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Effects of Carbon Emission Trading Policy on the Low-Carbon Transition of Industrial Energy: Evidence from China

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Abstract

In the context of global climate change and promoting green development, the industrial sector's significant contribution to carbon emissions necessitates effective policies for low-carbon energy transition. Understanding the role of carbon emission trading policy (CETP) in facilitating the low-carbon transformation of industrial energy (LTIE) is important. However, the effectiveness of CETP in driving LTIE and the mechanisms through which it operates remain underexplored. This study systematically examines the effects of CETP on LTIE and its underlying mechanisms across 30 Chinese provinces from 2005 to 2021. The findings show that first, CETP substantially facilitates LTIE, and the results remain consistent after undergoing parallel-trend, placebo, and other robustness tests. Second, CETP primarily facilitates this transformation through multiple channels, namely, energy-saving and carbon-reduction innovations, industrial structure transformation, and government support. Third, heterogeneous results indicate that the policy effect is highly pronounced in inland regions and areas with low levels of industrial governance investment. This study demonstrates that CETP is an effective tool for advancing China's industrial energy transformation toward low-carbon models, whose effectiveness is influenced by regional characteristics and governance levels. These findings provide a scientific basis for formulating differentiated environmental strategies.

Keywords: carbon emission trading policy; low-carbon transition of industrial energy; energy-saving and carbon-reduction innovation; industrial structure transformation; government support

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1. Introduction

The Industrial Revolution resulted in the widespread use of fossil fuels, which remarkably accelerated economic growth but also gave rise to two major challenges: environmental pollution and resource depletion [1]. In 2024, the global energy-related carbon dioxide emissions totaled over 3.63 billion tons [2]. Global warming is significantly exacerbated by the industrial sector, which contributes one-third of the world's carbon emissions from production activities, which are marked by high energy consumption and high emissions [3]. China's industrial sector faces a severe carbon emission problem, with its total emissions far exceeding the global average. Within this sector, energy consumption accounts for

two-thirds of the total, contributing approximately 70% to carbon emissions, creating a serious situation [4].

In response to these global concerns, China has undertaken a thorough exploration. In September 2020, during the United Nations General Assembly, China announced its ambitious dual carbon goals: to peak carbon dioxide emissions by 2030 and attain carbon neutrality by 2060 [5]. The 14th Five-Year Plan for a Modern Energy System establishes strategic objectives to expedite the green and low-carbon transition of energy. By 2025, non-fossil fuel consumption will constitute around 20%, non-fossil fuel-generated electricity will account for around 39%, and electricity will represent about 30% of final energy consumption. The facilitation of the low-carbon transformation of industrial energy (LTIE) is essential to attain these goals [6].

Administrative command-and-control measures [7] or fiscal and tax reform strategies have often been utilized to alleviate the increasingly urgent pressure imposed by emission reduction [8]. Carbon emission trading policy (CETP) is regarded as an efficient, flexible solution [9]. CETP is an environmental economic policy that controls greenhouse gas emissions through market mechanisms. CETP involves commoditizing carbon emission rights and leveraging market transactions to achieve emission reduction targets. In terms of institutional design, this policy internalizes external environmental costs into corporate production expenses by establishing a system of total volume control and quota allocation [10]. Numerous enterprises proactively adopt energy-saving technologies, optimize production processes, or invest in renewable energy substitution projects to minimize compliance costs [11]. This approach compels the entire industrial chain to evolve toward a green, low-carbon development. Theoretically, this tool avoids the economic disruptions that administrative emission reductions may trigger, allowing enterprises at different stages of development to make autonomous decisions on the basis of marginal abatement costs. This approach ensures policy flexibility while stimulating the innovative vitality of market entities [12]. In terms of practice, the European Union (EU) launched the world's first carbon emission trading system (EU ETS) in 2005 [13]. Subsequently, New Zealand launched its emission trading system in 2008 [14]. Currently, 34 countries and regions, including China, Japan, and Canada, have implemented CETP [15]. However, given the varying national circumstances, systematic identification and measurement of the effects of CETP on energy decarbonization are crucial [16]. In October 2011, the Chinese government released the Notice on Initiating Pilot Programs for Carbon Emission Rights. Since 2013, eight provinces and municipalities in China—Beijing, Tianjin, Shanghai, Guangdong, Hubei, Chongqing, Sichuan, and Fujian—were sequentially designated to trial carbon emission pricing schemes [17]. The nationwide carbon emission trading market began in July 2021. As of July 15, 2024, cumulative transactions reached 465 million tons of carbon dioxide equivalent, with a total transaction value of 27 billion yuan, thereby establishing China as the world's largest carbon emission trading market [18].

