Shi, X., and Li, L. (2019). Green Total Factor Productivity and its Decomposition of Chinese Manufacturing Based on the MML index:2003-2015. *J. Clean. Prod.* 222, 998–1008. doi:10.1016/j.jclepro.2019.03.080

Song, M., Du, J., and Tan, K. H. (2018). Impact of Fiscal Decentralization on Green Total Factor Productivity. *Int. J. Prod. Econ.* 205, 359–367. doi:10.1016/j.ijpe.2018.09.019

Soundarrajan, P., and Vivek, N. (2016). Green Finance for Sustainable Green Economic Growth in India. *Agric. Econ. - Czech* 62, 35–44. doi:10.17221/174/2014-agricecon

Tuzcuoğlu, T. (2020). The Impact of Financial Fragility on Firm Performance: An Analysis of BIST Companies. *Quantitative Finance Econ.* 4, 310–342. doi:10.3934/qfe.2020015

Wang, M., Pang, S., Hmani, I., Hmani, I., Li, C., and He, Z. (2021). Towards Sustainable Development: How Does Technological Innovation Drive the Increase in Green Total Factor Productivity? *Sust. Dev.* 29, 217–227. doi:10.1002/sd.2142

Wen, F., Cao, J., Liu, Z., and Wang, X. (2021). Dynamic Volatility Spillovers and Investment Strategies Between the Chinese Stock Market and Commodity Markets. *Int. Rev. Financial Anal.* 76, 101772. doi:10.1016/j.irfa.2021.101772

Wen, F., Li, C., Sha, H., and Shao, L. (2021). How Does Economic Policy Uncertainty Affect Corporate Risk-Taking? Evidence from China. *Finance Res. Lett.* 41, 101840. doi:10.1016/j.frl.2020.101840

Wen, F., Zhang, K., and Gong, X. (2021). The Effects of Oil price Shocks on Inflation in the G7 Countries. *North Am. J. Econ. Finance* 57, 101391. doi:10.1016/j.najef.2021.101391

Wen, F., Zou, Q., and Wang, X. (2021). The Contrarian Strategy of Institutional Investors in Chinese Stock Market. *Finance Res. Lett.* 41, 101845. doi:10.1016/j.frl.2020.101845

Wen, Z., and Ye, B. (2014). Analyses of Mediating Effects: The Development of Methods and Models. *Adv. Psychol. Sci.* 22, 731–745. doi:10.3724/SP.J.1042.2014.00731

Xiao, J., Wen, F., Zhao, Y., and Wang, X. (2021). The Role of US Implied Volatility index in Forecasting Chinese Stock Market Volatility: Evidence from HAR Models. *Int. Rev. Econ. Finance* 74, 311–333. doi:10.1016/j.iref.2021.03.010

Xu, S. (2020). International Comparison of Green Credit and its Enlightenment to China. *Green. Finance* 2, 75–99. doi:10.3934/gf.2020005

Yu, D., Li, X., Yu, J., and Li, H. (2021). The Impact of the Spatial Agglomeration of Foreign Direct Investment on green Total Factor Productivity of Chinese Cities. *J. Environ. Manage.* 290, 112666. doi:10.1016/j.jenvman.2021.112666

Yuan, B., Li, C., and Xiong, X. (2021). Innovation and Environmental Total Factor Productivity in China: The Moderating Roles of Economic Policy Uncertainty and Marketization Process. *Environ. Sci. Pollut. Res.* 28, 9558–9581. doi:10.1007/s11356-020-11426-3

Zhang, B., Yang, Y., and Bi, J. (2011). Tracking the Implementation of Green Credit Policy in China: Top-Down Perspective and Bottom-Up Reform. *J. Environ. Manage.* 92, 1321–1327. doi:10.1016/j.jenvman.2010.12.019

Zhang, J., Fang, H., Peng, B., Wang, X., and Fang, S. (2016). Productivity Growth-Accounting for Undesirable Outputs and its Influencing Factors: The Case of China. *Sustainability* 8, 1166. doi:10.3390/su8111166

Zheng, Y., Chen, S., Chen, S., and Wang, N. (2020). Does Financial Agglomeration Enhance Regional Green Economy Development? Evidence from China. *Green. Finance* 2, 173–196. doi:10.3934/gf.2020010

Zheng, Y., Zhou, M., and Wen, F. (2021). Asymmetric Effects of Oil Shocks on Carbon Allowance price: Evidence from China. *Energ. Econ.* 97, 105183. doi:10.1016/j.eneco.2021.105183

Zhou, X., Tang, X., and Zhang, R. (2020). Impact of Green Finance on Economic Development and Environmental Quality: A Study Based on Provincial Panel Data from China. *Environ. Sci. Pollut. Res.* 27, 19915–19932. doi:10.1007/s11356-020-08383-2

Zoundi, Z. (2017). CO2 Emissions, Renewable Energy and the Environmental Kuznets Curve, A Panel Cointegration Approach. *Renew. Sust. Energ. Rev.* 72, 1067–1075. doi:10.1016/j.rser.2016.10.018

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: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

frontiers in Energy Research

ORIGINAL RESEARCH
published: 11 March 2022
doi: 10.3389/fenrg.2021.804706

Towards Achieving Environmental Sustainability: The Role of Nuclear Energy, Renewable Energy, and ICT in the Top-Five Carbon Emitting Countries

Anam Azam[1], Muhammad Rafiq[2]*, Muhammad Shafique[3]* and Jiahai Yuan[1]*

[1]School of Economics and Management, North China Electric Power University, Beijing, China, [2]Department of Electrical Engineering, University of Engineering and Technology, Taxila, Pakistan, [3]Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong SAR, China

In the era of globalization, the incidence of global warming emerges from the issue of climate change, which attracts the attention of several scholars to attain sustainability with respect to ensuring sufficient energy access and diminishing environmental adversities. However, in view of these circumstances, this study examines the heterogenous impacts of nuclear energy, renewable energy, and information and communication technologies (ICTs) on pollution emissions reduction for the top-five emitter countries, covering the data from the period from 1995–2017. This study employs an advanced panel quantile regression model that takes into account both unobserved individual heterogeneity and distributional heterogeneity. The findings illustrate that the effect of all the selected explanatory variables on CO_2 emissions is heterogenous along the quantiles. Our outcome supports the notion that nuclear energy consumption is insignificant in contributing to lower environmental pollution. Renewable energy consumption and ICT significantly decrease the carbon emissions of emitter economies, but the negative influence is more robust at the quantiles level (0.30–0.80) and (0.10, 0.20), both factors correct the environmental pollution in the five emitter countries. Finally, the findings of the study provide crucial policy recommendations to policymakers.

Keywords: sustainability, economic growth, energy consumption, CO_2 emission, panel data

OPEN ACCESS

Edited by:
Xiaohang Ren,
Central South University, China

Reviewed by:
Cheng Cheng,
Shanxi University of Finance and Economics, China
Yan Zheng,
Central South University, China

****Correspondence:***
Anam Azam
anamrafiq95@gmail.com
Muhammad Rafiq
jutt96@gmail.com
Muhammad Shafique
m.shafique@my.cityu.edu.hk

Specialty section:
This article was submitted to Sustainable Energy Systems and Policies,
a section of the journal Frontiers in Energy Research

Received: *29 October 2021*
Accepted: *17 December 2021*
Published: *11 March 2022*

Citation:
Azam A, Rafiq M, Shafique M and Yuan J (2022) Towards Achieving Environmental Sustainability: The Role of Nuclear Energy, Renewable Energy, and ICT in the Top-Five Carbon Emitting Countries.
Front. Energy Res. 9:804706.
doi: 10.3389/fenrg.2021.804706

1 INTRODUCTION

Energy is the basic building block of all sectors of modern economic growth and is considered a basic factor of production, including capital and labor (Alam et al., 2016; Solarin et al., 2017). However, energy consumption has become a crucial aspect of the economic growth (GDP) of any nation (Azam et al., 2020a; Azam et al., 2020c; Iheonu et al., 2020; Azam et al., 2021a; Azam et al., 2021c). Due to the rapid growth of the global economy, energy consumption is rapidly increasing as a result of globalization and industrialization (Shafique et al., 2020; Shafique et al., 2021a). Most of this demand is fulfilled through fossil fuel energy sources: coal consumption (CC, 38%), and oil consumption (OC, 23%) globally. Fossil fuel combustion is the primary cause of global warming, which has resulted in greenhouse gas (GHG) emissions, with carbon dioxide (CO2) being the most significant contributor to environmental pollution (Chaudhry et al., 2012; Azam et al., 2020b; Azam et al., 2021b; Shafique and Luo, 2021; Azam et al., 2021c; Azam et al., 2021d).

The consequences of CO_2 emission endanger the atmosphere and bring climate change worldwide. Climate change and global warming are the most highlighted issues that threaten the world (Liu et al., 2020; Shafique et al., 2021b). The incidence of environmental degradation has serious implications for our health and economy (Yahya and Rafiq, 2020). According to the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC), the global temperature has increased by 1.5°C, which is quite high (IPCC, 2018a). Amidst the growing awareness of environmental jeopardy, a demand for clean energy has emerged. Thus, a considerable amount of attention has been paid to lessening CO_2 emissions and building a low-carbon economy.

