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Construction of the Pilot Free Trade Zone and Chinese Green Total Factor Energy Efficiency

Haikuo Zhang [1] and Chaobo Zhou [2,*]

1 College of Wealth Management, Ningbo University of Finance and Economics, Ningbo 315175, China
2 School of International Economics and Trade, Ningbo University of Finance and Economics, Ningbo 315175, China
* Correspondence: zhouchaobo@whu.edu.cn

Abstract: In the context of China's "double carbon" target, paying attention to regional green total factor energy efficiency (GTFEE) is crucial for ensuring a fundamental guarantee for China's free trade zones for the promotion of sustainable development in China's free trade zones. However, the existing literature lacks focus on the environmental effects of these zones. This study takes advantage of the pilot free trade zone (PFTZ) implemented in 2013 as a natural experiment, utilizing panel data from 2009 to 2020 for Chinese prefecture-level cities. It adopted a progressive difference-in-difference model to assess the effect of the PFTZ on GTFEE. The findings demonstrate a remarkable improvement in GTFEE due to the PFTZ, which remains robust even after conducting robustness checks, including the parallel trend test. The PFTZ achieves this improvement by facilitating industrial structure upgrading and promoting green technology innovation. The positive influence of the PFTZ on GTFEE is particularly prominent in coastal cities and non-resource-based cities. This study contributes to the understanding of the environmental effects of free trade zones, providing a direct response to the key question of whether the free trade zone policy can effectively support high-quality economic development in the new era. Moreover, it offers useful policy implications for advancing further openness, winning the battle against pollution, and boosting high-quality economic development.

Keywords: green total factor energy efficiency; free trade zone; difference-in-difference

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1. Introduction

China's rapid industrialization and urbanization have led to a remarkable increase in energy consumption and a rigid energy demand. China's urbanization rate is projected to reach approximately 65% by 2022, which still lags behind the urbanization rates of developed countries. This condition indicates that China's infrastructure construction will continue for the foreseeable future, allowing for further growth in total energy consumption [1]. However, the surge in energy consumption has resulted in a rise in carbon emissions. In 2021, China emitted more than 11.9 billion tons of CO_2, accounting for 33% of total global emissions [2]. Moreover, China is expected to contribute to half of the world's carbon emissions by 2040 [3]. To actively address climate change, China has committed to implementing stronger policies and achieving carbon neutrality by 2060, as outlined in its 14th Five-Year Plan. Enhancing green total factor energy efficiency (GTFEE) serves as a crucial pathway to support the realization of China's carbon neutrality goals. GTFEE involves both expected and unexpected outputs, capturing the negative environmental impact resulting from the energy consumption process during the evaluation of TFEE. Historically, China's economy relied on a crude growth model, with the cost of economic development being paid at the expense of energy and the environment. With the increasing shortage of resources and increasing environmental problems, China has shifted toward high-quality development to improve economic development, while reducing the pressure on resources. Although energy consumption remains a necessary input factor in the production process, China's energy consumption per unit of gross domestic product (GDP) is far below the world average [4]. Therefore, improving GTFEE is of great importance for China to achieve its goals of green and sustainable development.

To navigate the complex international environment, align with international high-standard economic and trade rules, and bolster its position in the international trading system, the Chinese government has proactively introduced the pilot free trade zone (PFTZ) construction program. This initiative aims to expand China's openness to the world and promote the formation of a new comprehensive opening pattern [5]. The China (Shanghai) PFTZ was officially established in October 2013 and had expanded to 21 provinces by the end of 2020, forming a strategic framework encompassing China's coastal and western regions. One of the PFTZ's key objectives is to facilitate trade and investment while implementing reforms in various sectors [6,7]. However, acknowledging the potential negative effects of trade liberalization is necessary while reaping its benefits, particularly concerning the decline in environmental quality resulting from the relocation of polluting industries. To address this issue, China has prioritized the development of green trade within the PFTZ, encouraging enterprises to establish green supply chain management systems, implement clean production practices, and promote the green transformation of trade [8]. As China strives to achieve its ambitious target of carbon neutrality, examining the impact of PFTZ construction on the environment and its potential to drive high-quality urban economic development remain important, thereby contributing to the improvement of GTFEE. The PFTZ can optimize the allocation of market resources such as regional information, production factors, and capital, thereby affecting green technological innovation (GTI) and industrial structure upgrading (ISU) of the pilot areas. The levels of GTI and ISU are important factors that affect the GTFEE. Therefore, PFTZ may affect GTFEE through two potential channels: GTI and ISU.

