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Research on the Effects of Carbon Emissions from China's Technology Transfer: Domestic and International Perspectives

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Abstract: Technology transfer represents a critical avenue for addressing the challenges associated with carbon emission reduction, warranting thorough investigation into the effects of both domestic and international technology transfer on carbon emissions. This study employs data mining techniques to extract comprehensive data on patent transfers across 334 prefecture-level cities in China from 2000 to 2021, analyzing the influence of technology transfer on carbon emissions from both domestic and international perspectives. The findings indicate that domestic technology transfer and international technology transfer significantly contribute to carbon emission reduction, with international technology transfer exerting a more substantial effect than its domestic counterpart. To mitigate endogeneity concerns, the study utilizes the shortest distance from each city to the telegraph lines established during the late Qing Dynasty as an instrumental variable and the resulting conclusions remain robust. Heterogeneity tests reveal significant regional disparities, particularly in areas located southeast and northwest of the Hu Huanyong line, as well as between regions inside and outside the five major urban agglomerations. The mechanisms underlying carbon reduction suggest that improvements in energy efficiency and upgrades in industrial structure serve as the primary pathways for carbon emission reductions resulting from both domestic and foreign technology transfers. These conclusions provide a theoretical foundation and empirical insights to facilitate the acceleration of technology flow within the context of high-quality development, particularly concerning environmental protection.

Keywords: technology transfer; carbon emissions; energy efficiency; industrial structure; telegraph lines of the late Qing Dynasty

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1. Introduction

Global warming has precipitated a multitude of adverse effects, including extreme weather events, water scarcity, environmental degradation, and economic losses, which have long been a concern for nations worldwide. In response to the imperative of preventing "dangerous" human interference with the climate system, a series of international emission reduction initiatives have been implemented. China, guided by its "dual carbon" objectives, aims to establish a green and low-carbon societal framework. However, the "Global Carbon Budget 2023", published by the Global Carbon Project, indicates that global carbon emissions are projected to reach 40.9 billion tons in 2023, with emission levels remaining elevated and significantly deviating from established global reduction targets. Concurrently, China has experienced a substantial increase in carbon emissions in 2023, driven by post-pandemic economic recovery and reduced rainfall, which have intensified the demand for coal-fired power generation. Despite the acceleration of emission reduction efforts, the rate of energy consumption and total carbon emissions necessary for development remains considerable. Given China's current economic scale, population density, and social structure, achieving a "decoupling" of economic growth from carbon emissions—thereby fulfilling the dual objectives of high-quality economic development alongside energy conservation and emission reduction—presents significant challenges and obstacles. A critical component in the endeavor to reduce carbon emissions is technology transfer, which can facilitate the creation of "technological wormholes" that diminish the technological gap between urban areas. By enabling the flow and integration of scarce resources, including technological knowledge, advancements in technology, commodity trade, management expertise, and skilled professionals, technology transfer fosters the diffusion and replication of advanced regional technologies, thereby promoting technological advancement and the development of green and low-carbon innovations. Consequently, technology transfer emerges as a vital mechanism for bridging the low-carbon technology divide between regions and enhancing overall technological capacity, serving as a key element in achieving China's carbon peak and carbon neutrality objectives.

There are already numerous well-established theoretical studies on carbon emissions, including the IPAT model, the STRIPAT model, and the LMDI model, among others (Ehrlich & Holdren, 1971; Dietz & Rosa, 1997; Wang & Feng, 2018). Subsequent scholars have utilized these established frameworks and models to inform their studies on carbon emissions, drawing from various theoretical perspectives, including environmental economic theory, environmental innovation theory, innovation network theory, input–output theory, and knowledge production theory. However, due to variations in research subjects, data utilized, and methodologies employed, the results obtained can differ significantly. For instance, concerning the technology-driven factors closely related to this paper, there are divergent opinions on the existence of a carbon-reducing effect attributed to technological factors and the underlying mechanisms involved. Consequently, the driving factors and effects of carbon emissions also exhibit substantial variability. For instance, Shuai et al. (2017) employed the STIRPAT model to examine 125 countries from 1990 to 2011, concluding that the influence of technological factors on carbon reduction ranks between affluence and population. In contrast, group studies indicate that technological factors are the most significant in high-income countries, while they are the least important in low-income countries. Y. Chen and Lee (2020), based on research conducted from 1996 to 2018 across 96 countries, found that the global carbon reduction effect of technological innovation is not substantial. Regarding the carbon-reduction mechanisms associated with technological factors, J. Chen et al. (2020) argue that the carbon reduction effect of technology is contingent upon whether the change is in environmental technology or production technology. X. Zhang et al. (2012) contend that technological progress primarily reduces carbon emissions by enhancing the efficiency of fossil energy. And L. Wu et al. (2021) further assert that upgrading industrial structures is a critical mechanism for carbon reduction. It is evident that there exists a significant divergence among researchers regarding the carbon reduction effect of technological factors and their impact mechanisms, underscoring the necessity for further exploration in this area.

Innovation economics theory posits that "innovation is the recombination of factors of production" (Schumpeter, 1934). Technology, as a crucial factor of production, represents a flow of production inputs through technology transfer. This process can simultaneously influence technological innovation and progress through the exchange of information and innovation. Currently, numerous studies examine the environmental impacts of the flow of capital, labor, and other factors (Qi & Xu, 2019; Destek et al., 2023). However, there is a relative scarcity of research investigating the environmental effects of technological factor flows. Existing literature on technological factors predominantly focuses on the transfer of green and sustainable technologies (Fernandes et al., 2021), with insufficient attention given to a comprehensive perspective on technology transfer.

The studies most closely related to this paper are those by Shang et al. (2023), Jin and Duan (2024) and Wei and Zeng (2024). The first paper analyzes low-carbon technology transfer's impact on carbon emissions between Chinese cities, the second examines green technology flow effects in the Yangtze River Economic Belt, and the third discusses spatial spillover effects of technology transfer on carbon emissions, lacking exploration of underlying mechanisms. In light of the accelerating regional economic integration and the ongoing process of global economic globalization, the pace of economic integration and technological collaboration among countries is continuously increasing. In this context, technological factors not only flow across regions but also encompass cross-border movements. Domestic technology transfer within China can enhance the supply of technology and facilitate the market allocation of technological resources, while international technology transfer can promote global technological cooperation and sharing.

In light of the aforementioned considerations, this paper adopts both international and domestic perspectives, utilizing data on urban patent transfers in China from 2000 to 2021, to investigate the effects of technology transfer on carbon emissions and to elucidate the regional disparities in these impacts. This analysis offers novel insights for enhancing both domestic and international technology transaction markets and serves as a reference for advancing high-quality, green, and low-carbon economic development. The potential marginal contributions of this paper are as follows: First, it examines both domestic and international aspects of technology transfer, incorporating both inflows and outflows. This approach enriches the research perspective on technology flows and broadens the scope of studies on factor mobility. Second, the paper introduces mechanisms related to energy efficiency and industrial structure, thereby enhancing the understanding of the drivers behind the impact of technology transfer on carbon emissions and the pathways to achieving carbon peaks from an efficiency-structure perspective. This provides valuable insights for future research and policymakers. Finally, this paper is the first to utilize the shortest distance from each city to the telegraph lines of the late Qing Dynasty as an instrumental variable. The foundational role of the Qing Dynasty telegraph lines in China's information infrastructure and external communication patterns offers a compelling explanation for their relevance to technology transfer. Furthermore, the historical context helps address endogeneity issues, serving as a reference for the selection of instrumental variables in future studies.