The growing concerns including rapid climate change, environmental degradation, and requirements for clean energy justice, have become human rights issues globally (Azam et al., 2021e; Azam et al., 2021f; Baloch et al., 2019). However, ecologists and energy economists are urging policymakers to shift their energy usage toward clean energy sources (renewable and nuclear) in order to address the aforementioned environmental and health challenges. In this regard, the use of nuclear energy and renewable energy plays a crucial role in CO_2 emission reductions as well as establishing substantial economic and socioeconomic benefits. Globally, both nuclear and renewable energy sources are important for controlling energy security and pollution emission (Chu and Chang, 2012). Renewable energy and nuclear energy may have an adverse influence on CO_2 emission, an effect that is beneficial to the atmosphere (Menyah and Wolde-Rufael, 2010; Al-Mulali and Ozturk, 2016). Both energies have increased in use in recent years due to the lower cost as well as to achieve a sustainable environment. In the modern era of industrialization and globalization, the growing concerns of ICT contribute more to several economic sectors; consequently, the environmental performance of ICT cannot be ignored (Cheng et al., 2021). ICT plays a vital role in enhancing energy usage in terms of industrialization development; subsequently, growing energy consumption due to industrial development has a harmful effect on environmental quality (Khan et al., 2018). While on the other hand, ICT reduces mobility and physical presence, including e-commerce, e-government, e-banking, and virtual education; in this way, it has a crucial role in decreasing CO_2 emissions. Ambient air pollution can be improved through huge ICT development (Añón Higón et al., 2017). Consequently, a large investment in the latest technologies decreases environmental degradation (Wang et al., 2015; Latif et al., 2017). Despite the huge environmental pressure, the use of alternative and clean energy and ICT are considered well-known and sustainable to mitigate carbon emission reduction.

Currently, several pieces of literature on the energy-growth-environment nexus have been investigated by using different econometric techniques, countries, and regions over the years. Recently, some empirical studies such as (Bilgili et al., 2016; Bulut, 2017; Dong et al., 2018; Paramati et al., 2017) have argued that clean energy plays a crucial role in improving environmental quality. Still, apart from this, few studies (Apergis et al., 2010; Bölük and Mert, 2015) disagree with the statement that renewable energy consumption (REC) cannot mitigate CO_2 emission. **Table 1** summarizes the previous work to analyze nuclear energy, renewable energy, ICT, and environmental pollution nexus. As discussed by (Al-Mulali and Ozturk, 2016) the use of REC has a negative effect on CO_2 emission and helps to maintain and improve environmental sustainability.

Meanwhile, clean energy such as nuclear energy consumption (NEC) sources gets enormous attention among researchers (Azam et al., 2020b; Azam et al., 2021b). The development of nuclear power has huge potential and enhancing the share of nuclear energy is a viable target to reduce pollution in developing countries (Peng et al., 2019). According to recent literature (Menyah and Wolde-Rufael, 2010; Park et al., 2016; Lau et al., 2019; Peng et al., 2019; Hassan et al., 2020), nuclear energy is a capable and well-known energy source to mitigate CO_2 emission and improve environmental sustainability. However, some recent studies (Jin and Kim, 2018; Prăvălie and Bandoc, 2018; Aydın, 2020; Mahmood et al., 2020) report that nuclear energy has a positive and significant effect on CO_2 emissions due to the negative impact of radioactive waste and atomic accidents which have a serious impact on humans and the environment as well. Moreover, in recent years significant numbers of studies have discussed the influence of ICT on CO_2 emission; for instance, (Coroama et al., 2012; Al-Mulali et al., 2015; Asongu et al., 2018) states that ICT improves the environmental quality by a reduction of CO_2 emission.

From the literature reviewed, it can be concluded that the studies found mixed results for clean energy sources (renewable energy and nuclear power) and CO_2 emissions as well as ICT and CO_2 emissions. However, no consensus has been reached on whether consumption of renewable energy or nuclear energy can counteract environmental pollution, not by incorporating a recent factor of ICT. Therefore, this present study is motivated to investigate the effect of NEC, REC, and ICT on CO_2 emission in the top five CO_2 emitter countries.

Why have we selected only the top emitter countries as our case study? The top five emitter economies (China, United States, India, Japan, and South Korea) have experienced rapid economic growth, much larger foreign direct investment, and engrossed extensive foreign exchange reserves. Consequently, together all these aspects contribute to carbon dioxide (CO_2) emission and other global warming emissions (Baloch and Wang, 2019; Duan et al., 2021; Ren et al., 2021). The total CO_2 emission in top emitter economies contributes significantly, such as in China (27.8%), United States (15.2%), India (7.3%), Japan (3.4%), and South Korea (2.1%) during the year 2019 (British Petroleum, 2018). Further, these countries together contribute 65% of global economic growth, 80% of total fossil fuel combustion at an international level, and 67.5% of total CO_2 emissions from fuel combustion worldwide (IPCC, 2018a).

Further, the top emitter economies all plan to diminish their CO_2 emission following the 2015 UN conference on climate change (COP21) which is starting to invigorate public and private actions target to decline the temperature worldwide

TABLE 1 | Summary of studies on the link between nuclear and renewable energy consumption- ICT on CO_2 emission.

Study	Countries (Period)	Methodology	Related variables	Key findings
Alsayed et al. (2020)	India (1969–2014)	ARDL Model	CO_2, NEC, OC,CC, trade openness	NEC mitigates CO_2 both in the long run and short run
Jin and Kim, (2018)	30 countries (1980–2014)	Panel Cointegration and Granger causality test	CO_2, REC, NEC, GDP, Coal price	Their results suggest that REC improves the environment in the long run but NEC cannot contribute to mitigating CO_2 emission. So the study suggests that REC plays a crucial role, not nuclear energy, in lowering environmental degradation
Hassan et al. (2020)	BRICS countries (1993–2017)	CUP-FM, CUP-BC	CO_2, REC, NEC, GDP	Their outcomes summarize that both NEC and REC improve environmental quality
Mahmood et al. (2020)	Pakistan (1973–2017)	ARDL	CO_2, GDP, NEC	They find that NEC has a negative impact on CO_2 emission and also find bidirectional causality between NEC and CO_2 emission
Khan et al. (2018)	Emerging economies (1990–2014)	MG, AMG analysis	CO_2,ICT, financial development, energy consumption, GDP, urbanization	In this study, the ICT and GDP mitigate the CO_2 emission, FD, EC, and stimulate the level of pollution
Baek, (2016)	United States (1960–2010)	ARDL	CO_2, GDP NEC,REC, Energy consumption	They suggest that NEC mitigate the CO_2 emission both in the short-run and long-run but REC is only helpful in the short term to improve the environment
Lee et al. (2017)	18 countries (1970–2015)	Panel cointegration test, DOLS	CO_2, GDP NEC, REC	Their results indicate that NEC improves environmental quality
Añón Higón et al. (2017)	1995–2010	142 countries	ICT, CO_2	ICT mitigate the CO_2 emission
Lau et al. (2019)	18 OECD countries (1995–2015)	GMM, FMOLS	NEC, non-renewable, trade openness	NEC improves environmental performance
Al-Mulali, (2014)	30 nuclear countries (1990–2010)	Panel co integration, FMOLS, VECM	CO_2, GDP NEC, investment, fossil fuels, urbanization	In this study, NEC has a significant impact on GDP in the long term but has no influence on CO_2 emission mitigation
Danish, (2019)	Belt and Road countries (1990–2016)	GLS	CO_2, GDP, ICT, Foreign direct investment, trade	The indicates that ICT improve the environment

(IPCC, 2018b). These countries have the latest technologies, skilled labor, political stability, and a significant share of nuclear and renewables in the total energy mix. So, these economies should develop policies to support the adoption of innovations that might help in the generation of renewable and nuclear energy. Hence, prompt action is required to decrease the total amount of CO_2 emissions without harming the economy (Baloch et al., 2019).

Against this backdrop, it is quite clear that studying the energy consumption-environment nexus for emitter countries is required regarding the energy efficiency policies and planning the ICT for alternative energy sources. For this, the novelties of this paper are as follows: 1) First, we believe that this is the first empirical study that takes the top five CO_2 emitter countries such as (China, United States, India, Japan, and South Korea) into account over the period 1995–2017. As previous works have paid attention to panel data of several country groups, namely; Emerging economies, BRICS (Brazil, Russia, India, China, and South Africa); Developed countries, Belt and Road countries, India; United States, Pakistan, nuclear countries, G-20 countries and the OECD (Organization for Economic Cooperation and Development). The highest CO_2 emitting countries have not been scrutinized in the energy-growth-environment literature. Particularly, the present study is the most inclusive study on disaggregated energy consumption, covering the top five economies with the highest CO_2 emissions globally. These five economies affairs, as countries with the greatest CO_2 emissions, make them of particular interest. Second, we examined the role of ICT in the process of pollution emission reductions. Further, we incorporated disaggregated energy such as nuclear energy, renewable energy, oil consumption, and coal consumption as determinants of CO_2 emission. Moreover, we include GDP as an additional variable as an important factor in environmental literature.