This study aimed to address the following questions: Does the PFTZ enhance GTFEE? What are the mechanisms through which the PFTZ influences GTFEE? Are there regional differences in the role of the PFTZ in GTFEE? Exploring the impact of entering the PFTZ participation on GTFEE will provide valuable insights for decision makers regarding China's increased openness to the world and its commitment to green growth and development. The possible contributions of this study are as follows: Although the existing literature has extensively discussed the economic effects of by PFTZ, insufficient attention has been paid to its environmental effects. This study fills this gap by examining the environmental effects of the PFTZ from the perspective of GTFEE. Given China's current focus on carbon reduction and achieving carbon neutrality, improving energy efficiency is a primary goal. The direct impact of the PFTZ on regional GTFEE has been explored, and the mediating effects of industrial structure upgrading and green technological innovation have been further examined, providing a reference for the government to further improve the effectiveness of the PFTZ. The heterogeneity of cities has been analyzed in accordance with their geographical locations and types, and relevant policy recommendations have been proposed, which provide a reference for promoting ecological protection in the PFTZ and achieving the goal of carbon neutrality. The establishment of the PFTZ presented an exogenous shock that provided a quasi-natural experiment. In this study, we constructed a multiple difference-in-difference (DID) specification based on this setting to investigate the causal relationship between trade liberalization and environmental protection. Although most of the literature examines the effect of financial development on export trade using cross-national panel data or corporate panel data, the traditional empirical methods of econometric regression often struggle to effectively address endogeneity issues. The research method employed in this study allowed for the evaluation of the objective effect of trade liberalization on environmental protection and provided a robust scientific test for the conclusions drawn in such literature.

The rest of this article is arranged as follows: The second section provides a comprehensive literature review. The third section introduces the model, defines variables, and provides an overview of the data used. The fourth section presents the benchmark regression, robustness tests, mechanism tests, and heterogeneity analysis. The fifth section provides the conclusions and policy implications for future decision making.

2. Literature Review

2.1. Policy Effects of PFTZs

Many studies have investigated the relationship between the construction of free trade zones (FTZs) and their environmental benefits. The effects of free trade on the environment can be both positive and negative. On the one hand, free trade may increase the environmental burden and harm the environment. Grossman and Krueger (1991) found that foreign inflows from the North American Free Trade Agreement exacerbated atmospheric pollution in Mexico despite contributing to the country's economic growth [9]. Similar findings have been observed in other developing regions [10,11]. On the other hand, free trade may improve environmental quality. Antweiler et al. (2001) concluded that free trade can have beneficial effects on the environment, considering factors such as structural changes, economies of scale, and technological advancements [12]. In terms of the relationship between the construction of FTZ and environmental benefits, Aloise et al. (2017) believed that the FTZ policy formulation should prioritize atmospheric environmental issues [13]. FTZ policies can promote green technological progress and achieve sustainable development by improving foreign investment systems and incorporating advanced foreign technologies [14,15]. China's PFTZs share commonalities and particularities with FTZs worldwide. The PFTZs are not solely focused on expanding openness and attracting foreign investment; they are also centered around deepening reforms and institutional innovation. This indicates that the PFTZs are no longer merely "copies" of past economic-focused openness but should represent an "upgraded version" of an environmental and economic win-win situation. Existing research on the policy effects of China's PFTZs has mainly focused on their economic effects. On the basis of urban-level data, scholars have empirically studied this and found that PFTZs have a positive promoting effect on regional industrial structure, resource allocation efficiency, and innovation level [5–8]. Yao and Whalley (2016) showed that the establishment of the Shanghai PFTZ remarkably contributed to local financial liberalization and capital flows, employing a counterfactual model [16]. Jiang et al. (2021) examined the impact of PFTZs on the scale and structure of China's exports using the DID method and Chinese customs database. They found that the construction of PFTZs promotes the growth of urban product exports but does not effectively drive the structural change in export mode from processing trade to general trade, for the time being [17]. Chen et al. (2022) found that the construction of PFTZs can increase the share of general trade and reduce the share of processing trade based on provincial export data. However, only a few studies have been conducted on the environmental effects of PFTZs in China [18]. Hu et al. (2022) investigated the effects of PFTZs on air quality using the spatial DID method and found that their establishment remarkably reduced air pollution concentrations in pilot cities [19]. The establishment of PFTZs also had a remarkable improvement effect on air pollution conditions in neighboring non-pilot cities. Natalia et al. (2021) analyzed the environmental effects of the ASEAN-China FTZ's construction using data from 2005 to 2010, and the study revealed a negative impact on air quality resulting from the FTZ [20].