In this process, can such market-based policy mechanisms truly drive LTIE? How do they influence this transformation? Do their effects vary across different regions and industrial sectors in environmental governance? Although existing literature has documented the association between the CETP and outcomes like energy efficiency or carbon intensity, critical limitations persist. On the one hand, existing studies often rely on fragmented indicators, failing to capture the multidimensional nature of LTIE. On the other hand, few studies have revealed the causal effect of CETP on an energy-structure-based LTIE index under staggered adoption. Based on this, this study examines the effects of CETP on LTIE and their potential transmission pathways by systematically analyzing data from 30 Chinese provinces between 2005 and 2021. Unlike prior study that emphasizes either administrative directives or fiscal subsidies [7,8], this study integrates government support,

energy-saving and carbon-reduction technological innovation, and industrial structure optimization into a unified analysis. Moreover, this study transcends the single internal factor analysis framework by introducing external variables, such as geographical location characteristics and industrial governance investments. This study empirically tests the heterogeneous effects of these variables on the industrial ecologization process.

The primary contributions of this study are as follows: First, existing literature has given minimal attention to the relationship between CETP and LTIE, presenting an opportunity for this study. Unlike traditional studies that focus on a single dimension, such as carbon emission intensity or energy efficiency [19–21], this study innovatively employs the enhanced weighted multidimensional vector angle method to measure LTIE, which is considered to offer a more comprehensive assessment. Second, although previous studies have examined the influence of technological innovation drivers, cost constraint mechanisms, and energy consumption structure transformation [22–24], they have not sufficiently addressed the crucial roles of energy-saving and carbon-reduction innovation, industrial structure transformation, and government support. This study fills this gap. Third, this study further explores the effects of external factors, such as regional geography and industrial governance investments, providing relevant insights and lessons for governments seeking to advance LTIE.

2. Literature Review

2.1. Economic Consequences of CETP

Coase's theorem emphasizes the use of market mechanisms to achieve optimal resource allocation, laying the theoretical foundation for the emergence of CETP. Carbon emission trading, as a market-based environmental regulatory tool, compels high-energy-consuming enterprises to bear the external costs of carbon emissions by establishing a cap-and-trade mechanism. This mechanism forces enterprises to adjust their production practices and energy structures [25,26]. The core logic of CETP lies in guiding resource allocation and innovation direction through price signals. A prior study has extensively analyzed the economic impacts and emission reduction outcomes of CETP [13]. First, the carbon pricing mechanism necessitates that firms enhance research and development as well as the implementation of low-carbon technologies. Moreover, market incentives drive companies to generate revenue by selling surplus allowances, thereby achieving a green cycle [27]. Second, carbon trading can effectively enhance resource allocation and exchange, guiding resources toward entities with low emission reduction costs. Furthermore, carbon markets also foster new business models, such as carbon asset management, and promote the development of green finance [28]. Meanwhile, carbon trading reshapes the competitive landscape among enterprises, propels a shift from fossil fuel dependence to green and low-carbon drivers, and cultivates emerging growth sectors [29].