Third, the present study implies up-to-date econometrics techniques in an empirical analysis. It is evident that previous studies examined the energy-growth-environment nexus by using standard panel estimation techniques such as vector error correction and vector autoregressive method, fully modified ordinary least square, dynamic ordinary least square, generalized least squares, and no one use panel quantile regression (PQR) method on the evidence of nuclear energy consumption, renewable energy consumption, ICT and CO_2 emission. This method has been widely used and has become a core research subject in the economics literature (Huang et al., 2020; Ike et al., 2020). This method has some advantages; first, it

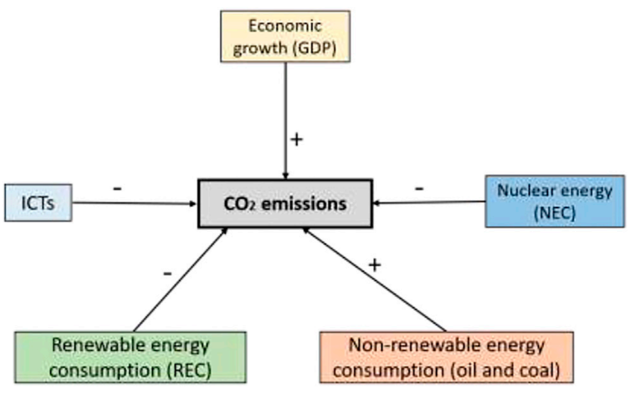


FIGURE 1 | Conceptual framework of this study.

can be applied in order to avoid over and underestimation of target and explanatory variables. It can explain the intact conditional distribution of the target variable (CO_2 emissions); therefore, it provides us a complete picture of the factors that cause pollutant emission; in particular, PQR presents one solution to each quantile. The outcomes of the PQR method are more efficient and reliable than conventional OLS regression because the findings are robust in order to capture outlying observations of the response variable, in particular when the error term is non-normal (Alsayed et al., 2020). Several policy questions remain. First, Does nuclear and renewable energy contribute to mitigating carbon emissions? Does ICT have an effect on CO_2 emission reduction? Finally, Does oil and coal energy consumption effect CO_2 emission?

2 DATA, MODEL AND ECONOMETRIC METHODOLOGY

2.1 The Theoretical Framework of the Study

Firstly, we talk about the present theoretical background of the study before constructing the econometric model specifications; this will help our study to choose the exposure variables for this research. The variable economic growth not only raises the economic structure but stimulates the level of CO_2 emission through the combustion of fossil fuel, transportation, structural transformation, and the behavioral demand of consumers in the country, which ultimately disturbs the environmental quality. Moreover, ICT and energy consumption reinforce each other, and therefore ICT increases environmental degradation through its role in aiding industrial development. Similarly, efficient and reliable nuclear and renewable energy is important to control CO_2 emissions. Keeping all this in view, we build a conceptual framework of the study as **Figure 1**.

2.2 Empirical Model Specifications

Most literature studying the determinants of CO_2 emission depends on the linear model such as (Hasnisah et al., 2019; Qiao et al., 2019; Salman et al., 2019)**.** Based on the conceptual model as presented above, we specify the following econometric form:

$$CO_{2=}f\left(GDP + ICT + NEC + REC + OC + CC\right) \quad (1)$$

We transformed all variables into natural logarithms; the reason behind taking logarithms for each series is to investigate the elasticity between variables and to smooth the data. Thus, transforming **Eq. (1)** into log form as follows:

$$lnCO_{2=}\alpha_0 + \alpha_1 lnGDP + \alpha_2 lnICT + \alpha_3 lnNEC + \alpha_4 lnREC + \alpha_5 lnOC + \alpha_6 lnCC \quad (2)$$

Following (Baloch et al., 2019), we incorporate the interaction variable between carbon dioxide emission and ICT in order to validate the assumption that ICT simultaneously improves the environment and economic growth in the highest co_2 emitting countries. In addition, this study used panel data for the top five emitter countries based on available data. The panel data model was first presented by (Al-Mulali et al., 2013). Panel data has numerous advantages such as it increases the degree of freedom which improve the capacity of econometrics evaluation, it requires a massive number of data points (N, T), to control the effects of heterogeneity and co-linearity problem between the variables, and also it is well-known for its consistency as compared to the time series model. In addition, the error term is added to the economic growth model. Thus, we can re-write **Eq. (2)** into panel data form expressed as follows:

$$lnCO_{2it=}\alpha_0 + \alpha_1 lnGDP_{it} + \alpha_2 lnICT_{it} + \alpha_3 lnNEC_{it} + \alpha_4 lnREC_{it} + \alpha_5 lnOC_{it} + \alpha_6 lnCC_{it} + \mu_{it} \quad (3)$$

Where, in the above **Eq. 2**, CO_2 indicates the carbon dioxide emission, GDP indicates economic growth, ICT represents information and telecommunication technology, NEC is nuclear energy consumption, REC is the renewable energy consumption, OC means the oil consumption and CC denotes the coal consumption. The subscript t means the time dimensions, i shows the number of cross-sections; α_0 allows for the possible country-fixed effect while α_1, α_2, α_3, α_4, α_5, α_6 are the parameters with respect to GDP, ICT, NEC, REC, OC, and CC, μ indicates the white noise error term.

The expected sign of GDP is positive because economic growth increases the level of pollution, as shown in **Figure 1**. ICT can have either a positive or negative effect on the environment because the role of ICT in CO_2 emissions is unclear (Shahzad et al., 2020). Clean and sustainable energy sources such as REC and NEC get huge attention in the economics literature. Moreover, REC and NEC's positive and significant role is in curbing the emissions, which is the key focus of our study. The expected coefficient of OC and CC is positive because energy usage from non-renewable energy sources such as (oil and coal) causes environmental degradation.

2.3 Methodology

In our study, this paper establishes a fixed effect panel quantile regression model to investigate the impact of Nuclear energy consumption, renewable energy consumption, and ICT on CO_2 emission. The panel quantile regression technique was first introduced by Koenker and Bssett (1978), which helps to

TABLE 2 | Ellipsis used for variables (British Petroleum, 2014; IEA, 2015; The World Bank, 2015; The World Bank, 2015; British Petroleum, 2018).

Code	Description of variable	Source
CO_2	Carbon dioxide emissions (metric tons per capita)	WDI
GDP	Economic growth (as per capita constant 2010 US$)	WDI
ICT	Information and communication technology (number of people)	WDI
NEC	Nuclear energy consumption (KWH)	EIA
REC	Renewable energy consumption (KWH)	EIA
OC	Oil consumption (Mtoe)	BP, Statistical Review
CC	Coal consumption (Mtoe)	BP, Statistical Review

Note: annual data is used over the period 1995–2017.

study the distribution of variables' asymmetry (Sharif et al., 2020). In addition, this approach is a generalization of the median regression analysis to other quantiles. This method can model the full conditional distribution, so it provides a diversified effect of independent variables on the dependent variable due to variable quantiles. PQR additionally assesses multiple slope coefficients at different quantiles and controls hidden heterogeneity for each cross-section. Assessing the value of the coefficient at the extremity of the distribution is also interesting for policy considerations. To determine the effects and unobserved individual heterogeneity, the conditional quantile functions of the response of Y_{it} given X_{it} are illustrated as follows in **Eq. 4**:

$$Qy_{it}(\tau|X_{it}) = X_{it}^{'}\beta_{\tau} \tag{4}$$

Here, $Qy_{it}(\tau|X_{it})$ Indicates the τ-th conditional quantile of the target variable of CO_2, X_{it} represents the vector of exposure variables for each country i at time t for quantile τ and β_τ signify the parameters to be estimated of the explanatory variables for quantile τ. The conditional quantile function for quantile τ as follows in **Equation (5)**:

$$q\left(\frac{CO_{2it}}{\Omega_t}\right) = \alpha_{0\tau} + \alpha_{1\tau} lnGDP_{it} + \alpha_{2\tau} lnICT_{it} + \alpha_{3\tau} lnNEC_{it} + \alpha_{4\tau} lnREC_{it} + \alpha_{5\tau} lnOC_{it} \alpha_{6\tau} lnCC_{it} + \mu_{it} \tag{5}$$

Here, q (CO_2/Ω_t) indicates the conditional quantile of CO_2, Ω_t consist of available information at time t.

2.4 Data

2.4.1 Data Source

In panel data analysis, country selection is a decisive aspect and we should be careful in-country selection for analysis. This may influence not only the analysis of the result of our study but also encourage the possibility of country selection bias. In our analysis, we consider the following top five CO_2 emission countries such as China, the United States, India, Japan, and South Korea. The purpose of our study is to investigate the effect of ICT, NEC, and REC on CO_2 emission in a multivariate framework. Thus, we imply annual data of the top five emitting countries over the period 1995–2017.