2.2. Influence Factors of GTFEE

GTFEE is developed on the basis of single factor energy efficiency (SFEE) and TFEE. SFEE measures energy efficiency directly by calculating the ratio of energy input to GDP. It is advantageous due to its easy data accessibility and simple calculation. However, SFEE ignores the substitution among input factors, leading to potentially inaccurate results. TFEE, constructed by Hu and Wang (2006), is based on the concept of total factor productivity (TFP) and fully considers non-energy factors, such as labor and capital as inputs, making it a greater improvement over SFEE [21]. However, TFEE only considers the desired output, GDP, and ignores the non-desired outputs that have adverse effects on the environment during the production process. To address this limitation, Li and Hu (2012) proposed GTFEE, which incorporates both desired and non-desired outputs, making it a better indicator of the environmental impact of energy efficiency [22]. This study focused on GTFEE, which evaluates TFEE by considering the economic value and environmental impact. With the increasing urgency for environmental protection in the context of continuous social and economic development, scholars have begun investigating various factors that influence GTFEE. Recent studies have identified several factors that remarkably impact GTFEE, including broadband infrastructure [23], information and communication technology [24], market fragmentation of energy resource prices [25], digitalization [26], internet development [27], outward foreign direct investment [28], the carbon trading market [29,30], green finance [31], and government resource allocation efficiency [4].

The literature regarding the environmental effects of PFTZs is relatively limited, and different scholars have reached inconsistent conclusions based on different sample data. As China enters a new stage of development, opening up to the world and striving to achieve sustainable development by accelerating its carbon neutralization goal, GTFEE has become a key environmental variable in Chinese society. However, none of the literature has reported on the impact of the China's PFTZ establishment on GTFEE. In addition, existing scholars have mostly used the DID method when evaluating the policy effects of PFTZ. Considering that China's pilot cities for PFTZ are being promoted in batches, the traditional DID method cannot accurately evaluate the policy effects of PFTZ. This study intended to investigate the possible environmental benefits of PFTZs from the perspective of GTFEE using a progressive DID method, and provide suggestions for promoting high-quality economic development and designing subsequent PFTZs.

3. Model and Variables

3.1. Benchmark Model

With the advancement of China's PFTZ construction process, pilot cities in FTZs are being promoted, from coastal areas to inland regions. The establishment of PFTZs demonstration cities is being gradually promoted. The academic community often directly uses the traditional DID method to evaluate the policy effects of PFTZs. When using the DID method for policy evaluation, the research sample needs to be divided into two categories: those affected by the policy (experimental groups) and those not affected by the policy (control groups). The DID method evaluates the causal effect of policies by comparing the differences between the experimental groups and control groups, before and after the event. However, the traditional DID model is only suitable for evaluating the policy effectiveness at a single time point and cannot comprehensively identify FTZs established at multiple time nodes [17]. This study utilized a progressive DID model to investigate the influence of PFTZs on GTFEE based on the studies conducted by Jiang et al., (2021) [17]. The Chinese Ministry of Commerce provides specific information on the construction of each PTFZ, including the pilot zone's name, batch establishment, establishment time, and the specific implementation city for each zone. Thus, cities approved for PTFZ projects were considered treatment groups, and cities not approved for pilot projects were considered control groups. On the basis of the PFTZ implemented in 2013, a progressive DID model was constructed to test the impact of PFTZs on GTFEE.

$$GTFEE_{it} = \alpha_0 + \alpha_1 Treat_i \times Time_t + \alpha_2 CV_{it} + \mu_i + \gamma_t + \varepsilon_{it}, \quad (1)$$

where i and t represent the city and year, respectively. *GTFEE* refers to the green total factor energy efficiency. The key explanatory variable in Equation (1) is $Treat \times Time$, which represents the interaction term between the policy intervention variable and time; $Treat \times Time$ captures the net effect of the PFTZ on GTFEE. The parameter α_1 represents the magnitude of this effect. *CV* is shorthand for several different control factors that influence GTFEE. The fixed effects μ and γ represent the city and year, respectively.