2.2. CETP and LTIE

Domestic and international studies have generally acknowledged the reshaping effect of CETP on the energy structure. At the macro level, CETP is compelling energy-intensive industries to move up the value chain, fostering the emergence of new industrial clusters [29]. Zhang et al. proved through their study that CETP significantly enhances the advancement of new high-quality productive forces in the industrial industry [30]. This backward pressure process not only results in immediate emission reduction impacts but also directs long-term investment towards clean technology via price signals [31]. This process creates a substitution effect for traditional high-carbon pathways. However, the varying degrees of enforcement across regions and corporate heterogeneity can result in divergent outcomes in carbon emission reductions [19]. In some developing countries,

weak regulation has resulted in market inefficiencies, undermining policy effectiveness [32]. At the micro level, enterprises proactively adjust their energy mix in production processes to avoid high carbon costs [20], as manifested by increasing the share of clean energy, phasing out outdated production capacity, and upgrading equipment [33,34]. For example, the implementation of the EU ETS has prompted regulated manufacturing enterprises to shift production from coal to natural gas or renewable energy sources, resulting in a 14–16% reduction in carbon dioxide emissions without any notable contraction in economic activity [13]. Existing study has rarely investigated the effects of CETP on LTIE, and this study builds upon that foundation. Furthermore, most existing studies measure LTIE from a single perspective. Building upon this foundation, this paper proposes an enhanced weighted multidimensional vector angle method to measure the LTIE, which is considered to offer a more comprehensive assessment.

Existing study has also analyzed how CETP specifically influences decision-making behavior at various levels. On the one hand, there is technological innovation. Empirical evidence indicates that enterprises participating in carbon markets exhibit substantial growth in patent output [31,35]. Zhu et al. employed the latest patent data and a quasi-experimental design and revealed for the first time that at the firm level, CETP increased low-carbon innovation by 5–10% among participating firms [22]. On the other hand, there is the cost constraint mechanism. When carbon prices exceed a critical threshold, firms tend to absorb environmental costs internally [36], prioritizing investments in energy-saving technologies or purchasing offset credits. Dai and He empirically demonstrated that from 2010 to 2021, CETP enhanced corporate environmental, social, and governance (ESG) performance by constraining external financing and incentivizing internal green technological innovation [23]. Zheng et al. conducted a comprehensive analysis of the above two aspects, confirming that CETP resulted in a significant reduction of approximately 38.61% in carbon emissions [24]. Sun et al. also demonstrated that the short-term effects of CETP are primarily manifested through cost shifting, and sustained momentum in the medium to long term relies on technological iteration and structural optimization [9].

In summary, existing study has systematically reviewed the theoretical foundations, practical effects, and outcomes of CETP. Scholars' explorations from various dimensions have provided valuable insights. Nonetheless, further in-depth investigation is still required. First, prior study has predominantly investigated the impact of CETP on regional or company energy efficiency [21,34], carbon intensity [19,20,24], and ESG performance [23] while overlooking CETP's crucial role in facilitating LTIE. Moreover, previous studies have focused solely on the impact of CETP on single-dimensional indicators; this study innovatively employs the enhanced weighted multidimensional vector angle method to measure LTIE, which is considered to offer a more comprehensive assessment. Second, prior study has disproportionately concentrated on the impacts of technological innovation drivers, cost constraint mechanisms, and energy consumption structure transformation [22–24], while failing to adequately address the crucial roles of energy-saving and carbon-reduction innovation, industrial structure transformation, and government support. This current study addresses this drawback. Finally, this study further examines the influence of external factors, such as regional geography and industrial governance investments, providing relevant insights and lessons for governments seeking to advance LTIE.

3. Theoretical Analysis and Hypotheses

3.1. Direct Effect of CETP on LTIE

The concept of emissions trading has its roots in applying the Coase Theorem's notion of property rights to pollution control. This market-based mechanism encourages enterprises to independently select the most cost-effective emission reduction pathways,