In this empirical study, the dependent variable is carbon dioxide emission emitted by fuel combustion which is measured in metric tons per capita. Our main variables of interest are ICT, REC, and NEC. Economic growth is the independent variable expressed (as per capita constant 2010 US$), information and telecommunication technology is expressed in terms of (number of people). Moreover, disaggregated energy consumption such as nuclear energy consumption, renewable energy consumption, oil consumption, and coal consumption are also taken as independent variables measured in KWH and MTOE. The data is obtained from World Development Indicators (WDI) and EIA. In our paper, the data are preprocessed and we take logarithms of all larger values of variables. The description of each variable is illustrated as follows in **Table 2**.

2.5 Data Analysis

Table 3, depicts the statistical analysis of each variable consisting of their mean, median, maximum, minimum, standard deviation, and Jarque-Bera statistics, along with their corresponding *p*-values for the top five selected countries from 1997–2017. In statistical analysis, the mean value of CO_2 emission of the five countries is 1.838262 per capita metric tons with their standard deviation of 0.966141. The average value of GDP is 9.269712 with a standard deviation of 1.538287 billion US$. Further, the mean value for ICT is 19.54465 with a standard deviation of 1.274295. NEC of the sampled countries has an average value of 4.542592 with a standard deviation of 1.569634 (KWH). The mean value of REC is 4.732299 (KWH) with a standard deviation of 1.683789. On the other hand, non-renewable energy sources (such as coal and oil) have a mean value of 5.46884 and 5.5093831 respectively, withtheir standard deviation of 1.108366 and 0.803499 (MT oil equivalent).

In a descriptive statistical analysis apart from the mean and standard deviation, the basic statistics test is the Skewness, Kurtosis. The pre-conditions of the skewness and the Kurtosis test statistics coefficients are that the skewness coefficient needs to be equal to 0 and for kurtosis must be equal to three for normal distribution. In this study, based on our findings of skewness and kurtosis, we clearly find that the distribution of all series are skewed and the distribution of kurtosis values indicates that seven variables distribution are more concentrated than the normal distribution of the long tails. In addition, the Jarque-Bera test statistics determine whether the distribution of the variable is normal or not through probability values. The Jarque-Bera test statistics indicate that only NEC and CC are normally distributed, while all other variables are non-normal distribution rejecting the null hypothesis. When the data samples have non-normal distribution, the use of panel quantile regression methods is more appropriate to analyze the effects and veracity of influencing factors.

3 EMPIRICAL RESULTS

This study starts with the smooth scrutiny of the data series. Firstly, based on the unit root test results, we determine whether

TABLE 3 | Descriptive statistics.

Variable	Co_2	GDP	ICT	NEC	REC	OC	CC
Mean	1.838262	9.269712	19.54465	4.542592	4.732299	5.509383	5.468843
Median	2.244435	9.910020	19.51388	4.818748	5.024670	5.369242	5.316648
Maximum	3.004630	10.88524	21.04997	6.693286	7.407032	6.874819	7.585332
Minimum	0.172050	6.514149	17.62424	–0.916291	1.033184	4.010963	3.335770
Std. Dev	0.966141	1.538287	1.274295	1.569634	1.683789	0.803499	1.108366
Skewness	–0.800370	–0.491947	–0.160546	–0.409440	–0.909967	0.445942	0.171259
Kurtosis	2.346710	1.602597	1.531343	2.764595	2.837094	1.940873	2.106560
Jarque-Bera	14.32304[a]	13.99542[a]	10.82941[b]	3.478660	15.99792[b]	9.186618[b]	4.387027

[a]Statistical significance at the 10%
[b]Statistical significance at the 5%
[c]Statistical significance at the 1%

TABLE 4 | stationary test results of each variable.

Variable	Co_2	GDP	ICT	NEC	REC	OC	CC
Levels	—	—	—	—	—	—	—
Fisher-ADF	–1.870938	–2.106435	–2.187263	–2.763502	–2.884862	–3.075639	–2.983972
Fisher-PP	–1.946099	–2.203909	–2.279954	–2.628109	–2.940984	–2.941465	–1.707828
IPS	–1.05444	0.8091	1.3553	3.5448	4.06971	–1.6696[b]	-0.9927
LLC	2.16440	–0.96008	–0.25032	1.20728	2.29395	–1.69939[b]	–0.77261
Breitung	0.46243	6.83625	1.87213	1.85548	5.54988	–0.00219	1.49696
First-order difference	—	—	—	—	—	—	—
Fisher-ADF	–10.56107[c]	–10.46267[c]	–10.61352[c]	–11.08747[c]	–10.62464[c]	–12.94348[c]	–4.269482[c]
Fisher-PP	–10.56107[c]	–10.46267[c]	–10.61452[c]	–11.09732[c]	–10.63758[c]	–13.07853[c]	–14.34524[c]
IPS	–5.1183[c]	–1.6587[b]	–1.5483[a]	–3.7478[c]	–8.1333[c]	–7.2756[c]	–7.6716[c]
LLC	–1.96682[b]	–5.76085[c]	–2.10558[b]	–5.42958[c]	–9.68000[c]	–8.01406[c]	–4.73689[c]
Breitung	–1.73845[b]	–4.69853[c]	–1.58027[b]	–3.00294[c]	–5.33490[c]	–5.08637[c]	–7.16060[c]

[a]Statistical significance at the 10%
[b]Statistical significance at the 5%
[c]Statistical significance at the 1%

the panel cointegration method is appropriate for this study or not. Then, we apply a panel PQR technique for empirical analysis.

3.1 Results of the Stationary Test

Before using the PQR method, it is necessary to check the stability of each series. For this, the panel unit root test was applied. There have been five methods for selecting the unit root of the panel: the fisher type test, and Augmented-Dickey-Fuller (ADF), Phillips-Perron (PP) (Maddala and Wu, 1999; Breitung, 2001), IPS Im-Pesaran-Shin (Im et al., 2003), LLC (Levine, Lin, Chu (Levin et al., 2002). **Table 4** illustrates the results of panel unit root tests. The findings show that all series are stationary at the first-order difference and integrated at an order one I (1). The variables are significant at 1, 5, and 10% significance levels and after first-order difference, each variable becomes smooth.

3.2 Results of Panel Johansen Fisher Co-integration Method

Once it is confirmed that all the variables are integrated in the same order I (1), we can proceed to analyze the long-run relationship amid the variables by applying the panel Johansen Fisher cointegration method reported by (Maddala and Wu, 1999). The findings of Johansen Fisher's cointegration rely on the VAR system lag order. The panel Johansen Fisher co integration findings are illustrated in **Table 5** and the results indicate that six cointegrating vectors exist. Therefore, we reject the null hypothesis. So, based on the panel Johansen Fisher cointegration test, we confirmed that a long-run relationship exists amid the CO_2, GDP, ICT, NEC, REC, OC, and CC.

3.3 Panel Quantile Regression Results

On the basis of the PQR technique, the heterogeneous effects of NEC, REC, ICT, and other decisive factors on CO_2 emission are examined in this study. For comparison, we first provide the OLS regression estimation results. This method presents a baseline of average effects and then we compare these to estimates for separate quantiles in the conditional distribution of CO_2 emission. This research has used the nine quantiles for a comprehensive analysis of the NEC, REC, and determinant factors of $CO_{2.}$ emissions. Both OLS and panel quantile regression results are displayed in **Table 6** and **Figure 2** illustrates the graphics of estimated coefficients NEC, REC, and other factors on $CO_{2.}$ emissions of emitter countries. The results are reported for nine quantiles (i.e. 10th, 20th, 30th, 40th, 50th, 60th, 70th, 80th' and 90th quantiles). First, the conventional OLS results represent that GDP has a positive and significant impact on CO_2 emission, meaning that a 1% increase in per capita GDP will augment CO_2 emission by 0.237%. Also note the coefficient of ICT is negative and highly significant at a 1% level as expected, which shows that a 1% increase in ICT will decrease CO_2 emission by -0.343%. We further observe the

TABLE 5 | Fisher panel Johansen co-integration test results.

Hypothesized No. of CE(s)	Fisher stat. [a] (from trace test)	Prob	Fisher stat. [a] (from max-eigen test)	Prob
None	58.03	0.0000	58.03	0.0000
At most 1	262.5	0.0000	133.4	0.0000
At most 2	182.3	0.0000	111.0	0.0000
At most 3	104.1	0.0000	44.07	0.0000
At most 4	72.09	0.0000	44.29	0.0000
At most 5	40.95	0.0000	31.60	0.0005
At most 6	27.95	0.0018	27.95	0.0018

[a]*Probabilities are computed using asymptotic Chi-square distribution.*

TABLE 6 | Panel Quantile Regression results.