The structure of this paper is organized as follows: Section 2 presents the theoretical framework and research hypotheses; Section 3 outlines the research design; Section 4 analyzes the empirical results; and Section 5 concludes with the findings and their implications.

2. Theoretical Framework and Research Hypotheses

2.1. The Influence of Technology Transfer on Carbon Emissions

Technology transfer is a dynamic process that reallocates information resources related to technology and knowledge. It can take various forms, including the trade of goods, technology exchange, direct investment, strategic alliances, university–industry collaboration, scientific and technological exchanges, and technology assistance. Technology transfer facilitates the dissemination of technology and enhances the symmetry of technological information, thereby reducing regional technological disparities. It serves as a transmission mechanism for technological innovation and is a crucial link in the advancement of technology. Consequently, technological progress resulting from technology transfer can lead to a reduction in carbon emissions by improving management practices and decreasing the reliance on fossil fuels. For instance, agricultural technology transfer primarily lowers carbon emissions by reducing the level of agricultural chemical use and by promoting advanced agricultural production technologies and equipment. In the industrial sector, technology transfer can mitigate carbon emissions by fostering industrial agglomeration and encouraging industrial upgrading. Based on the aforementioned content, this paper will examine the impact of technology transfer on carbon emissions from four dimensions: domestic technology inflows, domestic technology outflows, international technology inflows, and international technology outflows (as illustrated in Figure 1).

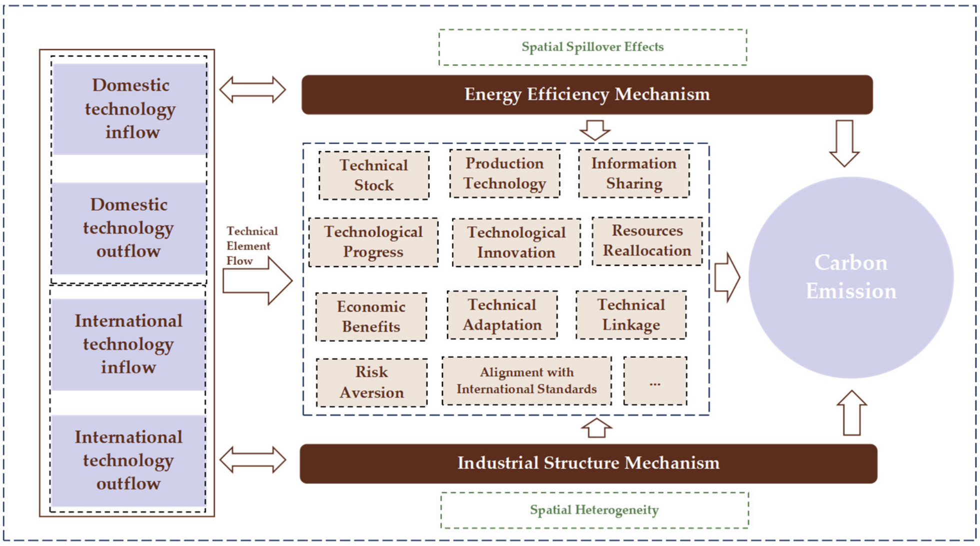

Figure 1. Mechanism analysis chart.

2.1.1. The Influence of Domestic Technology Transfer on Carbon Emissions

From the perspective of domestic technology transfer, the relatively minor cultural differences and the consistency of policies and regulations within a country contribute to a robust adaptability of domestic technology transfer mechanisms. Consequently, both horizontal technology transfers among enterprises and vertical technology transfers from academic institutions to production enterprises can be effective. Domestic technology inflow primarily facilitates the reduction of carbon emissions through the upgrading of industrial structures and technological innovation (L. Sun et al., 2020). Firstly, recipient regions of technology transfer can mitigate the uncertainties associated with high-risk, long-cycle research and development (R&D). They can swiftly acquire technology patents and achieve the industrial application of new technologies in the short term. This process promotes the upgrading of industrial structures and facilitates the flow of resources toward more advanced, greener, and low-carbon industries. Secondly, technology inflow can generate a long-term accumulation effect, thereby increasing the technological stock necessary for independent innovation. Lastly, to leverage the technological benefits of this stock, enterprises are likely to implement measures such as enhancing training for technical personnel, increasing research and development funding, and investing in human capital. These actions aim to transform the internal environment to better accommodate the growth of technology localization, ultimately promoting carbon emission reductions through technological innovation. Conversely, domestic technology outflow primarily contributes to carbon emission reduction through capital accumulation and the dissemination of technical information. Technology outflow can yield economic benefits that enhance research and development capital, stimulate enthusiasm for scientific and technological innovation, and attract a concentration of exceptional talent. Furthermore, domestic technology outflow fosters technical cooperation, exchange, and coordinated development through the sharing of technology, thereby generating a technological linkage effect that enhances the research and innovation capabilities of both technological partners and the originating entities. In summary, both domestic technology inflow and outflow play a significant role in facilitating carbon emission reductions.

2.1.2. The Influence of International Technology Transfer on Carbon Emissions

From the perspective of international technology transfer, the inflow of technology plays a significant role in facilitating carbon emission reduction through the concept of "latecomer advantage" and access to advanced international technological information. Firstly, it is important to note that imported international technology, even if considered relatively outdated by developed countries, may surpass the existing technological capabilities within the recipient country (Mansfield & Romeo, 1980). The advanced and cutting-edge nature of international technology enables the recipient country to capitalize on the latecomer advantage, thereby achieving accelerated technological catch-up, progress, and industrial upgrading. Secondly, access to cutting-edge technological information can stimulate and guide domestic research and development (R&D), which is particularly beneficial for the strategic selection of "learning by doing". This process, in turn, fosters greater technological accumulation in the independent innovation of sustainable technologies, including green and low-carbon solutions. For instance, Foreign Direct Investment (FDI) can generate substantial technology spillover effects through various channels, including market competition, labor mobility, production demonstrations, and both forward and backward linkages within the supply chains of multinational corporations (Sinani & Meyer, 2004; Djulius, 2017). These effects can enhance the labor productivity and total factor productivity of local firms (Lall, 1978; Kokko, 1994). Furthermore, international technology outflow, while providing economic benefits, also necessitates a high standard of technology adaptation. To sustain economic advantages and maintain technological bargaining power in the context of international technology outflow, R&D entities must actively or passively increase their investment in research and development and employ a greater number of R&D personnel. This enhancement of technological competitiveness is essential for adapting to market demands for high-standard international technology, ultimately promoting independent technological innovation capabilities. In summary, international technology transfer serves to reduce global technological disparities, fosters international technological exchanges, and is instrumental in addressing low-end technological challenges. It further supports the advancement of medium and high-end, green, and clean technological development.