ultimately achieving overall emission reduction targets at the lowest total social cost possible. Importantly, a recent study by Sun et al. [21] and Liu et al. [9] has shown that this market-based mechanism continues to effectively incentivize enterprises to optimize emission reduction strategies while achieving overall targets at minimal social cost in current industrial systems. The effect of CETP on LTIE is reflected in three aspects. First, by commoditizing carbon emission rights, enterprises are confronted with an explicit comparison between emission reduction costs and quota costs [37]. When carbon prices exceed the marginal emission reduction costs, enterprises voluntarily opt for technological upgrades, clean energy substitution, or downsizing [38], thereby achieving a low-carbon energy transition. Second, carbon emission trading enables enterprises with energy efficiency levels exceeding industry averages to earn surplus quota revenues [39], thus creating economic incentives for the low-carbon transformation of energy systems. Wu et al. and Ren et al. demonstrated that when a policy extends to energy-intensive industries, such as steel and cement production, emission reductions achieved through industrial innovation, such as hydrogen-based steelmaking and carbon capture technologies, can be directly converted into carbon asset revenue [40,41]. Accordingly, this conversion incentivizes the adoption of low-carbon energy transition within these sectors. Zhang et al. confirmed that when policy coverage extends to energy-intensive sectors, such as electricity and heat production plants, the CETP positively impacts participating enterprises' profitability and greenhouse gas emissions reductions [34], aligning with Wu et al.'s [40] findings on hydrogen-based metallurgy applications. Third, carbon emission allowances can be converted into financial instruments, such as carbon asset-backed loans, providing enterprises with low-cost financing channels [42] and thereby supporting the implementation of energy-saving and decarbonization projects. International experience demonstrates that the EU ETS effectively channels resources toward low-energy-consumption, high-value-added sectors through cross-industry collaboration and regional factor reallocation [43]. Wei et al. confirmed that the pilot regions in China incentivize interregional industrial relocation and technology diffusion through differentiated quota allocation [44]. Notably, policy effectiveness is considerably influenced by the regulation intensity and the maturity of the market [45]. Song et al. confirmed that inadequate monitoring systems in carbon emissions trading processes reduce transaction efficiency [46]. Overall, CETP reconfigures production factors while addressing the trade-off between growth and emissions, forming the theoretical basis for our hypothesis testing. Based on this debate, this study posits Hypothesis 1.

H1: *The implementation of CETP has had a positive effect on LTIE.*

3.2. Mechanism Pathway

CETP, as a core market-based mechanism for advancing China's dual carbon goals, can effectively incentivize corporate emission reductions and technological innovation, lower the overall societal cost of emission reduction, and foster new growth areas in emerging industries. On this basis, this study examines the relationship between CETP and LTIE from three perspectives, namely, energy-saving and carbon-reduction innovation, industrial structure transformation, and government support, as shown in Figure 1.

The Porter hypothesis asserts that environmental restrictions can incentivize regulated enterprises to seek technical advancements to minimize compliance costs, resulting in an innovation-offsetting effect. In recent years, extensive study has demonstrated that the core value of CETP lies in stimulating technological innovation dividends [22,31]. For instance, Zhu et al. demonstrated that China's pilot CETP resulted in a 5–10% rise in low-carbon patent outputs among participating enterprises, demonstrating its role in inducing technological innovation [22]. When carbon prices exceed a certain threshold, enterprises prioritize developing energy-saving processes, upgrading equipment efficiency,

or developing carbon capture technologies to meet emission standards [31]. Cheng and Meng confirmed that carbon emission trading remarkably enhances firms' total factor productivity and substantially increases the number of green patent grants [47]. Cai et al. further demonstrated that such innovations generate dual spillover effects [48]: encompassing intra-industry technology diffusion, such as the adoption of co-processing waste technologies in cement production [49], and cross-industry supply chain synergies, as exemplified by collaborative innovation within the new energy vehicle sector [50]. Notably, small and medium-sized enterprises may face innovation barriers resulting from capital constraints. In such cases, government-provided R&D subsidies or financial instruments supporting carbon emission trading can serve as critical catalysts [51]. For example, Jiang et al. highlighted that green finance mechanisms significantly improve energy-saving outcomes in SMEs, particularly under artificial intelligence-enhanced policy environments [11]. Therefore, CETP serves not only as a regulatory instrument but also as a key driver for innovation in energy conservation and carbon reduction. On the basis of this discussion, this study proposes Hypothesis 2.