Variables	OLS	Quantile regressions								
—	—	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
GDP	0.237[c] (0.0000)	0.575[c] (0.0000)	0.578[c] (0.0000)	0.580[c] (0.0000	0.670[c] (0.0000)	0.695[c] (0.0000)	0.561[c] (0.0000)	0.551[c] (0.0000)	0.540[c] (0.0000)	0.521[c] (0.0000)
ICT	−0.343[c] (0.0000)	−0.717[c] (0.0000)	−0.623[c] (0.0000)	−0.535[c] (0.0000)	−0.456[c] (0.0000)	−0.352[c] (0.0000)	−0.230[c] 0.0052	−0.148[a] 0.0600	−0.361 0.3176	−0.470[a] 0.0923
NEC	−0.00066 (0.9562)	−0.016 (0.2171)	−0.00872 (0.2136)	−0.0088 (0.2019)	−0.0108 (0.1659)	−0.0092 (0.2099)	−0.0032 (0.6748)	−0.00079 (0.9273)	−0.012 (0.7544)	0.026 (0.0840)
REC	−0.236[c] (0.0000)	−0.529[c] (0.0000)	−0.527[c] (0.0000)	−0.568[c] (0.0000)	−0.608[c] (0.0000)	−0.596[c] (0.0000)	−0.551[c] (0.0001)	−0.581[c] (0.0009)	−1.031[c] (0.0000)	−0.551 (0.7507)
OC	0.293[c] (0.0000)	1.371 (0.0000)	1.322[c] (0.0000)	1.287[c] (0.0000)	1.216[c] (0.0000)	0.446[c] (0.0001)	0.417[c] (0.0000)	0.333[c] (0.0001)	0.317[c] (0.0000)	0.259[c] (0.0000)
CC	0.366[c] (0.0000)	0.729[c] (0.0005)	0.708[c] (0.0073)	−0.358[b] (0.0101)	−0.170[b] (0.0267)	−0.085 (0.2660)	−0.080 (0.2775)	0.236[a] (0.0677)	0.266[b](0.0154)	0.269[c] (0.0018)

[a]*Statistical significance at the 10%*
[b]*Statistical significance at the 5%*
[c]*Statistical significance at the 1%.*

estimated coefficient of NEC is negative, but the effect is feeble. The estimated coefficient of REC is negative and statistically significant at a 1% level. For the non-renewable energy sources (oil, coal), their impacts are positive and significant at a 1% level. The result illustrates that the augmentation of oil and coal by 1% increases environmental degradation. The conventional panel regression model has only one output, which is the estimation result of the mean of the dependent variable. The panel quantile regression model, on the other hand, is unique. The PQR model is used to estimate the different distributed results of the output variables, thus making the estimation more complete.

The PQR findings suggest some important differences over different points in the conditional distribution of CO_2 emission. Regarding the GDP, we can observe that the impact of GDP on CO_2 emission is positive and statistically significant at a 1% level in all quantile levels, which indicates that environmental pollution increases with GDP. This finding is aligned with the previous works of (Chen et al., 2020; Zheng et al., 2021b). Concerning the role of ICT, the result shows that the coefficient of ICT is negative and significant in all quantiles except at high (80th) quantile it is negative but insignificant, it clearly shows that the environmental pollution lessens with ICT in top emitter economies which is consistent with the previous studies (Añón Higón et al., 2017; Danish et al., 2018). The effect of NEC on CO_2 emission is negative and insignificant in all quantiles except at (90th) high quantile, it is significant. These results are in line with (Jaforullah and King, 2015; Jebli et al., 2016; Mahmood et al., 2020). Moreover, the coefficient of renewable energy consumption is negative and significant in all quantiles, but it is not significant at the 95th quantile. However, our results are different from those studies (Apergis et al., 2010; Bölük and Mert, 2015) who stated that renewable energy accelerates, instead of mitigating carbon emission. In terms of non-renewable energy sources (oil, coal), we can find that oil and coal consumption increase environmental pollution in emitter countries. The coefficient of oil is positive and significant at 1% level in all quantiles level. This result is consistent with (Wen et al., 2020; Zheng et al., 2021a). The coefficient of coal consumption is significant at lower quantiles (10th and 20th), at other quantiles (30th, 40th, 50th, 60th), the coefficient is negative but significant but in (50th, 60th) quantile it is insignificant and at higher quantiles, it is positive and significant.

Our PQR results indicate that nuclear energy consumption, which is alternative and environmentally friendly, is negative but insignificant in explaining the environmental quality in emitter countries, as shown in **Figure 2**. This may occur because the share of NEC is a relatively low and insignificant contribution to the total

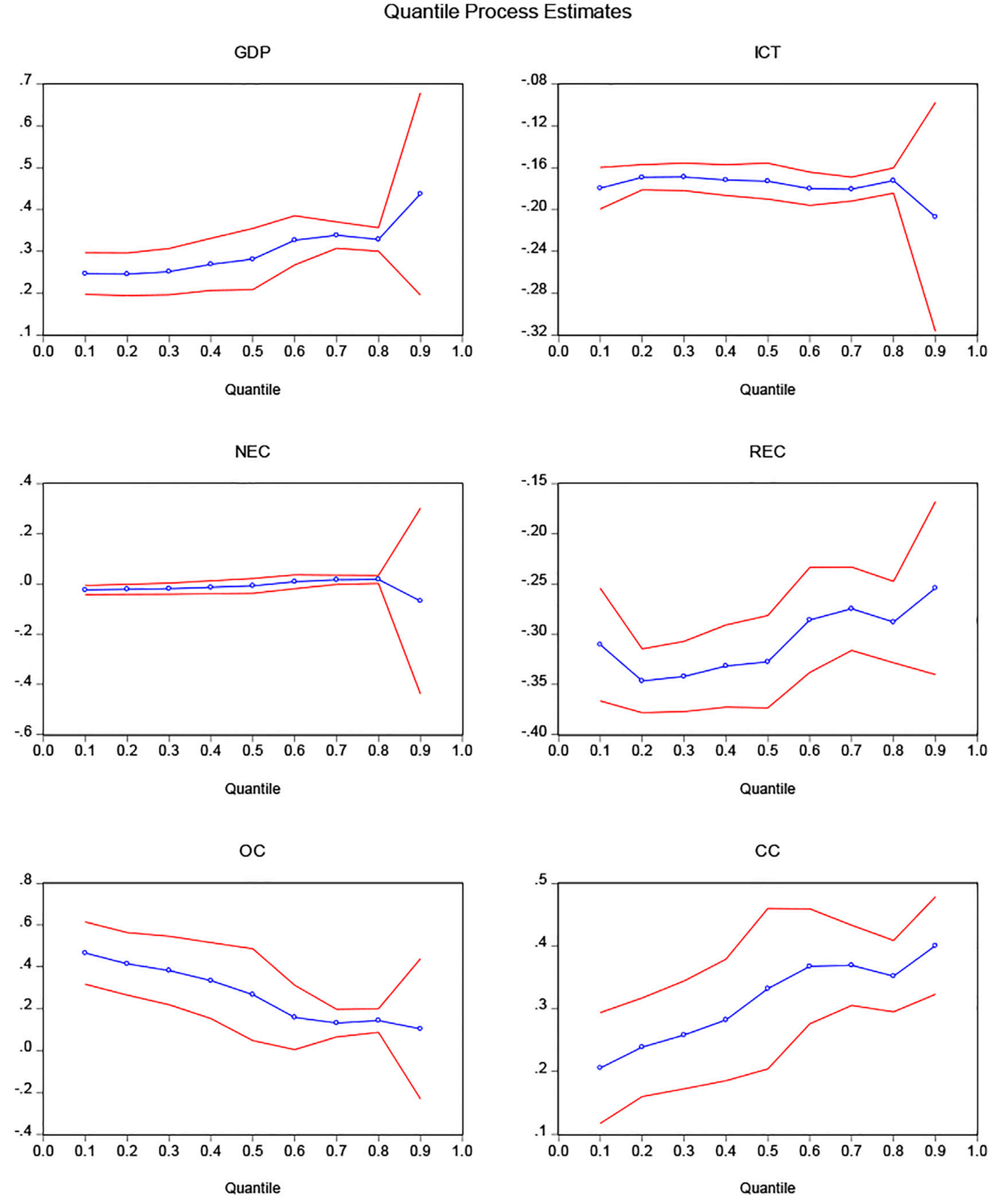


FIGURE 2 | Summary of the Quantile Process results.

energy supply in these countries. It is undeniable that nuclear energy is an alternative and better solution to improve environmental quality and has minimal risk compared to conventional energy sources. In addition, emitter economies should develop nuclear energy-related investment programs and strategies.

Further, renewable energy contributes to improve the environmental quality in these selected countries. Thus, emitter countries should follow initiate step-wise transformation from conventional energy sources (oil, coal) to clean and alternative energy implying in domestic use, industrial and commercial sectors. In addition, we find that the effect of renewable energy consumption is relatively low, but the investment of fossil fuel sources (coal, oil) is relatively large. For obvious understanding, emitter countries need to bring reforms to diminish the use of traditional energy consumption by amplification of nuclear energy and renewable energy sources. Innovation plays an important role in carbon emission mitigation, and focusing on technologies that can increase economic and environmental sustainability.

However, clean energy innovations and ICT needed more investment which might be helpful to increase environmental sustainability. The rapid advancement of technology is also contributing to global warming through destructive greenhouse gas emissions. The effect of ICT on CO emissions is heterogeneous and significantly negative at all quantiles and the effect is diverse at different quantiles. The ICT sector is one of the fastest expanding, influencing practically every other technology. Clean energy and global warming mitigation are now an ambition and reality for all policymakers and researchers involved in this technology. Therefore, a combined collaboration of clean technologies and innovations is needed for excessive energy supply and a sustainable environment.