In summary, from both domestic and international perspectives, technology transfer plays a significant role in reducing carbon emissions. Domestic technology transfer primarily focuses on minimizing carbon emissions through technology sharing, enhancing technological reserves, optimizing resource allocation throughout the industrial chain, and strengthening competitive advantages within industries. In contrast, international technology transfer emphasizes collaboration with the global community by acquiring cutting-edge and more advanced technologies than those available domestically. This approach facilitates leapfrog development in national technology, particularly by swiftly narrowing the international gap in green and low-carbon technologies. Based on this analysis, the present study proposes the following research hypotheses:

Hypothesis 1. *The inflow and outflow of domestic technology contribute positively to the reduction of carbon emissions.*

Hypothesis 2. *The inflow and outflow of international technology contribute positively to the reduction of carbon emissions.*

2.2. Mechanisms of Technology Transfer Influencing Carbon Emissions

Energy efficiency and industrial structure are widely recognized as critical determinants of carbon emissions. Furthermore, technology transfer, as a component of factor flow, exerts a significant influence on both energy efficiency and industrial structure. Consequently, this paper posits that technology transfer affects carbon emissions through the mechanisms of enhancing energy efficiency and facilitating the upgrading of industrial structures.

2.2.1. Energy Efficiency

Improving energy efficiency is a critical component in addressing the challenges posed by climate change (Lee et al., 2017). Energy efficiency can be categorized into two distinct types: economic energy efficiency and physical energy efficiency. Economic energy efficiency is defined as the ratio of final economic output to energy input, while physical energy efficiency refers to the ratio of energy output before and after the process of energy conversion. Numerous scholars contend that advancements in technology play a significant role in enhancing energy efficiency (Fan & Lei, 2014; R. Zhang & Fu, 2022). In the context of developing countries, technology transfer, akin to independent innovation, serves as a primary avenue for fostering technological progress. Empirical studies have indicated that models focused solely on technology transfer yield a more pronounced positive impact on technological advancement (L. Jiang & Zhang, 2018). Consequently, this paper posits that technology transfer contributes to the improvement of energy efficiency. Theoretically, enhancing energy efficiency can decelerate the rate of energy consumption and decrease the overall volume of energy utilized, thereby mitigating the carbon dioxide emissions associated with energy consumption. From the standpoint of domestic technology transfer, the influx of high-level technologies can improve the efficiency of fossil fuel combustion and the operational efficiency of energy equipment. This improvement can lead to a reduction in energy input and consumption while maintaining the same output level, ultimately resulting in lower carbon emissions. The inflow of domestic technology can yield various advantages related to technological spillovers, including the reduction in research and development (R&D) costs associated with the transformation and upgrading of energy-saving technologies, the minimization of R&D failure risks, and the enhancement of the success rates of advanced energy-saving and emission-reduction technologies through the availability of skilled personnel and technological resources. The economic benefits derived from domestic technology outflow can provide financial support for the continued advancement of energy utilization efficiency technologies. This support not only directly increases funding sources for R&D but also enhances regional talent development. Furthermore, it accelerates technology cycles and updates through technology output, fostering a competitive and collaborative domestic technological environment that promotes significant advancements in green, low-carbon technologies and R&D focused on energy savings and emission reductions. From an international perspective, technology spillover and technological progress primarily occur through international import trade, patent licensing, and the introduction of international technological talent, all of which are vital channels for enhancing energy efficiency. Due to existing technological barriers, the focus of international technology transfer tends to be on basic and general technologies, while cutting-edge, major, and core technologies may not be readily transferable across national borders. Existing research has established that international technology spillover serves as a crucial external driving force for improving the total-factor energy efficiency within the manufacturing sector, with technology imported from developed countries directly promoting energy efficiency. The inflow of international technology provides host countries with access to advanced technological capabilities, facilitating alignment with global technological standards while also fostering learning effects that create opportunities for technology imitation, consumption, and absorption. Additionally, international technology outflow cultivates partnerships in energy technology research, enhances interactions in energy technology, and ultimately contributes to reductions in carbon emissions. In summary, this paper proposes the following hypotheses:

Hypothesis 3. *The inflow and outflow of domestic technology has the potential to enhance carbon emission reduction by increasing the efficiency of energy utilization.*

Hypothesis 4. *The inflow and outflow of international technology may facilitate the reduction in carbon emissions by enhancing the efficiency of energy utilization.*

2.2.2. Industrial Structure Upgrading

Industrial structure adjustment represents a critical approach to addressing environmental challenges (Zhu & Zhang, 2021). The process of industrial structure upgrading primarily involves the dynamic evolution of industrial frameworks from lower to higher levels. Technology transfer plays a pivotal role in facilitating industrial upgrading through various pathways, including the modernization of traditional industrial technologies, the enhancement of high-quality new assets, the technological spillover effects on local enterprises, and the development of high-tech industries. The upgrading of industrial structures inherently carries environmental implications; the ongoing enhancement of industrial frameworks signifies a transition from primary and secondary industries to the tertiary sector, which has a substantial direct impact on reducing carbon emissions. Moreover, industrial structure-upgrading is instrumental in transforming traditional economic models characterized by high emissions and energy consumption into a new paradigm centered on environmentally friendly high-tech industries. This transition can yield indirect carbon emission reductions through economic mechanisms. Additionally, the upgrading process exhibits competitive and demonstrative effects, which may result in indirect spillover impacts on carbon emissions in adjacent regions. Consequently, industrial upgrading influences carbon emissions through both direct and indirect mechanisms. From the perspective of domestic technology inflow, regions with advanced industrial structures possess greater technological reserves and enhanced capabilities for technological absorption, thereby facilitating the swift application of introduced technologies in production practices and promoting carbon reduction in the short term. In terms of domestic technology outflow, regions with sophisticated industrial structures benefit from a more efficient allocation of factor resources, leading to more effective returns from technology outflow that stimulate the enthusiasm of research and development personnel and attract high-tech talent. This, in turn, supports the application and research of green and sustainable energy technologies. Regarding international technology inflow, regions with advanced industrial structures exhibit stronger technological absorption capabilities and broader application markets. These areas can rapidly implement introduced technologies across various sectors, including machinery, energy, chemicals, information, and transportation, thereby generating significant environmental benefits. Conversely, in the context of international technology outflow, regions with advanced industrial structures typically demonstrate enhanced technological innovation capabilities and host a greater number of multinational corporations and foreign trade enterprises. These factors contribute to an accelerated pace of technology exports. Consequently, to meet the technical standards and quality requirements for exports, the technological level and environment for independent innovation in these regions have also seen corresponding improvements. In light of these observations, this paper proposes the following hypotheses:

Hypothesis 5. *The inflow and outflow of domestic technology has the potential to facilitate the reduction in carbon emissions through mechanisms related to industrial structure upgrading.*

Hypothesis 6. *The inflow and outflow of international technology may facilitate the reduction in carbon emissions through mechanisms related to industrial structure upgrading.*