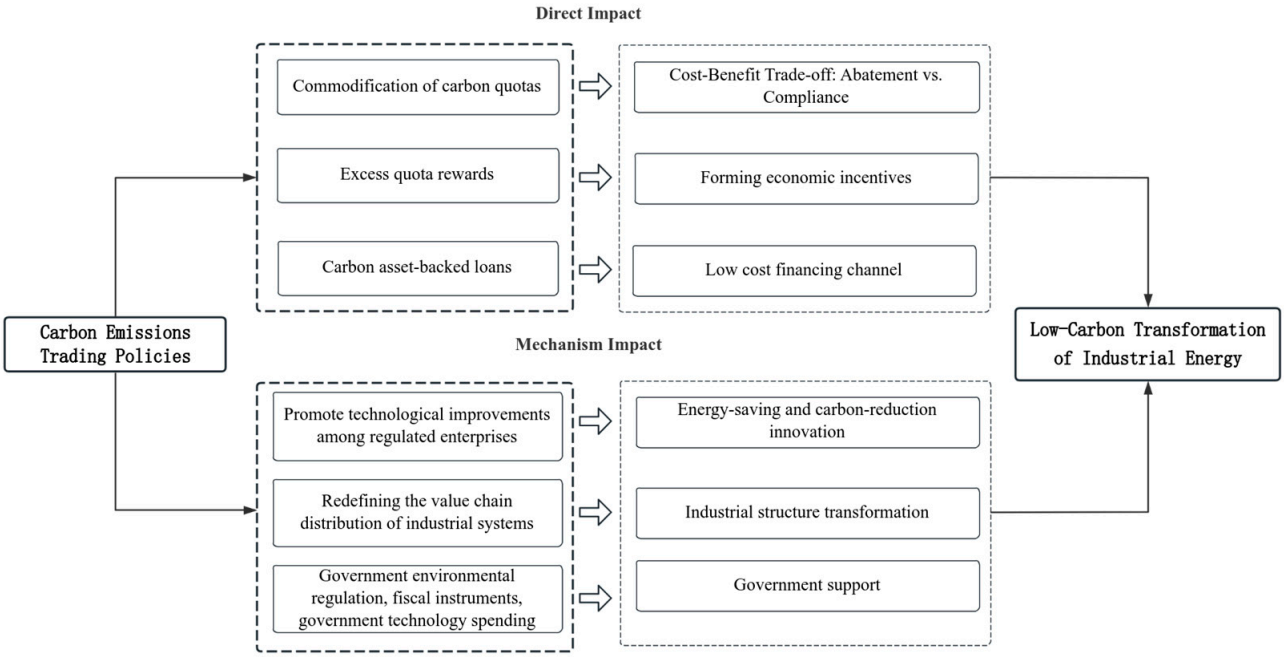


Figure 1. Mechanism of the influence of CETP on LTIE.

H2: *CETP can positively affect LTIE through energy-saving and carbon-reduction innovation.*

From a macro perspective, CETP is reshaping the distribution of value chains within industrial systems [52]. World Bank study indicates that resource-intensive industries have seen diminished competitiveness due to rising carbon costs, while low-value-added sectors such as steel, cement, and textile manufacturing have accelerated industrial relocation [53]. This structural shift is particularly evident in China's regional development landscape: following stricter emission controls in coastal provinces, labor-intensive industries have progressively shifted inland [52]. Meanwhile, these provinces have progressively cultivated strategic emerging industrial clusters, such as photovoltaic assembly production bases and offshore floating wind power generation, to advance the development of green energy industries [29,54]. These transformations fully demonstrate the role of policy guidance in reallocating resources toward high-value-added sectors. Moreover, CETP has fostered new circular economy models. For instance, steel enterprises have spearheaded the development of scrap steel recycling systems [55], and chemical industrial parks have established

symbiotic networks to recover byproducts from pollution [56]. Such explorations enable the closed-loop operation of pollution sources and energy flows. This structural transformation is not merely deindustrialization; rather, it is a shift from scale expansion to quality and efficiency gains through factor reallocation, ultimately forming an industrial upgrading pathway that aligns with carbon budgets [30]. Based on the preceding discussion, this study posits Hypothesis 3.