3.2. Explained Variable

GTFEE. We used the super-efficiency slack-based-measure undesirable model to calculate GTFEE, following the methods proposed by Zhou and Qi (2022) [31]. Labor force, capital stock, and energy were selected as the inputs. Industrial sulfur dioxide, industrial smoke, and industrial wastewater were selected as undesirable outputs, and GDP was selected as the desirable output. Total electricity consumption was used as a proxy indicator of energy based on the methods outlined by Zhou et al., (2023) [30].

3.3. Core Explanatory Variables

PFTZ. This study constructed an interaction term between the dummy variable for city type and the dummy variable for pilot policies implemented in PFTZ cities. We investigated the relationship between the two variables. *Treat* $\times$ *Time* was used to measure the net effect of PFTZs on GTFEE. *Treat* was a binary variable used to define pilot cities, with a value of 1 assigned to pilot cities and 0 assigned to non-pilot cities. *Time* was used to identify the occurrence of a PFTZ. If city i implemented PFTZ in time *t* or later, *Time* was assigned a value of 1; otherwise, it was set to 0.

3.4. Control Variables

Following the method of Wu et al., (2020), the following control variables were selected to capture the possible impact of other relevant factors on GTFEE [4]. Specifically, the logarithm of the population of a city was used to represent the level of population density (Lnpeople). The logarithm of the ratio of GDP to the total population was used to represent the per capita regional GDP (Lnpgdp). Foreign direct investment (Fdi) represented the percentage of GDP contributed by foreign investment. The ratio of R&D internal expenditure to GDP was used to represent R&D expenditure (Rd). Industrialization (Indus) was denoted by the ratio of the secondary industry value to GDP. The ratio of the outstanding balance of all loans held by financial institutions as a percentage of GDP was used to denote the financial development level (Fdl).

Panel data from 270 prefecture-level cities in China from 2009 to 2020 were selected as a sample to study the impact of the PFTZ on the GTFEE. After eliminating urban samples with serious data loss and discontinuity, 3240 observation samples were finally included. The data were sourced from the China City Statistical Yearbook. Table 1 provides the descriptive statistics of the variables.

Table 1. Descriptive statistics.

	Obs	Mean	Std. Dev.	Min	Max
GTFEE	3240	1.012	0.469	0.242	6.586
Indus	3240	0.489	0.105	0.122	0.841
Fdi	3240	0.019	0.016	0	0.099
Rd	3240	0.014	0.027	0.002	0.047
Lnpgdp	3240	8.953	0.669	6.373	14.053
Lnpeople	3240	5.841	0.892	1.681	8.084
Fdl	3240	0.792	0.541	0.043	1.963

4. Empirical Results

4.1. Analysis of Benchmark DID Results

Table 2 presents the results of the PFTZ effect on GTFEE. The first column shows the raw data without controlling the CV and the fixed effects of city and year. Columns (2) to (4) display the regression outcomes after adding the CV, year, and city fixed effects. The results indicate that the coefficients of *Treat* $\times$ *Time* are all significantly positive, revealing that the pilot policies have had a positive effect on increasing GTFEE. In the past, local governments have often compromised environmental quality standards to attract more foreign direct investment, leading to resource waste and mismatches that negatively affect economic development and the ecological environment [31]. However, China's PFTZs were established to provide a level playing field for domestic and foreign enterprises, dovetailing with high-standard international economic and trade rules to further promote trade liberalization and eliminate policy barriers. The concentration of industries in PTFZs also increases competition among enterprises, weakening government intervention and strengthening the role of the market in factor allocation [7]. With the further deepening of marketization, the mismatch of environment-related resources has effectively improved, and PFTZs can eliminate inefficient and backward enterprises, enabling resources and labor to be transferred to more productive enterprises. This helps to reduce pollution emissions and improve GTFEE. The research results of this study indicate that FTZs can have positive environmental effects, which is consistent with the findings of existing studies [18,19]. This study provides a theoretical basis for examining the relationship between FTZs and environmental pollution issues by integrating trade liberalization, pollution emissions, and energy efficiency into a unified analytical framework.