4 CONCLUSION AND DISCUSSION

In light of growing concern over greenhouse gas emissions from traditional energy sources (oil, coal, gas) and limited energy supply has ultimately elicited global attention to achieve sustainability to ensure adequate energy access and curb environmental risks. Keeping both these targets in mind, this study investigates the role of nuclear energy, renewable energy, and ICT in CO_2 emissions in the context of the five emitter countries by taking the longest available data span from 1995 to 2017. In differing from earlier studies, we apply the advanced panel quantile regression method to achieve the targets. This model takes into account the unobserved individual heterogeneity and distributional heterogeneity. Further, in contrast with OLS regression, the panel quantile regression model can help us achieve a more complete picture of the factors affecting CO_2 emissions.

Our findings show that the impact of GDP on CO_2 emission is positive and statistically significant, meaning that GDP has a positive influence on environmental pollution. With respect to nuclear energy consumption, which is insignificant in explaining environmental pollution, it shows that the contribution of nuclear energy contribution is unclear. Moreover, the coefficient of renewable energy consumption and ICT is negative and statistically significant, meaning that accelerated investment in renewable energy consumption and ICT would improve the environmental quality in emitter countries. In addition, fossil fuel energy sources (oil, coal) show that oil and coal consumption increase environmental pollution in emitter countries. The coefficient of oil is positive and significant at a 1% level in all quartiles level. The coefficient of coal consumption is significant at lower quantiles; at other quantiles, the coefficient is negative and significant but at higher quantiles, it is positive and significant.

In light of the outcomes of the study, some policy implications are recommended. Although, the coefficient of nuclear energy is negative its reduction effect is insignificant, nuclear energy is clean and environmentally friendly, and also cost-effective. However, it is worth bearing in mind that nuclear power ensures energy security as well as boosts economic growth, and is appropriate for environmental sustainability. Thus, improvement in infrastructure development for nuclear power generation should be the initial step as well as operational performance, efficiency, and monitoring checks are important to ensure environmental improvement. Therefore, emitter countries should maintain a clear sense of this dilemma and establish several effective short, medium, and long-term energy policies in order to mitigate the CO_2 emission level by adjusting the share of nuclear energy consumption in the total primary energy mix. Moreover, the potential of renewable energy to mitigate the CO_2 emission is negative and significant which suggests these countries should increase the share of renewable energy consumption in the long term. It is critical to enhance projects and investments that promote the role of renewable energy by offering incentives to renewable manufacturers and encouraging new renewable energy research. This will expand the role of renewable energy, which will not only help to create more jobs in construction and manufacturing but will also benefit renewable energy technologies in achieving economies of scale, lowering the cost of these energy sources. In addition, our results infer that the use of ICT lessens the CO_2 emission level in emitter countries. The ICT sector pursuing environmental sustainability and energy efficiency for its own sake, as well as it is also assisting in the reduction of electrical consumption by infusing technology into other sectors. = However, the development of energy-efficient ICT devices and to improve energy efficiency in systems and devices, particularly networks, a multidisciplinary R&D effort is necessary for these countries to lessen environmental degradation. In addition, skills and knowledge about the subject must be extensively disseminated so that it reaches all stakeholders, not just researchers. Last but not least, these countries must replace fossil fuel sources (coal and oil) with clean energy sources for sustainable economic development and environmental quality. In this paper, we investigate the impacts of nuclear energy, renewable energy, and ICT on CO_2 emissions in the top-five carbon emitting countries. However, the status of different dimensions is different for developing countries or developed countries. In addition, the methodology may be different for them. Therefore, in the future, we could apply different models and variables on CO_2 emissions for larger samples including developed and developing economies.

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

AA: Conceptualization, Methodology, Software, Data curation, Writing e original draft, Visualization, Validation, Writing-Reviewing and Editing; MR: Conceptualization, Methodology, Software, Writing original draft, Writing-Reviewing and Editing; MS: Conceptualization, Methodology, Writing-Reviewing and Editing; JY: Conceptualization, Methodology, Supervision.

REFERENCES

Adebola Solarin, S., Al-Mulali, U., and Ozturk, I. (2017). Validating the Environmental Kuznets Curve Hypothesis in India and China: The Role of Hydroelectricity Consumption. *Renew. Sustainable Energ. Rev.* 80, 1578–1587. doi:10.1016/j.rser.2017.07.028

Al-Mulali, U., Fereidouni, H. G., Lee, J. Y., and Sab, C. N. B. C. (2013). Examining the Bi-directional Long Run Relationship between Renewable Energy Consumption and GDP Growth. *Renew. Sustainable Energ. Rev.* 22, 209–222. doi:10.1016/j.rser.2013.02.005

Al-Mulali, U. (2014). Investigating the Impact of Nuclear Energy Consumption on GDP Growth and CO 2 Emission: A Panel Data Analysis. *Prog. Nucl. Energ.* 73, 172–178. doi:10.1016/j.pnucene.2014.02.002

Al-Mulali, U., and Ozturk, I. (2016). The Investigation of Environmental Kuznets Curve Hypothesis in the Advanced Economies: the Role of Energy Prices. *Renew. Sustainable Energ. Rev.* 54, 1622–1631. doi:10.1016/j.rser.2015.10.131

Al-Mulali, U., Sheau-Ting, L., and Ozturk, I. (2015). The Global Move toward Internet Shopping and its Influence on Pollution: an Empirical Analysis. *Environ. Sci. Pollut. Res.* 22, 9717–9727. doi:10.1007/s11356-015-4142-2

Alam, M. M., Murad, M. W., Noman, A. H. M., and Ozturk, I. (2016). Relationships Among Carbon Emissions, Economic Growth, Energy Consumption and Population Growth: Testing Environmental Kuznets Curve Hypothesis for Brazil, China, India and Indonesia. *Ecol. Indicators* 70, 466–479. doi:10.1016/j.ecolind.2016.06.043

Alsayed, A. R. M., Isa, Z., Kun, S. S., and Manzi, G. (2020). Quantile Regression to Tackle the Heterogeneity on the Relationship between Economic Growth, Energy Consumption, and CO2 Emissions. *Environ. Model. Assess.* 25, 251–258. doi:10.1007/s10666-019-09669-7

Añón Higón, D., Gholami, R., and Shirazi, F. (2017). ICT and Environmental Sustainability: A Global Perspective. *Telematics Inform.* 34, 85–95. doi:10.1016/j.tele.2017.01.001

Apergis, N., Payne, J. E., Menyah, K., and Wolde-Rufael, Y. (2010). On the Causal Dynamics between Emissions, Nuclear Energy, Renewable Energy, and Economic Growth. *Ecol. Econ.* 69, 2255–2260. doi:10.1016/j.ecolecon.2010.06.014

Asongu, S. A., Le Roux, S., and Biekpe, N. (2018). Enhancing ICT for Environmental Sustainability in Sub-saharan Africa. *Technol. Forecast. Soc. Change* 127, 209–216. doi:10.1016/j.techfore.2017.09.022

Aydın, C. İ. (2020). Nuclear Energy Debate in Turkey: Stakeholders, Policy Alternatives, and Governance Issues. *Energy Policy* 136, 111041. doi:10.1016/j.enpol.2019.111041

Azam, A., Rafiq, M., Shafique, M., Yuan, J., and Salem, S. (n.d). Human Development Index, ICT and Renewable Energy-Growth Nexus for Sustainable Development: A Novel PVAR Analysis. *Front. Energ. Res.* 760. doi:10.3389/fenrg.2021.760758

Azam, A., Rafiq, M., Shafique, M., Ateeq, M., and Yuan, J. (2020a). Causality Relationship between Electricity Supply and Economic Growth: Evidence from Pakistan. *Energies* 13, 837. doi:10.3390/en13040837

Azam, A., Rafiq, M., Shafique, M., and Yuan, J. (2021b). Renewable Electricity Generation and Economic Growth Nexus in Developing Countries: An ARDL Approach. *Econ. Research-Ekonomska Istraživanja* 34, 2423–2446. doi:10.1080/1331677X.2020.1865180

Azam, A., Rafiq, M., Shafique, M., Ateeq, M., and Yuan, J. (2021a). Investigating the Impact of Renewable Electricity Consumption on Sustainable Economic Development: a Panel ARDL Approach. *Int. J. Green Energ.* 18, 1185–1192. doi:10.1080/15435075.2021.1897825

Azam, A., Rafiq, M., Shafique, M., and Yuan, J. (2021e). An Empirical Analysis of the Non-linear Effects of Natural Gas, Nuclear Energy, Renewable Energy and ICT-Trade in Leading CO2 Emitter Countries: Policy towards CO2 Mitigation and Economic Sustainability. *J. Environ. Manage.* 286, 112232. doi:10.1016/j.jenvman.2021.112232