3. Research Design

3.1. Model Specification

In light of the differences between domestic and international technology transfer, as well as the dynamics of inflow and outflow, this study establishes a fundamental econometric model to assess the impact of technology transfer on carbon emissions. The analysis is conducted from two perspectives: domestic technology inflow and outflow, and international technology inflow and outflow. Following the methodology proposed by Cheng et al. (2024), all explanatory variables are lagged by one period to mitigate potential environmental endogeneity issues. The basic regression model is formulated as follows:

$$\ln co2_{it} = \beta_0 + \beta_1 \ln zr_{it-1} + \beta_2 \ln zc_{it-1} + \beta_3 X_{it-1} + T_t + V_i + E_{it} \tag{1}$$

$$\ln co2_{it} = \beta_0 + \beta_1 \ln fzr_{it-1} + \beta_2 \ln fzc_{it-1} + \beta_3 X_{it-1} + T_t + V_i + E_{it} \tag{2}$$

Equation (1) represents the impact of domestic technology inflow and outflow on carbon emission effects, whereas Equation (2) represent the impact of international technology inflow and outflow on carbon emission effects. In the model, i (=1, 2, . . . , 334) represents the city, and t (=2000, 2001, . . . , 2021) represents the year. The dependent variable $\ln co2_{it}$ is the carbon emission of city i in year t, measured by the logarithm of per capita carbon emissions. $\ln zr_{it-1}$, $\ln zc_{it-1}$, $\ln fzr_{it-1}$, and $\ln fzc_{it-1}$ represent the logarithms of the explanatory variables for domestic technology inflow, domestic technology outflow, international technology inflow, and international technology outflow, respectively. X_{it} is the set of control variables; T_t is the time fixed effect; V_i is the individual fixed effect; E_{it} is the random disturbance term; and β_1 and β_2 are the corresponding coefficients.

3.2. Variable Selection and Data Description

Dependent Variable: The dependent variable in this study is carbon emission. Since carbon dioxide emissions are the primary source of greenhouse gases, this paper adheres to established practices (Xu et al., 2006; B. Q. Lin & Jiang, 2009) by using per capita carbon emissions as a proxy. This metric is calculated as the ratio of a city's total CO_2 emissions to its year-end population. Considering that the carbon emission data for prefecture-level cities in the widely used Carbon Emission Accounts and Datasets (accessible at https://www.ceads.net/data/county/, accessed on 24 September 2024) have not been updated since 2019, this paper utilizes the Open Source Data Inventory of Anthropogenic Carbon Dioxide (ODIAC), which is highly authoritative and internationally recognized (Oda et al., 2018; Zheng et al., 2020). This dataset provides gridded data with a resolution of 1 km × 1 km, estimated based on the carbon emission intensity and geographical location of power plants, as well as nighttime light data observed by satellites. The data are available on the official website of the Center for Global Environmental Research (https://db.cger.nies.go.jp/dataset/ODIAC/DL_odiac2022.html, accessed on 24 September 2024). This paper processes the corresponding gridded layers using ArcGIS software (10.8.2 version) and subsequently aggregates the data on an annual basis. It employs tools such as the Zonal Statistics tool and the Raster Calculator to obtain the total carbon emissions data for Chinese cities from 2000 to 2021 (measured in million tons).

Core Explanatory Variable: The primary explanatory variable examined in this study is technology transfer. This paper defines technology transfer as the process through which patented technology is conveyed from the supplier to the recipient. This process is specifically characterized by the transfer of patent ownership and the associated application rights. In accordance with relevant literature (Duan et al., 2018; Shi et al., 2023), the number of patent transfers serves as a proxy for this core explanatory variable. Patent transfer is a primary mechanism for the flow, diffusion, and transfer of regional technological knowledge (Maggioni et al., 2014). Compared to other indicators of technology transfer, patent transfer provides a micro-level perspective on the pathways through which technology radiates. It serves as a direct reflection and a key carrier of technology transfer, making it a reliable indicator for studying technological change (Acs et al., 2002). The data utilized in this analysis is acquired through data mining techniques from the patent search platform of the China National Intellectual Property Administration. This dataset encompasses various elements, including patent numbers, ownership changes, classification numbers, detailed information regarding patent owners before and after ownership changes, addresses, and authorization announcement dates. To identify the prefecture-level cities associated with changes in patent rights, Python 3.10 programming is employed. Subsequently, the social network data analysis capabilities of GEPHI are applied to compute the weights and sums of all arcs originating from and terminating at city nodes, thereby quantifying the patent inflow and outflow for each city. Patent transfers are indicative of the interactive process of technology resource aggregation and diffusion, wherein the patent provider transmits technology resources to the patent recipient. This mechanism serves as a significant method for assessing technology flow. Technology transfer can be categorized into two main types: international technology transfer and domestic technology transfer, based on the distinctions between subjects and objects involved. Domestic technology inflow (zr) and domestic technology outflow (zc) refer to the number of patents transferred into and out of a city from other domestic cities, respectively. In contrast, international technology inflow (fzr) denotes the number of patents transferred into a city from foreign countries, while international technology outflow (fzc) signifies the number of patents transferred out of a city to foreign countries.

Control Variables: In order to account for additional factors that may influence carbon emissions, the following control variables have been identified, ① Economic development level: This is assessed through real per capita GDP. The present study argues that the level of economic development exerts a positive influence on carbon emissions. ② Financial development scale: This scale is assessed by the year-end balances of various deposits and loans held by financial institutions. The extent of financial development, particularly in relation to green financial services—such as green credit, insurance, and bonds that emphasize energy conservation, clean energy, and sustainable transportation—plays a crucial role in facilitating financial support and risk-sharing for enterprises and national carbon reduction initiatives. Consequently, this paper posits that an increase in the scale of financial development is positively correlated with enhanced efforts in carbon reduction. ③ Educational attainment level: This metric is defined as the ratio of individuals possessing a college degree or higher to the total urban population. Higher education serves as a critical catalyst for stimulating innovation and fosters urban technological advancements, environmentally sustainable production practices among enterprises, and green consumption behaviors among residents. This paper posits that an increased proportion of educated individuals correlates with a reduction in carbon emissions. ④ Transportation infrastructure: This is assessed by the extent of urban road networks. Well-developed urban transportation infrastructure enhances the efficient movement of individuals, goods, technology, and capital across both temporal and spatial dimensions. Such infrastructure contributes to the reduction in communication and transaction costs for businesses, optimizes resource utilization in collaboration, and facilitates the introduction and advancement of green and low-carbon technologies, thereby potentially fostering carbon reduction indirectly. ⑤ Government research and development expenditure: This metric is assessed by the ratio of local government expenditure on science and technology relative to gross domestic product (GDP). Government funding for research and development serves as a crucial financial resource for entities engaged in scientific and technological innovation, including colleges, universities, and enterprises. An increase in government support is associated with heightened motivation among technology providers, leading to more substantial outcomes in scientific and technological innovation, which demonstrates a clear positive correlation. ⑥ Openness to the global economy: This is quantified by the ratio of foreign direct investment (FDI) to gross domestic product (GDP). Openness to the global economy serves as a significant conduit for a nation's external technological connectivity, financial integration, and trade facilitation. Consequently, this paper posits that the degree of openness to the global economy exerts varying effects on a country's carbon emissions across different temporal contexts and geographical regions.