H3: *CETP can positively affect LTIE through industrial structure transformation.*

Government support is a key lever for amplifying CETP [57]. Most successful cases benefit from multidimensional government support [58]. First, government environmental regulation is needed. For example, the European Union incorporated CETP into the Lisbon Treaty framework to ensure legal authority [59]. Second, fiscal instruments, including carbon tax offsets, green bond interest subsidies, and tax incentives, are employed to complement these efforts. For instance, the U.S. Inflation Reduction Act incorporates tax credits for clean energy investments [60]. Third, government science and technology expenditures, such as providing research funding support to small and medium-sized enterprises and offering energy efficiency diagnostic services, are essential [61]. In China, the linkage mechanism between central environmental inspections and local officials' performance evaluations has effectively addressed implementation deviations at the grassroots level, and the nationwide networking of carbon emission data monitoring platforms has laid the foundation for targeted policy implementation [62]. Lin and Huang found that carbon trading effectively curbs carbon emissions [63]. However, it is worth noting that due to potential imperfections in China's current carbon market mechanisms and limited industry coverage, market mechanisms alone may not yield significant results. Government support and coordinated efforts are therefore required [63]. This situation demonstrates that an effective governance system can organically integrate market mechanisms with administrative power to form a synergistic force for LTIE. On the basis of this discussion, this study proposes Hypothesis 4.

H4: *CETP can positively affect LTIE through government support.*

4. Research Design

4.1. Model

The difference-in-differences model is a robust approach for assessing policy effects. This approach determines the net effect of policy alterations by contrasting the average changes between the experimental and the control groups. This study utilizes the model to assess whether China's CETP influences LTIE. Based on the modeling methodology of Liu et al. [21], the model is developed as follows:

$$lnLCT_{i,t} = \alpha_0 + \alpha_1 DID_{it} + \gamma Z_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \quad (1)$$

where $lnLCT_{i,t}$ is the dependent variable (the subscript i denotes province and t denotes year), $DID_{i,t}$ is the dummy variable for the CETP, $Z_{i,t}$ is the set of control variables, λ_t is the time-fixed effect, μ_i is the province fixed effect, and ε is a random disturbance term.

This study examines the influencing mechanisms from three perspectives: energy-saving and carbon-reduction innovation, industrial structure transformation, and government support. This study follows the following argumentative approach: First, we propose path variables that logically establish direct and evident causal relationships with the dependent variables based on theory. Second, we use econometric methods to verify only the causal relationship between the path and the explanatory variables [64]. Draw-

ing on the methodology proposed by Hou et al. [65], Jiang [66], and Zhu et al. [67], we examine only the front end of the path influence, while the back end is supported and explained by existing literature. This approach constructs the following mechanism validity testing model:

$$M_{it} = \delta_0 + \delta_1 DID_{it} + \gamma Z_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \quad (2)$$

where M_{it} represents the mechanism variable, primarily encompassing energy-saving and carbon-reduction innovation, industrial structure transformation, and government support. The other variables are consistent with those mentioned above.

4.2. Variable Selection

4.2.1. Low-Carbon Transition of Industrial Energy

Existing studies employed varying indicators for energy decarbonization transitions, but the common metrics for measuring energy decarbonization included energy efficiency [20,21], carbon emission intensity [19,24], and ESG performance [23]. However, these metrics often represent single-perspective approaches that lack precision and systematic rigor. This work utilizes the approaches of Wan et al. and Zhu et al. [67,68] to quantify LTIE. We employ the enhanced weighted multidimensional vector angle method to measure LTIE because it is comprehensive, please see the Appendix A. Ultimately, we derive an index and take its natural logarithm. High values indicate advanced LTIE.