Table 2. Effect of the PFTZ on GTFEE.

	(1)	(2)	(3)	(4)
	GTFEE	GTFEE	GTFEE	GTFEE
Treat × *Time*	0.106 ***	0.09 **	0.114 ***	0.128 ***
	(0.0372)	(0.036)	(0.0367)	(0.0234)
Indus		−0.0489 ***	−0.0489 ***	0.0529
		(0.0108)	(0.0102)	(0.0562)
Fdi		0.281 ***	0.284 ***	0.125 **
		(0.0269)	(0.0339)	(0.0541)
Rd		0.218 ***	0.219 ***	0.142 ***
		(0.0351)	(0.0329)	(0.0398)
Lnpgdp		0.577 ***	0.521 ***	0.332 **
		(0.112)	(0.114)	(0.14)
Fdl		0.0731 ***	0.0748 ***	0.12 ***
		(0.0215)	(0.0255)	(0.0189)
Lnpeople		0.0691 ***	0.0709 ***	0.69 ***
		(0.0105)	(0.0105)	(0.0525)
ID Effect	NO	NO	NO	YES
Year Effect	NO	NO	YES	YES
Observations	3240	3240	3240	3240
R-squared	0.003	0.18	0.188	0.796

Note: **, and *** represent the significance level at 5%, and 1%, respectively, with robust standard errors in parentheses. This also applies to subsequent tables in this paper.

4.2. Robustness Test

4.2.1. Parallel Trend Test

The validity of the DID technique is contingent on satisfying the parallel trend hypothesis. Before the PFTZ is implemented, the same trends should be evident in the experimental and control groups. The parallel trend test was conducted to rule out the possibility that the influence of the PFTZ on GTFEE is interfered with by other non-observed missing variables. The current study constructed the following model:

$$GTFEE_{it} = \beta_0 + \sum\nolimits_{t=-3}^{4} \beta_t Treat_i \times Time_t + \beta_1 CV_{it} + \mu_i + \gamma_t + \varepsilon_{it}, \quad (2)$$

Table 3 reports the empirical results of the parallel trend test. Before the pilot policies were implemented, the estimated coefficients of *Treat* × *Time* were not significant at the 10% level, indicating that before the PFTZ, no statistically considerable differences were noted in the trends of GTFEE variation between the two groups. The parallel trend test suggests that no significant difference was observed in terms of GTFEE between the control group and the experimental group before the issuance of GB, indicating that no significant two-way causal relationship existed between the implementation of the PFTZ and GTFEE of the cities.

Table 3. Parallel trend test.

	(1)	(2)
	GTFEE	GTFEE
$Treat \times Time_{-1}$	−0.0246	−0.0666
	(0.0298)	(0.0557)
$Treat \times Time_{-2}$	−0.0129	−0.0391
	(0.0318)	(0.0354)
$Treat \times Time_{-3}$	−0.0373	−0.0688
	(0.04)	(0.0425)
$Treat \times Time_{1}$	0.137 ***	0.125 ***
	(0.0331)	(0.0359)
$Treat \times Time_{2}$	0.120 ***	0.142 ***
	(0.032)	(0.0348)
$Treat \times Time_{3}$	0.127 ***	0.171 ***
	(0.0308)	(0.0343)
$Treat \times Time_{4}$	0.1 ***	0.178 **
	(0.0336)	(0.0703)
CV	NO	YES
ID Effect	YES	YES
Year Effect	YES	YES
Observations	3240	3240
R-squared	0.796	0.748

Note: **, and *** represent the significance level at 5%, and 1%, respectively.