Data sources: In addition to the previously mentioned data sources, this study incorporates control variable data from the "China City Statistical Yearbook" and the "China Science and Technology Statistical Yearbook". In light of the mechanism variable data that will be discussed subsequently, this research focuses on a sample of 334 cities in China from the years 2000 to 2021, resulting in a total of 7348 data points. In addition, given that linear interpolation is widely used, which provides straightforward estimates, and helps avoid the issue of overfitting the data, some missing values were filled using the linear interpolation method.

4. Results and Analysis

4.1. Statistical Tests

Before conducting basic regression analysis, this paper first employed the LLC method to perform unit root tests on the data, with the results presented in Table 1. All variables exhibit a significance level of 1%, indicating the absence of unit roots and confirming the stationarity of the data, which ensures the reliability of the subsequent regressions.

Table 1. Unit root tests.

Variable	Test Statistic Value	Variable	Test Statistic Value
lnzr	−13.6983 ***	lnfindev	−13.1030 ***
lnzc	−11.6707 ***	edule	−12.4385 ***
lnfzr	−7.7750 ***	lnroad	−7.4382 ***
lnfzc	−9..9801 ***	govrdf	−14.0302 ***
gdpp	−9.2902 ***	fdii	−8.2305 ***

Note: The ADF lagged value is at the first order. *** indicate significance levels of 1%.

At the same time, this paper examines multicollinearity among the data by utilizing the correlation coefficient and the Variance Inflation Factor (VIF) to assess the relationships among the explanatory variables. As shown in Table 2, the correlation coefficients for all explanatory variables are below 0.8, and the mean VIF values are under 10. Therefore, it can be concluded that there is no multicollinearity issue in the data used in this study, allowing for the next step of analysis to proceed.

Table 2. Multicollinearity test.

Variable	lnzr	lnzc	lnfzr	lnfzc	gdpp	lnfindev	edule	lnroad	govrdf	fdii
lnzr	1.000									
lnzc	0.758	1.000								
lnfzr	0.523	0.537	1.000							
lnfzc	0.424	0.445	0.684	1.000						
gdpp	0.266	0.274	0.211	0.228	1.000					
lnfindev	0.600	0.588	0.228	0.166	0.140	1.000				
edule	0.183	0.190	0.112	0.094	0.611	0.120	1.000			
lnroad	0.534	0.519	0.113	0.077	0.121	0.708	0.112	1.000		
govrdf	−0.018	−0.016	0.018	0.007	−0.007	0.018	−0.004	0.022	1.000	
fdii	0.013	0.013	0.031	0.017	−0.002	0.041	0.004	0.038	0.770	1.000
VIF	8.490	8.378	5.430	4.388	4.821	3.449	4.875	2.948	2.880	2.776

4.2. Basic Regression Results

Table 3 presents the baseline regression analyses for models (1) and (2), incorporating dual-fixed effects for both time and region. Column (1) details the baseline regression results concerning the impact of domestic technology transfer on carbon emissions, while Column (2) outlines the corresponding results for international technology transfer. To facilitate a comparative analysis of the effects of different types of technology transfers on carbon emissions, the variables lnzr, lnzc, lnfzr, and lnfzc are included in the model concurrently, with the results displayed in Column (3). The regression results presented in column (1) indicate that both domestic technology inflows and outflows are significant at the 1% level, with regression coefficients of −0.0056 and −0.0122, respectively. This suggests that domestic technology transfer effectively promotes reductions in carbon emissions. The regression results in column (2) demonstrate that international technology inflows and outflows are significantly negatively correlated with carbon emissions at the 1% level, with regression coefficients of −0.0188 and −0.0620, respectively. Finally, based on column (3), we observe that both domestic and international technology transfers significantly reduce carbon emissions. Specifically, domestic technology inflows, domestic technology outflows, and international technology inflows are significant at the 5% level, with regression coefficients of −0.0047, −0.0096, and −0.0112, respectively. International technology outflows are significant at the 1% level, with a regression coefficient of −0.0548. These results suggest that domestic and international technology transfers can foster regional technological innovation and advancement through the flow of technological resources, facilitating the interaction and reconfiguration of various production factors, including technology, capital, information, and labor, thereby enhancing regional carbon emission reductions. Our findings align with those of Khan et al. (2022).

Since technology transfer is a standardized variable, we can compare the magnitudes of the regression coefficients and draw the following conclusions: (1) When both domestic and international technology transfers are included in the same regression model, their impact coefficients tend to decrease. This phenomenon may occur because international technology transfer often provides advantages in production efficiency, cost control, and product quality, which can overshadow some aspects of the domestic technology market. However, as domestic technology transfer increases, the technological autonomy of local firms gradually strengthens. This development is conducive to the formation and advancement of local technological standards, allowing for better alignment with local market demands and potentially constraining the international technology market. (2) International technology transfer has a more significant impact on reducing carbon emissions than domestic technology transfer. This can be attributed to several factors: While domestic technology transfer is important, the domestic technology market may not effectively supply certain key technologies. In comparison to international technology, domestic technology transfer still exhibits gaps in achieving carbon emission reductions. International technology transfer can optimize the global supply chain, thereby reducing unnecessary energy consumption and carbon emissions in global production and logistics. Additionally, it can channel international funds and investments into clean energy and environmental projects, thereby enhancing the research and deployment of carbon-reducing technologies. Furthermore, international technology transfer often entails the direct transfer of more advanced environmental and clean energy technologies from technologically advanced developed countries to developing nations. These technologies may not yet be widely adopted or fully developed in the domestic context, and their introduction can significantly promote carbon emission reductions. In summary, Hypotheses 1 and 2 are supported.

Table 3. Basic regression results.

	Domestic Technology Transfer	**International Technology Transfer**	**Technology Transfer**
	(1)	**(2)**	**(3)**
Inzr	−0.0056 *** (0.0181)		−0.0047 ** (0.0182)
Inzc	−0.0122 ** (0.0174)		−0.0096 ** (0.0174)
Infzr		−0.0188 ** (0.0010)	−0.0112 ** (0.0098)
Infzc		−0.0620 *** (0.0101)	−0.0548 *** (0.0101)
Control Variables	Y	Y	Y
Time Fixed Effects	Y	Y	Y
Regional Fixed Effects	Y	Y	Y
Adj. R^2	0.7411	0.7379	0.7414
N	7348	7348	7348

Note: The numbers in parentheses are standard errors; *** and ** indicate that the variable is significant at the 1% and 5% significance levels, respectively.

4.3. Robustness Analysis

This paper performs robustness tests on the baseline regression analysis in three key areas, as presented in Table 4. First, the dependent variable is altered. The previous analysis established the relationship between technology transfer and per capita carbon emissions. In this subsequent analysis, the dependent variable is modified to reflect total urban carbon emissions (logarithmically transformed), with the results detailed in Table 2. The regression outcomes concerning technology transfer and carbon emissions remain largely consistent with those of the baseline regression, thereby indicating the robustness of the initial findings. Second, the data sample is adjusted. Given that cities with higher administrative status possess enhanced capabilities for resource aggregation, integration, and coordination, this study excludes municipalities, provincial capitals, and sub-provincial cities to mitigate the influence of administrative factors on the results. The empirical findings from this adjustment are also presented in Table 4 and align with the basic regression results, further confirming the robustness of the baseline conclusions.