4.2.2. Carbon Emission Trading Policy Measures

Since 2013, China has systematically implemented the CETP in eight provinces and municipalities to enhance energy saving, reduce emissions, improve resource allocation, and support the national dual-carbon strategy. The value is 1 if the area is situated in Beijing, Shanghai, Tianjin, or Guangdong from 2013 onwards; in Hubei or Chongqing from 2014 onwards; or in Fujian or Sichuan from 2016 onwards; otherwise, it is 0. This study does not explicitly account for anticipatory behavior that may occur prior to a policy implementation. Regions with high sensitivity to environmental policies may adjust their practices in advance, potentially introducing bias into the DID estimates.

4.2.3. Control Variables

Regarding control variables, based on the technique of Huang et al. [6], the selected control variables for this study are as follows: (1) regional economic development (lnPGDP), which is quantified by calculating the natural logarithm of each province's per capita GDP. (2) foreign direct investment (FDI), which is Foreign direct investment (FDI) is quantified by calculating the natural logarithm of the overall FDI quantity; (3) population density (lnPOP), which is quantified by calculating the natural logarithm of the population density of each province. (4) industrial enterprise scale (lnFAC), which is measured by taking the natural logarithm of the total assets of industrial enterprises.

4.2.4. Mechanism Variables

The three main mechanism variables are as follows:

(1) Energy-saving and Carbon-reduction Innovation. Drawing upon the study of Chen and Yang, this study utilizes granted patents for energy-saving and carbon-reduction innovations as its primary data sources [12]. Specifically, these patents include: invention patents (Invent), utility model patents (Utility), design patents (Design) pertaining to energy-saving and carbon-reduction, and their total count (Total). Each of these data points is incremented by one and processed by taking the natural logarithm. CETP can effectively stimulate technological innovation dividends and promote the granting of various patents, thereby achieving energy-saving and carbon-reduction

innovations. Energy-saving and carbon-reduction innovations are crucial means for realizing the low-carbon transformation of energy.

(2) Industrial Structure Transformation. Referring to the study by Jiang et al. [69], industrial structure transformation is primarily examined from the perspectives of industrial upgrading (IDU) and green energy industries (GEI). IDU is quantified by the ratio of the tertiary sector to the secondary sector, whereas GEI is quantified by the number of green energy firms per 10,000 inhabitants. CETP has reshaped the distribution of industrial value chains, not only spurring the rise of GEI but also facilitating the restructuring of factors within these sectors. This industrial transformation has further accelerated the shift toward LTIE.

(3) Government Support. Government support is examined primarily from the perspectives of government environmental regulation (GER) and government research and development (GR&D) expenditure. Drawing upon the study of Gao et al. [70], GER is measured by the ratio of the frequency of terms related to environmental pollution in government work reports to the total word frequency. GR&D expenditure is measured by taking the natural logarithm of government financial outlays on science and technology. CETP serves as an effective tool for GER. Through various measures, including government technology expenditures, they can organically integrate market mechanisms with administrative power, forming a synergistic force for LTIE.

4.3. Sample Selection and Data Sources

An empirical study was undertaken throughout 30 provinces in China (excluding Tibet, Hong Kong, Macao, and Taiwan) from 2005 to 2021. The data used to calculate LTIE are from the China Industrial Statistical Yearbook. Other relevant data are sourced from the China Public Policy and Green Development Database, EPS Database, China National Intellectual Property Administration, China Statistical Yearbook, China Urban Statistical Yearbook, and government work reports. Stata 17 software is employed for data processing. Table 1 presents the results of the descriptive statistical analysis. According to the displayed results, the maximum value for LTIE (lnLCT) is 3.778, with an average of 2.918 and a median of 2.889. This finding indicates the presence of substantial variations in the level of LTIE across provinces. Pilot CETP (DID) has an average value of 0.114, indicating that the proportion of provinces formally implementing this pilot policy is small within the total sample. The implementation of pilot CETP has considerable research value in determining whether CETP drives LTIE, although this remains to be further examined. The instrumental and control variables broadly align with those in the prior study. Moreover, this study further examines multicollinearity, with the highest and mean variance inflation factor values being 5.57 and 2.75, respectively, indicating that no multicollinearity exists.

Table 1. Descriptive statistical analysis of variables.