4.2.2. Environmental Policy Effect Elimination

During the research period of this study, China implemented a carbon market policy and low-carbon city policy. To cope with climate change and reduce carbon emissions, the Chinese government implemented a carbon trading pilot policy (CTPP) in seven provinces, including Guangdong, Beijing, Tianjing, Shanghai, Shenzhen, Chongqing, and Hubei in 2013. The CTPP may have an impact on the production behavior of enterprises by allocating carbon quotas free of charge to enterprises. Existing research has found that CTPP has a remarkable improvement effect on GTFEE [4]. We eliminated the sample of the seven pilot provinces covered by the CTPP and re-estimated using Equation (1) to eliminate the interference of the CTPP. After eliminating the interference of CTPP, the coefficients of $Treat \times Time$ in columns 1 and 2 of Table 4 are significantly positive. China has actively implemented carbon emission reduction practices at the city level, such as implementing a pilot low-carbon city policy (PLC) to control energy consumption and promote the low-carbon transformation of the economy. The Chinese government initiated the first group of PLCs in 2010, and subsequently expanded the scope of emission reduction efforts with the second and third batches of PLCs in 2012 and 2017, respectively. To eliminate the interference of PLC, this study added a cross-multiplication term of city fixed effect and year fixed effect in Equation (1) to eliminate the impact of PLC. The DID coefficients in columns 3 and 4 of Table 4 remained significant at the 1% level.

Table 4. Excluding the impact of environmental policy.

	(1)	(2)	(3)	(4)
	GTFEE	GTFEE	GTFEE	GTFEE
$Treat \times Time$	0.085 ***	0.093 ***	0.1 ***	0.117 ***
	(0.0223)	(0.0231)	(0.0285)	(0.0238)
CV	NO	YES	NO	YES
ID Effect	YES	YES	YES	YES
Year Effect	YES	YES	YES	YES
Observations	2796	2796	3240	3240
R-squared	0.17	0.712	0.18	0.8

Note: *** represent the significance level at 1%.

4.2.3. Propensity Score Matching (PSM)–DID Estimation

When the country determines the pilot cities of the PFTZ, it may give priority to cities with a developed economy and location advantages. In reality, such sample selection bias is often difficult to avoid. To improve the accuracy of estimation, this study used a PSM-DID method for a robustness test to ensure that the experimental and control groups had the same time trend. Specifically, this study used the method of Zhang and Duan (2020) as a reference [32]. It used cities that had implemented the PFTZ as the treatment group, took the control variables in the basic regression as covariates, and used kernel matching to match the sample in the control group. The matched sample was then regressed in accordance with Equation (1). The DID coefficients in Table 5 are significant, indicating that the results obtained are robust.

Table 5. PSM–DID estimation.

	(1)	**(2)**
	GTFEE	GTFEE
Treat × *Time*	0.08 *	0.121 ***
	(0.046)	(0.303)
CV	NO	Yes
ID Effect	Yes	Yes
Year Effect	Yes	Yes
Observations	2854	2854
R-squared	0.514	0.623

Note: *, and *** represent the significance level at 10%, and 1%, respectively.

4.2.4. Reduce Sample Interval

The DID method may provide more accurate estimations for short-term period samples [33]. The sample period in this study spanned from 2009 to 2020. During this period, other unobservable factors that interfered with the results may have been observed. Therefore, we reduced the sample time to 2010 to 2016 and re-estimated using Equation (1) to address this issue. The DID coefficients in Table 6 are significant, indicating that the results obtained are robust.

Table 6. Replace sample interval.

	(1)	**(2)**
	GTFEE	GTFEE
Treat × *Time*	0.203 ***	0.123 ***
	(0.0378)	(0.0346)
CV	NO	Yes
ID Effect	Yes	Yes
Year Effect	Yes	Yes
Observations	1890	1890
R-squared	0.776	0.814

Note: *** represent the significance level at 1%.

4.3. Mechanism Analysis

A mediation effect model was constructed to test whether the PFTZ could improve GTFEE through ISU and GTI.

$$Med_{it} = \alpha_0 + \beta_1 Treat_i \times Time_t + \beta_2 CV_{it} + \mu_i + \gamma_t + \varepsilon_{it}, \tag{3}$$

$$GTFEE_{it} = \alpha_0 + \lambda_1 Treat_i \times Time_t + \lambda_2 Med_{it} + \lambda_3 CV_{it} + \mu_i + \gamma_t + \varepsilon_{it}, \tag{4}$$

where *Med* represents the mediating variable. The mediating mechanism variables selected included ISU and GTI. The level of ISU may be determined by calculating the ratio of the value contributed by tertiary industries to the value added by secondary industries. The number of patents submitted for environmentally friendly innovations is one indicator of GTI. The mediating effects of ISU and GTI can be tested through the significance of β_1, λ_1, and λ_2.