Table 4. Robustness test results.

	Domestic Technology Transfer				International Technology Transfer			
	Replacement of the Dependent Variable	**Alter the Data Sample**	**Instrumental Variable Method Second Stage**		**Replacement of the Dependent Variable**	**Alter the Data Sample**	**Instrumental Variable Method Second Stage**	
Inzr	−0.0097 ** (0.0089)	−0.2729 ** (0.0496)	−0.5458 * (0.0585)					
Inzc	−0.0025 ** (0.0011)	−0.2741 ** (0.0465)		−0.5299 *** (0.0594)				
lnfzr					−0.0353 *** (0.0057)	−0.3825 *** (0.0959)	−4.9670 *** (0.7943)	
Infzc					−0.0267 ** (0.0565)	−0.3274 *** (0.0040)		−11.1791 *** (2.3804)
Control Variables	Y	Y	Y	Y	Y	Y	Y	Y
Time Fixed Effects	Y	Y	Y	Y	Y	Y	Y	Y
Regional Fixed Effects	Y	Y	N	N	Y	Y	N	N
KPF			563.399	601.63			34.9549	11.4886
Adj. R^2	0.3601	0.7914	0.517	0.513	0.3248	0.7908	0.3782	0.2844
N	7348	6556	7348	7348	7348	6556	7348	7348

Note: The numbers in parentheses are standard errors; ***, **, and * indicate that the variable is significant at the 1%, 5%, and 10% significance levels, respectively.

Additionally, an instrumental variable approach is employed, treating domestic technology inflow, domestic technology outflow, international technology inflow, and international technology outflow as endogenous variables. The regression analysis is conducted using the two-stage least squares method. This study employs the geographical distance from each city to the telegraph lines established at the end of the Qing Dynasty as an instrumental variable. The telegraph lines from this period are vectorized utilizing geographic registration tools within ArcGIS software, allowing for the extraction of the shortest geographical distance from each city to these lines. The original telegraph data, as referenced in C. Lin et al. (2021), is primarily derived from local gazetteers and Jiaotongshi Dianzhengbian (History of Transportation: Telecommunications) compiled by the Ministry of Communications in 1931. The rationale for selecting the telegraph lines as an instrumental variable is twofold: first, these lines represent an early iteration of China's telecommunication network, significantly enhancing the efficiency of information transactions, broadening the information network, facilitating technology transfer, and establishing a crucial foundation for contemporary technology transfer. This characteristic satisfies the relevance criterion for instrumental variables in this analysis. Second, the Chinese government constructed telegraph lines predominantly for military and administrative purposes rather than for economic objectives, thereby fulfilling the exogeneity requirement pertinent to the analytical framework of this study. Given the panel data regression employed in this research, it is noted that the geographical distance variable lacks temporal variation, rendering it unsuitable for instrumental variable estimation. Consequently, this study approaches the use of geographical distance as an instrumental variable from a cross-sectional perspective, specifically by not controlling for regional-fixed effects while controlling for time-fixed effects within the model. The KPF (Kleibergen-Paap rk F) test indicates a rejection of the null hypothesis concerning weak instrumental variables. Furthermore, the analysis reveals that domestic technology inflow, domestic technology outflow, international technology inflow, and international technology outflow maintain a significant negative correlation with carbon emissions, thereby affirming the robustness of the baseline regression results.

4.4. Heterogeneity Analysis

The impact of technology transfer on carbon emissions may differ due to various factors, including regional resource endowments, policy orientations, and levels of economic development. This raises the question of whether regional location exerts a differential effect on the carbon emission outcomes associated with technology transfer. Furthermore, urban agglomerations, characterized by their inherent advantages in the flow of factors and the aggregation of resources, serve as critical hubs for national technological innovation. Consequently, it is pertinent to investigate whether urban agglomerations and non-urban agglomerations yield distinct impacts on carbon emissions as a result of technology transfer. The subsequent analysis will address these two inquiries through tests of urban location and the heterogeneity of urban agglomerations.

4.4.1. Urban Location Heterogeneity Test

The Hu Huanyong Line, despite being an artificially delineated diagonal line on the map of China, serves as a significant geographical, cultural, and economic demarcation within the country. The region located northwest of the Hu Huanyong Line is characterized by sparse population density, rugged terrain, a harsh climate, underdeveloped industries, and a stagnant economy, while also functioning as a crucial energy reserve base. Conversely, the area to the southeast of the Hu Huanyong Line is densely populated, featuring flat terrain, a mild climate, advanced industries, and a developed economy, albeit with a limited availability of traditional fossil energy resources. According to the urban location heterogeneity analysis presented in Table 5, cities situated northwest of the Hu Huanyong Line exhibit significant carbon emission reduction effects from both domestic and international technology inflows. However, domestic and international technology outflows do not demonstrate a significant impact on urban carbon emissions. This discrepancy with the baseline regression may be attributed to the low level of economic development and the rigid industrial structure prevalent in the northwest region. In this economically disadvantaged area, neither domestic nor international technology outflows effectively attract the transfer of high-quality research and development (R&D) talent, nor do they incentivize governmental or corporate investment in innovation and R&D. Consequently, this results in an environment that is not conducive to independent technological innovation. In contrast, for cities located on or southeast of the Hu Huanyong Line, domestic technology inflow, domestic technology outflow, and international technology outflow all yield significant carbon reduction effects, while international technology inflow does not contribute to a reduction in carbon emissions. This inconsistency with the baseline regression may stem from the southeast region's advanced economic development and robust R&D and innovation capabilities, which lead to the acquisition of non-critical technologies due to technological competition. Such technologies have a minimal impact on the carbon emissions of regions with already established industrial structures and may even induce substantial technological substitution effects, resulting in decreased investment in independent research and development, ultimately leading to an insignificant impact on carbon reduction. In summary, there exists a notable regional heterogeneity in the influence of technology transfer on carbon emissions between the northwest and southeast regions of China, as delineated by the Hu Huanyong Line.

Table 5. Heterogeneity Test Results 1.

	Domestic Technology Transfer		**International Technology Transfer**	
	The Northwest Side of the Hu Line	**On and to the Southeast of the Hu Line**	**The Northwest Side of the Hu Line**	**On and to the Southeast of the Hu Line**
Inzr	−0.0273 ** (0.0361)	−0.0105 ** (0.0195)		
Inzc	−0.0854 (0.0299)	−0.1125 *** (0.0195)		
lnfzr			−0.2547 *** (0.0804)	−0.0137 (0.0101)
Infzc			0.1128 (0.0804)	−0.0582 *** (0.0118)
Control Variables	Y	Y	Y	Y
Time Fixed Effects	Y	Y	Y	Y
Regional Fixed Effects	Y	Y	Y	Y
Adj. R^2	0.8921	0.7251	0.8930	0.7212
N	528	6820	528	6820

Note: The numbers in parentheses are standard errors; *** and ** indicate that the variable is significant at the 1% and 5% significance levels, respectively.