Azam, A., Rafiq, M., Shafique, M., and Yuan, J. (2021c). Does Nuclear or Renewable Energy Consumption Help to Control Environmental Pollution? New Evidence from China. *Renew. Energ. Focus* 39, 139–147. doi:10.1016/j.ref.2021.08.002

Azam, A., Rafiq, M., Shafique, M., Zhang, H., Ateeq, M., and Yuan, J., (2021d). Analyzing the Relationship between Economic Growth and Electricity Consumption from Renewable and Non-renewable Sources: Fresh Evidence from Newly Industrialized Countries. *Sustainable Energ. Tech. Assessments* 44(3):100991. doi:10.1016/j.seta.2021.100991

Azam, A., Rafiq, M., Shafique, M., Zhang, H., and Yuan, J. (2021f). Analyzing the Effect of Natural Gas, Nuclear Energy and Renewable Energy on GDP and Carbon Emissions: A Multi-Variate Panel Data Analysis. *Energy* 219 (13), 119592. doi:10.1016/j.energy.2020.119592

Baek, J. (2016). Do nuclear and Renewable Energy Improve the Environment? Empirical Evidence from the United States. *Ecol. Indicators* 66, 352–356. doi:10.1016/j.ecolind.2016.01.059

Baloch, M. A., and Wang, B. (2019). Analyzing the Role of Governance in CO2 Emissions Mitigation: The BRICS Experience. *Struct. Chang. Econ. Dyn.* 51, 119–125. doi:10.30848/pjb2019-3(32)

Baloch, M. A., Mahmood, N., and Zhang, J. W. (2019). Effect of Natural Resources, Renewable Energy and Economic Development on CO2 Emissions in BRICS Countries. *Sci. Total Environ.* 678, 632–638. doi:10.1016/j.scitotenv.2019.05.028

Ben Jebli, M., Ben Youssef, S., and Ozturk, I. (2016). Testing Environmental Kuznets Curve Hypothesis: The Role of Renewable and Non-renewable Energy Consumption and Trade in OECD Countries. *Ecol. Indicators* 60, 824–831. doi:10.1016/j.ecolind.2015.08.031

Bilgili, F., Koçak, E., and Bulut, Ü. (2016). The Dynamic Impact of Renewable Energy Consumption on CO 2 Emissions: A Revisited Environmental Kuznets Curve Approach. *Renew. Sustainable Energ. Rev.* 54, 838–845. doi:10.1016/j.rser.2015.10.080

Bölük, G., and Mert, M. (2015). The Renewable Energy, Growth and Environmental Kuznets Curve in Turkey: An ARDL Approach. *Renew. Sustainable Energ. Rev.* 52, 587–595. doi:10.1016/j.rser.2015.07.138

Breitung, J. (2001). *The Local Power of Some Unit Root Tests for Panel Data*. Emerald Group Publishing Limited.

British Petroleum (2014). *BP Statistical Review of World Energy*. Br. Pet. doi:10.1016/j.egypro.2013.06.172

British Petroleum (2018). *Statistical Review of World Energy | Energy Economics | Home [WWW Document]*. Stat. Rev. World Energy.

Bulut, U. (2017). The Impacts of Non-renewable and Renewable Energy on CO_2 Emissions in Turkey. *Environ. Sci. Pollut. Res.* 24, 15416–15426. doi:10.1007/s11356-017-9175-2

Chaudhry, I. S., Safdar, N., and Farooq, F. (2012). Energy Consumption and Economic Growth: Empirical Evidence from Pakistan. *Pakistan J. Soc. Sci.* 32, 371–382.

Chen, X., Li, Y., Xiao, J., and Wen, F. (2020). Oil Shocks, Competition, and Corporate Investment: Evidence from China. *Energ. Econ.* 89, 104819. doi:10.1016/j.eneco.2020.104819

Cheng, C., Ren, X., Dong, K., Dong, X., and Wang, Z. (2021). How Does Technological Innovation Mitigate CO2 Emissions in OECD Countries? Heterogeneous Analysis Using Panel Quantile Regression. *J. Environ. Manage.* 280, 111818. doi:10.1016/j.jenvman.2020.111818

Chu, H.-P., and Chang, T. (2012). Nuclear Energy Consumption, Oil Consumption and Economic Growth in G-6 Countries: Bootstrap Panel Causality Test. *Energy Policy* 48, 762–769. doi:10.1016/j.enpol.2012.06.013

Coroama, V. C., Hilty, L. M., and Birtel, M. (2012). Effects of Internet-Based Multiple-Site Conferences on Greenhouse Gas Emissions. *Telematics Inform.* 29, 362–374. doi:10.1016/j.tele.2011.11.006

Danish (2019). Effects of Information and Communication Technology and Real Income on CO2 Emissions: The Experience of Countries along Belt and Road. *Telematics Inform.* 45, 101300. doi:10.1016/j.tele.2019.101300

Dong, K., Sun, R., and Dong, X. (2018). CO2 Emissions, Natural Gas and Renewables, Economic Growth: Assessing the Evidence from China. *Sci. Total Environ.* 640-641, 293–302. doi:10.1016/j.scitotenv.2018.05.322

Duan, K., Ren, X., Shi, Y., Mishra, T., and Yan, C. (2021). The Marginal Impacts of Energy Prices on Carbon price Variations: Evidence from a Quantile-On-Quantile Approach. *Energ. Econ.* 95, 105131. doi:10.1016/j.eneco.2021.105131

Hasnisah, A., Azlina, A. A., and Taib, C. M. I. C. (2019). The Impact of Renewable Energy Consumption on Carbon Dioxide Emissions: Empirical Evidence from Developing Countries in Asia. *Ijeep* 9, 135–143. doi:10.32479/ijeep.7535

Hassan, S. T., Danish, M. A., Salah-Ud-Din khan, Z. H., Awais Baloch, M., and Tarar, Z. H. (2020). Is Nuclear Energy a Better Alternative for Mitigating CO2 Emissions in BRICS Countries? An Empirical Analysis. *Nucl. Eng. Technology* 52, 2969–2974. doi:10.1016/j.net.2020.05.016

Huang, Y., Zhu, H., and Zhang, Z. (2020). The Heterogeneous Effect of Driving Factors on Carbon Emission Intensity in the Chinese Transport Sector:

Evidence from Dynamic Panel Quantile Regression. *Sci. Total Environ.* 727, 138578. doi:10.1016/j.scitotenv.2020.138578
IEA (2015). *Energy and Climate Change, World Energy Outlook Special Report*.
Iheonu, C. O., Asongu, S. A., Odo, K. O., and Ojiem, P. K. (2020). Financial Sector Development and Investment in Selected Countries of the Economic Community of West African States: Empirical Evidence Using Heterogeneous Panel Data Method. *Financ. Innov.* 6, 1–15. doi:10.1186/s40854-020-00195-0
Ike, G. N., Usman, O., and Sarkodie, S. A. (2020). Testing the Role of Oil Production in the Environmental Kuznets Curve of Oil Producing Countries: New Insights from Method of Moments Quantile Regression. *Sci. Total Environ.* 711, 135208. doi:10.1016/j.scitotenv.2019.135208
Im, K. S., Pesaran, M. H., and Shin, Y. (2003). Testing for Unit Roots in Heterogeneous Panels. *J. Econom.* 115 (1), 53–74. doi:10.1016/S0304-4076(03)00092-7
IPCC (2018a). *An IPCC Special Report on the Impacts of Global Warming of 1.5°C*. IPCC. doi:10.1002/9780470996621.ch50
IPCC (2018b). *Global Warming of 1.5 °C. IPCC Special Report 1.5 Summary for Policymakers*. IPCC. doi:10.1017/CBO9781107415324
Jaforullah, M., and King, A. (2015). Does the Use of Renewable Energy Sources Mitigate CO 2 Emissions? A Reassessment of the US Evidence. *Energ. Econ.* 49, 711–717. doi:10.1016/j.eneco.2015.04.006
Jin, T., and Kim, J. (2018). What Is Better for Mitigating Carbon Emissions - Renewable Energy or Nuclear Energy? A Panel Data Analysis. *Renew. Sustainable Energ. Rev.* 91, 464–471. doi:10.1016/j.rser.2018.04.022
Khan, N., Baloch, M. A., Saud, S., and Fatima, T. (2018). The Effect of ICT on CO2 Emissions in Emerging Economies: Does the Level of Income Matters? *Environ. Sci. Pollut. Res.* 25, 22850–22860. doi:10.1007/s11356-018-2379-2
Latif, Z., Jianqiu, Z., Salam, S., Pathan, Z. H., Jan, N., and Tunio, M. Z. (2017). FDI and 'political' Violence in Pakistan's Telecommunications. *Hsm* 36, 341–352. doi:10.3233/HSM-17154
Lau, L.-S., Choong, C.-K., Ng, C.-F., Liew, F.-M., and Ching, S.-L. (2019). Is Nuclear Energy Clean? Revisit of Environmental Kuznets Curve Hypothesis in OECD Countries. *Econ. Model.* 77, 12–20. doi:10.1016/j.econmod.2018.09.015
Lee, S., Kim, M., and Lee, J. (2017). Analyzing the Impact of Nuclear Power on CO2 Emissions. *Sustainability* 9, 1428. doi:10.3390/su9081428
Levin, A., Lin, C. F., and Chu, C. S. J. (2002). Unit Root Tests in Panel Data: Asymptotic and Finite-Sample Properties. *J. Econom.* 108 (1), 1–24. doi:10.1016/S0304-4076(01)00098-7
Liu, M., Ren, X., Cheng, C., and Wang, Z. (2020). The Role of Globalization in CO2 Emissions: a Semi-parametric Panel Data Analysis for G7. *Sci. Total Environ.* 718, 137379. doi:10.1016/j.scitotenv.2020.137379
Maddala, G. S., and Wu, S. (1999). A Comparative Study of Unit Root Tests with Panel Data and a New Simple Test. *Oxf. Bull. Econ. Stat.* 61, 631–652. doi:10.1111/1468-0084.0610s1631
Mahmood, N., DanishWang, Z., Wang, Z., and Zhang, B. (2020). The Role of Nuclear Energy in the Correction of Environmental Pollution: Evidence from Pakistan. *Nucl. Eng. Technology* 52, 1327–1333. doi:10.1016/j.net.2019.11.027
Menyah, K., and Wolde-Rufael, Y. (2010). CO_2 Emissions, Nuclear Energy, Renewable Energy and Economic Growth in the US. *Energy Policy*, 38, 2911–2915. doi:10.1016/j.enpol.2010.01.024
Paramati, S. R., Mo, D., and Gupta, R. (2017). The Effects of Stock Market Growth and Renewable Energy Use on CO2 Emissions: Evidence from G20 Countries. *Energ. Econ.* 66, 360–371. doi:10.1016/j.eneco.2017.06.025
Park, S.-H., Jung, W.-J., Kim, T.-H., and Lee, S.-Y. T. (2016). Can Renewable Energy Replace Nuclear Power in Korea? An Economic Valuation Analysis. *Nucl. Eng. Technology* 48, 559–571. doi:10.1016/j.net.2015.12.012
Peng, L., Zhang, Y., Li, F., Wang, Q., Chen, X., and Yu, A. (2019). Policy Implication of Nuclear Energy's Potential for Energy Optimization and CO2 Mitigation: A Case Study of Fujian, China. *Nucl. Eng. Technology* 51, 1154–1162. doi:10.1016/j.net.2019.01.016
Prăvălie, R., and Bandoc, G. (2018). Nuclear Energy: Between Global Electricity Demand, Worldwide Decarbonisation Imperativeness, and Planetary Environmental Implications. *J. Environ. Manage.* 209, 81–92. doi:10.1016/j.jenvman.2017.12.043
Qiao, H., Zheng, F., Jiang, H., and Dong, K. (2019). The Greenhouse Effect of the Agriculture-Economic Growth-Renewable Energy Nexus: Evidence from G20 Countries. *Sci. Total Environ.* 671, 722–731. doi:10.1016/j.scitotenv.2019.03.336
Ren, X., Cheng, C., Wang, Z., and Yan, C. (2021). Spillover and Dynamic Effects of Energy Transition and Economic Growth on Carbon Dioxide Emissions for the European Union: A Dynamic Spatial Panel Model. *Sustainable Development* 29, 228–242. doi:10.1002/sd.2144
Salman, M., Long, X., Dauda, L., and Mensah, C. N. (2019). The Impact of Institutional Quality on Economic Growth and Carbon Emissions: Evidence from Indonesia, South Korea and Thailand. *J. Clean. Prod.* 241, 118331. doi:10.1016/j.jclepro.2019.118331
Shafique, M., Azam, A., Rafiq, M., and Luo, X. (2020). Evaluating the Relationship between Freight Transport, Economic prosperity, Urbanization, and CO2 Emissions: Evidence from Hong Kong, Singapore, and South Korea. *Sustainability* 12, 10664. doi:10.3390/su122410664
Shafique, M., Azam, A., Rafiq, M., and Luo, X. (2021a). Investigating the Nexus Among Transport, Economic Growth and Environmental Degradation: Evidence from Panel ARDL Approach. *Transport Policy* 109, 61–71. doi:10.1016/j.tranpol.2021.04.014
Shafique, M., Azam, A., Rafiq, M., and Luo, X. (2021b). Life Cycle Assessment of Electric Vehicles and Internal Combustion Engine Vehicles: A Case Study of Hong Kong. *Res. Transp. Econ.* 101112. doi:10.1016/j.retrec.2021.101112
Shafique, M., and Luo, X. (2021). Environmental Life Cycle Assessment of Battery Electric Vehicles from the Current and Future Energy Mix Perspective. *J. Environ. Manage.* 303, 114050. doi:10.1016/j.jenvman.2021.114050
Shahzad, K., Jianqiu, Z., Hashim, M., Nazam, M., and Wang, L. (2020). Impact of Using Information and Communication Technology and Renewable Energy on Health Expenditure: A Case Study from Pakistan. *Energy* 204, 117956. doi:10.1016/j.energy.2020.117956
Sharif, A., Mishra, S., Sinha, A., Jiao, Z., Shahbaz, M., and Afshan, S. (2020). The Renewable Energy Consumption-Environmental Degradation Nexus in Top-10 Polluted Countries: Fresh Insights from Quantile-On-Quantile Regression Approach. *Renew. Energ.* 150, 670–690. doi:10.1016/j.renene.2019.12.149
The World Bank (2015). *World Development Indicators*. DataBank. DataBank [WWW Document].
Wang, W.-H., Himeda, Y., Muckerman, J. T., Manbeck, G. F., and Fujita, E. (2015). CO2 Hydrogenation to Formate and Methanol as an Alternative to Photo- and Electrochemical CO2 Reduction. *Chem. Rev.* 115, 12936–12973. doi:10.1021/acs.chemrev.5b00197
Wen, F., Zhao, L., He, S., and Yang, G. (2020). Asymmetric Relationship between Carbon Emission Trading Market and Stock Market: Evidences from China. *Energ. Econ.* 91, 104850. doi:10.1016/j.eneco.2020.104850
Yahya, F., and Rafiq, M. (2020). Brownfield, greenfield, and Renewable Energy Consumption: Moderating Role of Effective Governance. *Energ. Environ.* 31, 405–423. doi:10.1177/0958305x19872936
Zhang, B., Wang, B., and Wang, Z. (2017). Role of Renewable Energy and Non-renewable Energy Consumption on EKC: Evidence from Pakistan. *J. Clean. Prod.* 156, 855–864. doi:10.1016/j.jclepro.2017.03.203
Zheng, Y., Yin, H., Zhou, M., Liu, W., and Wen, F. (2021a). Impacts of Oil Shocks on the EU Carbon Emissions Allowances under Different Market Conditions. *Energ. Econ.* 104, 105683. doi:10.1016/j.eneco.2021.105683
Zheng, Y., Zhou, M., and Wen, F. (2021b). Asymmetric Effects of Oil Shocks on Carbon Allowance price: Evidence from China. *Energ. Econ.* 97, 105183. doi:10.1016/j.eneco.2021.105183

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.

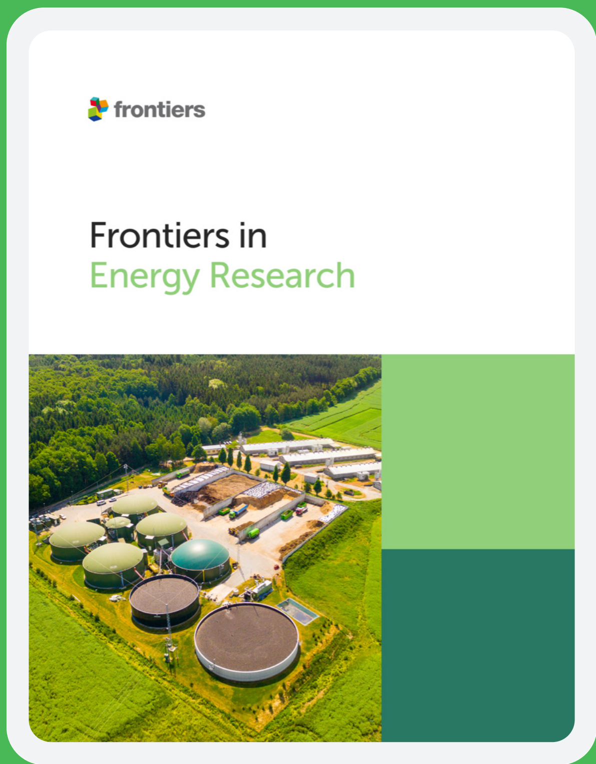
Frontiers in
Energy Research

Advances and innovation in sustainable, reliable and affordable energy

Explores sustainable and environmental developments in energy. It focuses on technological advances supporting Sustainable Development Goal 7: access to affordable, reliable, sustainable and modern energy for all.

Discover the latest Research Topics

See more →



Frontiers

Avenue du Tribunal-Fédéral 34
1005 Lausanne, Switzerland
frontiersin.org

Contact us

+41 (0)21 510 17 00
frontiersin.org/about/contact