4.3.1. GTI

The DID and *GTI* coefficients in columns 1 to 2 of Table 7 are significant, indicating that GTI serves as the mediating variable through which the PFTZ improves GTFEE. The PFTZ gradually enhanced the regional GTI capacity, which drives the improvement of resource utilization rate, promotes the development and utilization of clean resources, and ultimately improves GTFEE [30]. The PFTZ provides relevant financial and taxation policy system support, attracting foreign enterprises to settle there, and bringing in advanced energy-saving and emission reduction technologies and concepts, which promotes the development of GTI. Trade facilitation in the PFTZ strengthens competition among enterprises in the region, leading to the continuous enhancement of innovation ability, improvement of the production process, development of products with higher technology levels and relatively lower costs, and ultimately, accelerating the development of GTI. The establishment of the PFTZ attracts a large number of high-quality talented people who can cooperate closely, promoting the rapid spread of advanced production technology in the zone and enhancing the level of GTI. Therefore, the PFTZ enhances GTFEE through the mediating effect of GTI.

Table 7. Test results of mechanism research.

	(1)	**(2)**	**(3)**	**(4)**
	GTI	GTFEE	ISU	GTFEE
Treat × *Time*	0.291 * (0.16)	0.073 *** (0.019)	1.568 * (0.875)	0.053 *** (0.017)
GTI		0.162 * (0.088)		
ISU				0.028 * (0.052)
CV	YES	YES	YES	YES
ID Effect	YES	YES	YES	YES
Year Effect	YES	YES	YES	YES
Observations	3240	3240	3240	3240
R-squared	0.837	0.843	0.824	0.831

Note: *, and *** represent the significance level at 10%, and 1%, respectively.

4.3.2. ISU

The DID and *ISU* coefficients in columns 3 to 4 of Table 7 are significant, indicating that ISU acts as the mediating variable through which the PFTZ improves GTFEE. The PFTZ attracts advanced industries and technologies through tariff policies, promoting trade opening, and industrial transformation and upgrading. Industrial transformation and upgrading suppress pollution emission levels and improve GTFEE [30]. The construction of the PFTZ facilitates the expansion of openness, leading to a higher economic scale and development level. It promotes the transfer from primary and secondary industries to tertiary industries and helps reduce environmental pollution. The presence of foreign high-tech industries in the PTFZ brings advanced technology, provides high-tech support to enterprises, and guides the transformation and upgrading of resource-intensive enterprises into capital-technology-based industries. Foreign high-tech enterprises contribute to increased competitiveness in the pilot city and have a crowding-out effect on existing pollution-intensive industries, leading to the elimination of local enterprises with backward production methods and the optimization of the industrial structure. Therefore, the PFTZ enhances GTFEE through the mediating effect of ISU.

4.4. Heterogeneity Analysis

4.4.1. Regional Heterogeneity

The geographical location of the PFTZ may affect its impact on regional GTFEE. This study analyzed the heterogeneity of policy implementation in terms of geographical location by dividing the PFTZ areas into coastal and non-coastal cities; the results are presented in Table 8. The regression coefficients for the PFTZ implemented in coastal and non-coastal cities were 0.155 and 0.099, respectively, indicating that the PFTZ can contribute to the improvement of GTFEE in both coastal and non-coastal cities. However, the coefficients were larger in coastal areas than in non-coastal areas, and the regression results were more significant. This phenomenon may be because coastal areas have superior geographical conditions and have historically been the gateway to China's open foreign trade, even before the implementation of the PFTZ. They have undertaken the main import and export tasks with the help of relatively cheap shipping. The PTFZ policy may attract more foreign capital and technology to the coastal areas after its implementation, further strengthening ISU and GTI. The non-coastal areas lack certain geographical advantages and prior experience. Import and export activities cannot directly benefit from cheap shipping, which slightly weakens the implementation effect of the policy compared with coastal areas.

Table 8. Estimation results of heterogeneity.

	(1)	(2)	(3)	(4)
	Coastal region	Non-coastal region	Resource-based	Non-resource-based
	GTFEE	GTFEE	GTFEE	GTFEE
Treat × *Time*	0.155 ***	0.099 ***	0.079	0.163 ***
	(0.0939)	(0.0275)	(0.236)	(0.098)
CV	YES	YES	YES	YES
ID Effect	YES	YES	YES	YES
Year Effect	YES	YES	YES	YES
Observations	540	2700	1332	1908
R-squared	0.526	0.715	0.606	0.633

Note: *** represent the significance level at 1%.