4.4.2. Urban Agglomeration Heterogeneity Test

Excluding the Hong Kong and Macao regions, the five major urban agglomerations in China currently comprise the Beijing–Tianjin–Hebei Urban Agglomeration, the

Yangtze River Delta Urban Agglomeration, the Pearl River Delta Urban Agglomeration, the Chengdu–Chongqing Urban Agglomeration, and the Central Yangtze River Urban Agglomeration. In the context of high-quality economic development, urban agglomerations serve as crucial spatial organizational forms for integrating regional development advantages and play a pivotal role in promoting coordinated regional development, particularly in terms of technological collaboration. Consequently, this paper conducts heterogeneous regressions separately for areas within and outside the five major urban agglomerations, with the results presented in Table 6. It can be observed that within the five major urban agglomerations, domestic technology inflows, domestic technology outflows, and international technology outflows all demonstrate significant carbon-reducing effects. In contrast, international technology inflows have an insignificant impact on increasing carbon emissions. Conversely, outside the five major urban agglomerations, domestic technology inflows, domestic technology outflows, international technology inflows, and international technology outflows all exhibit significant carbon-reducing effects. Compared to the benchmark regression results, the potential reasons for the observed inconsistencies are as follows: The flow and aggregation of various factors in urban agglomerations, which reflect intercity interactions and agglomeration effects, typically occur in regions with relatively mature technological and industrial foundations. The five major urban agglomerations generally possess advanced technologies and management practices that are close to the technological efficiency frontier. Consequently, the international technology transferred to these regions does not yield a significant carbon-reducing effect. Additionally, the transferred international technology may stimulate economic growth, which is often accompanied by increased resource consumption and carbon emissions. The combined effects of these factors ultimately result in a negligible increase in carbon emissions. In summary, there are significant regional differences in the effects of technology transfer on carbon emissions, both within and outside the five major urban agglomerations. This finding is consistent with other relevant literature.

Table 6. Heterogeneity test results 2.

	Domestic Technology Transfer		**International Technology Transfer**	
	Within the Five Major Urban Agglomerations	**Outside the Five Major Urban Agglomerations**	**Within the Five Major Urban Agglomerations**	**Outside the Five Major Urban Agglomerations**
Inzr	−0.0118 ** (0.0092)	−0.0030 *** (0.0225)		
Inzc	−0.0050 *** (0.0079)	−0.1063 *** (0.0213)		
lnfzr			0.0025 (0.0062)	−0.0376 ** (0.0145)
Infzc			−0.0112 ** (0.0063)	−0.0744 *** (0.0167)
Control Variables	Y	Y	Y	Y
Time Fixed Effects	Y	Y	Y	Y
Regional Fixed Effects	Y	Y	Y	Y
Adj. R^2	0.9591	0.7218	0.9592	0.7328
N	2068	5280	2068	5280

Note: The numbers in parentheses are standard errors; *** and ** indicate that the variable is significant at the 1% and 5% significance levels, respectively.

4.5. Mechanism Analysis

Based on the theoretical analysis presented in the preceding text, this paper posits that technology transfer primarily facilitates carbon reduction through the mechanisms of enhanced energy efficiency and the upgrading of industrial structures. First, in alignment with established practices in the existing literature (Su & Hong, 2024), this study employs GDP per unit of energy consumption as a metric for energy efficiency. Given that the "China Energy Statistical Yearbook" only contains provincial-level energy consumption data, this research adopts a linear model without an intercept, following the methodologies of previous studies (J. S. Wu et al., 2014). This model utilizes the quantitative relationship between DMSP/OLS night-time light data and energy statistics to disaggregate provincial energy consumption data to the level of each prefecture-level city based on the corresponding light data values. Subsequently, city-level energy consumption per unit of GDP is calculated by dividing the total energy consumption by the gross domestic product. Second, in accordance with the methodologies employed by Zhou et al. (2024), the industrial structure hierarchy coefficient is utilized to represent the upgrading of the industrial structure. The specific calculation formula is provided in Equation (3), where y1, y2, and y3 denote the proportions of the output value of the primary, secondary, and tertiary industries in relation to GDP, respectively. A higher HI value indicates a greater level of industrial structure upgrading. The data utilized in this analysis is sourced from city statistical yearbooks spanning multiple years.

$$HI = y_1 \times 1 + y_2 \times 2 + y_3 \times 3 \tag{3}$$

This paper references the study conducted by T. Jiang (2022) and utilizes a two-step methodology to assess the effectiveness of the associated mechanisms. The previous analysis confirmed the inhibitory effect of technology transfer on urban carbon emissions, while the carbon-reducing impacts of energy efficiency and the upgrading of industrial structures have been thoroughly discussed in the theoretical hypothesis section. Consequently, it is essential to examine the influence of technology transfer on energy efficiency and industrial structure upgrading to substantiate the effectiveness of these mechanisms. In this study, the dependent variables in the foundational regression models (1) and (2) are substituted with the two mediating mechanism variables, while all other variables remain constant, resulting in the energy efficiency mechanism models (4) and (5), as well as the industrial structure mechanism models (6) and (7).

$$\ln nyxl_{it} = \beta_0 + \beta_1 \ln zr_{it-1} + \beta_2 \ln zc_{it-1} + \beta_3 X_{it-1} + T_t + V_i + E_{it} \tag{4}$$

$$\ln nyxl_{it} = \beta_0 + \beta_1 \ln fzc_{it-1} + \beta_2 \ln fzr_{it-1} + X_{it-1} + T_t + V_i + E_{it} \tag{5}$$

$$\ln cyjg_{it} = \beta_0 + \beta_1 \ln zr_{it-1} + \beta_2 \ln zc_{it-1} + \beta_3 X_{it-1} + T_t + V_i + E_{it} \tag{6}$$

$$\ln cyjg_{it} = \beta_0 + \beta_1 \ln fzc_{it-1} + \beta_2 \ln fzr_{it-1} + X_{it-1} + T_t + V_i + E_{it} \tag{7}$$

In these models, i (=1, 2, …, 334) represents the city, and t (=2000, 2001, …, 2021) represents the year. The dependent variable ln*nyxlit* is the energy efficiency of city i in year t, dependent variable ln*nyxlit* is the industrial structure upgrading of city i in year t. X_{it} is the set of control variables; T_t is the time-fixed effect; V_i is the individual fixed effect; E_{it} is the random disturbance term; and β_1 and β_2 are the corresponding coefficients.

4.5.1. Energy Efficiency Mechanism

The data presented in Table 7 indicate that domestic technology inflow, domestic technology outflow, international technology inflow, and international technology outflow significantly influence the enhancement of energy efficiency. The respective impact coefficients for these variables are 0.0099, 0.0053, 0.0173, and 0.0101, with significance levels of 5%, 5%, 5%, and 1%. These findings suggest that both domestic and international technology flows contribute positively to the allocation of technological resources, thereby facilitating improvements in energy efficiency through various mechanisms, including technology spillover, technological advancement, economic impacts, and scale effects. The conclusion aligns with the research findings of H. Sun et al. (2021) and He and Huang (2023). The results presented above provide confirmation for the establishment of Hypotheses 3 and 4.