4.4.2. City-Type Heterogeneity

Resource-based and non-resource-based cities differ remarkably in terms of resource endowment and resource utilization, with resource-based areas being among the most polluted and energy-intensive regions in the world. This study further examined the differences between different city types by dividing the sample into resource-based and non-resource-based cities, following the classification by Zhou and Qi (2022) [31]. The results in Table 8 show that the estimated coefficients of *Treat* × *Time* are significantly positive for non-resource-based cities in column (4), indicating that the PFTZ remarkably improved GTFEE in these cities. However, the estimated coefficients of *Treat* × *Time* are insignificant in resource-based cities in column (3), indicating that the PFTZ failed to effectively improve GTFEE in these cities. Resource-based cities rely heavily on fossil energy consumption, and their urban development has long depended on natural resources, such as coal and oil, resulting in a single energy consumption structure. At the same time, the backward industrial level of resource-based cities and the difficulty of industrial structure transformation and development have, to a certain extent, restricted their green development. Resource-based cities also lack talent and financial investment, leading to a lag in technological innovation, especially in GTI, which contributes to the PFTZ failing to remarkably improve GTFEE in these cities.

5. Conclusions and Policy Implications

In the context of the "double carbon" target, paying attention to regional GTFEE is a fundamental guarantee for China's free trade zones to promote regional sustainable development [34]. The PFTZ has increased the volume of foreign trade and promoted regional economic development [35,36]. To achieve sustainable development and the "double carbon" goal, it is worth conducting in-depth research on how PFTZs affect regional GTFEE. However, the existing literature has not studied the impact of PFTZs on regional GTFEE. A quasi-natural experiment was conducted to investigate the influence of the PFTZ on GTFEE by employing a staggered DID model with panel data from 270 Chinese prefecture-level cities from 2009 to 2020. The research findings suggest that the PFTZ remarkably improves GTFEE, and this conclusion remained true after conducting several robustness tests. The PFTZ promotes ISU and improves GTI, thereby enhancing GTFEE through the two channels. Moreover, PFTZ has a more remarkable effect on improving the GTFEE of coastal cities compared with non-coastal cities, and non-resource-based cities compared with resource-based cities. These findings provide empirical evidence to further promote the construction of PFTZs. Most current research on the policy effects of PFTZs has primarily focused on whether PFTZs can promote economic growth rather than high-quality development, and relevant empirical research is lacking. This study fills the relevant gap in the field of the environmental effects of the PFTZ and provide a certain supplement to the policy effects of PFTZs.

This study recommends the following policies to better harness the role of the PFTZ in improving GTFEE: As a new window for opening up in the new era, the establishment of free trade zones is an important measure for China to pursue high-quality economic development. The government should improve laws related to ecological protection and align environmental regulations with international standards to avoid negative environmental impacts resulting from the economic expansion of FTZs.

The research results in this article indicates that industrial structure is an intermediate channel for improving GTFEE. The governments of the PFTZ should further promote the improvement of the local industrial structure, transform traditional industries and services into new industries and modern services, and develop local advantageous industries in accordance with local conditions. The PFTZ can improve GTFEE by enhancing the innovation level of enterprises. The government needs to leverage the driving role of GTI, pay attention to the carbon emission reduction effect associated with technological progress, and further guide enterprises in the FTZ to make reasonable use of the technological spillover effect from foreign direct investment to improve resource utilization efficiency.

The impact of PFTZs on GTFEE varies across different regions, and PFTZ has been found to be more effective in promoting GTFEE in coastal cities. The government should prioritize the expansion of PFTZ construction in coastal areas, especially in the Pearl River Delta region, while also focusing on the development of PFTZs in inland areas and improving their overall layout.

In the strategic context of increasing reform and openness, the government should strengthen the important role of FTZs in promoting trade facilitation, investment liberalization, the transformation of government functions, and the development of financial markets. In addition, the government should actively promote and replicate successful cases and practical innovation policies within the FTZs. The original intention of establishing an FTZ was to promote GTFEE in pilot areas, and drive the improvement of GTFEE in surrounding areas and even the whole country. Therefore, in the process of continuous optimization and development, the FTZ needs to radiate and drive the green transformation and upgrading of surrounding industrial structures.

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