Table 7. Mechanism test results.

	Domestic Technology Transfer		**International Technology Transfer**	
	Energy Efficiency	**Industrial Structure Upgrading**	**Energy Efficiency**	**Industrial Structure Upgrading**
Inzr	0.0099 ** (0.0032)	0.0146 *** (0.0093)		
Inzc	0.0053 ** (0.0030)	0.0021 ** (0.0086)		
lnfzr			0.0173 ** (0.0081)	0.0343 *** (0.0070)
Infzc			0.0101 *** (0.0032)	0.0629 *** (0.0081)
Control Variables	Y	Y	Y	Y
Time Fixed Effects	Y	Y	Y	Y
Regional Fixed Effects	Y	Y	Y	Y
Adj. R^2	0.5336	0.7605	0.5328	0.7630
N	7348	7348	7348	7348

Note: The numbers in parentheses are standard errors; *** and ** indicate that the variable is significant at the 1% and 5% significance levels, respectively.

4.5.2. Industrial Structure Upgrading Mechanism

Table 7 demonstrates that both domestic technology inflow and domestic technology outflow significantly contribute to the upgrading of industrial structures at the 1% and 5% significance levels, with impact coefficients of 0.0146 and 0.0021, respectively. Furthermore, international technology inflow and international technology outflow exert a significant positive influence on the industrial structure mechanism at the 1% significance level, with impact coefficients of 0.0343 and 0.0629, respectively. These findings suggest that both domestic and international technology transfers can facilitate carbon emission reduction through the industrial structure mechanism. The results above confirm that the mechanism analysis presented earlier is relatively reliable, and supports Hypotheses 5 and 6. Other relevant studies have reached similar conclusions, although they have focused on the perspectives of technological innovation or technological progress (N. Wu & Liu, 2021; You & Zhang, 2022).

5. Conclusions and Recommendations

The spatial dynamics of technological factors represent a crucial avenue for fostering high-quality green development within the economy in the contemporary era. Technology serves as a fundamental catalyst for energy conservation, emission reduction, and sustainable development. The inquiry into how to establish energy-efficient and carbon-reducing industrial chains, as well as production and lifestyle models through the flow of technology, alongside the coexistence of technology and nature, constitutes a significant area of focus. In light of this, the present study empirically investigates the impact of technology transfer on carbon emissions from both domestic and international perspectives, utilizing a dataset comprising 334 research subjects in China from 2000 to 2021. The findings of the study are as follows: First, technology transfer demonstrates a positive effect on carbon emission reduction in China, with international technology transfer exerting a more substantial influence on carbon emissions. Second, a series of robustness tests—including the substitution of the explained variable, alterations to the data sample, and the application of instrumental variable methods—validate the robustness of the baseline regression results. Third, heterogeneity analysis reveals that domestic and international technology inflows in the northwest region of the Hu Huanyong Line, as well as domestic technology inflow, domestic technology outflow, and international technology outflow in the southeast region of the Hu Huanyong Line, along with domestic technology inflow, domestic technology outflow, and international technology outflow within the five major urban agglomerations, and outside these agglomerations, all exhibit significant carbon emission reduction effects. Conversely, the impact of technology transfer on carbon emissions in other regions is not statistically significant. Fourth, the mechanism analysis indicates that both domestic and international technology transfers can facilitate carbon emission reductions through mechanisms related to energy efficiency and green technology innovation. In light of these research findings, several policy recommendations are proposed.

To enhance the domestic technology transfer system, it is imperative to accelerate its construction, thereby fostering independent innovation and technological development. This approach aims to mitigate the substitution and competitive pressures posed by international technologies entering the domestic market, while also amplifying the carbon emission-reduction benefits associated with domestic technology transfer. Firstly, it is essential for governments to enhance the evaluation and appointment system for professional titles, as well as the promotion mechanisms for talent in technology transfer. Additionally, they should expedite the development of a national technology trading network that is interconnected, in order to consolidate innovative resources such as achievements, funding, talent, services, and policies. This network will facilitate the swift industrial application of scientific and technological innovations. Secondly, enterprises should establish mechanisms to cultivate and strengthen leading technology companies. These companies will guide the integration and innovation of both the upstream and downstream segments of the industrial chain, facilitating the faster market entry of new products. Lastly, research institutions should prioritize the strengthening of basic theories and fundamental principles to address key technological issues at their source and foundational level.

To enhance the coordinated regional development of technology transfer and to promote the environmental benefits associated with such transfers, it is essential to adopt a dual approach that addresses both supply-side and demand-side factors. This involves strengthening technology transfer initiatives in the northwest region of the Hu Huanyong Line as well as within the five major urban agglomerations. In addition to improving the capacity to absorb and assimilate technology, it is imperative to advance the development of industries towards greater intelligence and sustainability. This can be achieved by increasing investments in technology research and development, as well as by enhancing incentives and enforcement mechanisms aimed at carbon reduction.

To enhance foundational research on proprietary technologies within the energy sector and to foster innovation in core technologies, it is essential to promote differentiated strategies for energy innovation development through independent research and development as well as the introduction of foreign technologies. This approach aims to gradually advance the innovation of core energy technologies and reduce reliance on international technology imports. Based on the analysis presented in this paper, it is imperative to reassess and redefine the role of international technology acquisition in achieving objectives related to green energy, energy efficiency, and carbon reduction. Furthermore, it is crucial to improve incentive mechanisms that encourage originality, imitation, and the assimilation of domestic innovations. This can be achieved by promoting collaborative mechanisms among key innovation stakeholders, including government entities, enterprises, and research institutions. Ultimately, the goal is to maximize the synergistic effects of technology transfer on the independent innovation of technologies related to green energy and energy conservation through the effective integration of domestic and international technological resources.

To optimize industrial policies, foster the development of green industry clusters, and advance the high-end and low-carbon transformation of the industrial structure. This can be achieved by directing technology, capital, and other resources towards industries characterized by high added value, low energy consumption, and minimal emissions through effective policy guidance. Furthermore, it is important to facilitate the technological transformation and upgrading of traditional industries while reducing reliance on high carbon-emitting sectors. Concurrently, efforts should be made to enhance the cluster development of green technology and clean energy industries, thereby promoting the exchange and collaboration of green knowledge and technologies.

This study acknowledges several limitations and shortcomings. Due to space constraints, the paper focuses solely on analyzing the impact of technology transfer on carbon emissions and its mediating mechanisms. Other important aspects, such as moderating effects, threshold effects, and policy implications, require further investigation. In addition to patent transfer, other indicators of technology transfer—such as talent acquisition, technology services, information exchange, research collaboration, and government-university-industry partnerships—should be further defined and examined from multiple perspectives. Finally, this paper uses the overall flow of knowledge (technology) as its research foundation. Future studies could categorize patents more specifically and explore decarbonization from the viewpoints of various technological categories or industry heterogeneity.

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