Var	N	Max	Mean	Min	P50	SD
lnLCT	510	3.778	2.918	2.120	2.889	0.379
DID	510	1	0.114	0	0	0.318
Invent	510	1.605	0.061	0.000	0.011	0.169
Utility	510	1.716	0.115	0.000	0.032	0.247
Design	510	0.363	0.014	0.000	0.002	0.039
Total	510	3.424	0.191	0.000	0.046	0.437
IDU	510	5.297	1.117	0.500	0.934	0.642
GEI	510	5.928	0.610	0.011	0.319	0.820
GEE	510	0.032	0.019	0.009	0.018	0.004
GR&D	510	7.065	3.838	0.559	3.786	1.268

Table 1. *Cont.*

Var	N	Max	Mean	Min	P50	SD
lnPGDP	510	12.123	10.544	8.527	10.620	0.666
lnFDI	510	10.720	6.383	1.946	6.342	1.523
lnPOP	510	0.631	0.278	0.019	0.259	0.125
lnFAC	510	12.077	9.777	6.674	9.866	1.009

5. Results

5.1. Benchmark Results

Table 2 displays the foundational findings regarding the effects of CETP on LTIE. Column (1) displays the benchmark regression framework accounting for province- and time-specific fixed effects. Meanwhile, Column (2) illustrates the benchmark regression outcomes with the inclusion of supplementary control variables. The regression coefficients for each column are positive and statistically significant at the 1% level. This confirms a statistically significant positive correlation between CETP and LTIE. This discovery aligns with the conclusions of a prior study [65]. The primary reason may be that CETP leverages market mechanisms and economic incentives. The carbon pricing mechanism drives enterprises to optimize their energy structures, and the quota management system promotes industrial technological upgrades, providing systematic impetus for LTIE.

Table 2. Baseline regression.

	(1) lnLCT	(2) lnLCT
DID	0.130 ***	0.112 ***
	(4.975)	(4.231)
lnPGDP		0.178 ***
		(2.975)
lnFDI		0.007
		(0.410)
lnPOP		−0.053
		(−0.519)
lnFAC		−0.272 ***
		(−4.510)
Province FE	Yes	Yes
Year FE	Yes	Yes
_cons	2.862 ***	3.483 ***
	(125.055)	(7.432)
R2	0.206	0.240
F	7.069 ***	7.069 ***
N	510	510

*** denote significance at 1%; t-statistics are enclosed in parentheses.

5.2. Parallel Trend Test

This study employs the DID approach to evaluate the effect of CETP on LTIE. The parallel trend assumption must be satisfied to ensure the unbiasedness of the results derived from this method. The procedure entails demonstrating that no significant differences in LTIE trajectories exist between pilot and non-pilot provinces prior to the implementation of CETP. This study employs the approaches of Wu et al. and Rambachan and Roth [71,72] to construct Model (3) utilizing the event analysis approach for testing purposes.

$$\mathrm{lnLCT}_{i,t} = \alpha_0 + \sum_{j=-8}^{8} \alpha_j \mathrm{DID}_{i,t} + \gamma \mathrm{Control}_{i,t} + \delta_i + \lambda_t + \varepsilon_{i,t}, \quad (3)$$

where j denotes the j-th year since the implementation of CETP. J = 0 represents the year the policy was implemented, j < 0 indicates the j years preceding the policy implementation, and j > 0 denotes the j years after the policy implementation. The remaining variables are congruent with those of the previously indicated model.

To avoid multicollinearity, this study adopts the first year as the base period in the regression analysis. The horizontal axis in the figure represents the relative time of policy implementation, the vertical axis indicates the magnitude of the estimated coefficients, and the dashed lines denote 95% confidence intervals. Figure 2 displays the outcomes of the parallel trend test. Prior to policy implementation, the estimated coefficients for each year failed to reach statistical significance. This outcome indicates that before the implementation of CETP, there were no substantial disparities in LTIE usage between pilot and non-pilot provinces, hence fulfilling the parallel trend assumption. However, subsequent to the introduction of CETP, the predicted coefficients for each following year attained statistical significance, signifying that LTIE in the pilot provinces exhibited notable enhancements.

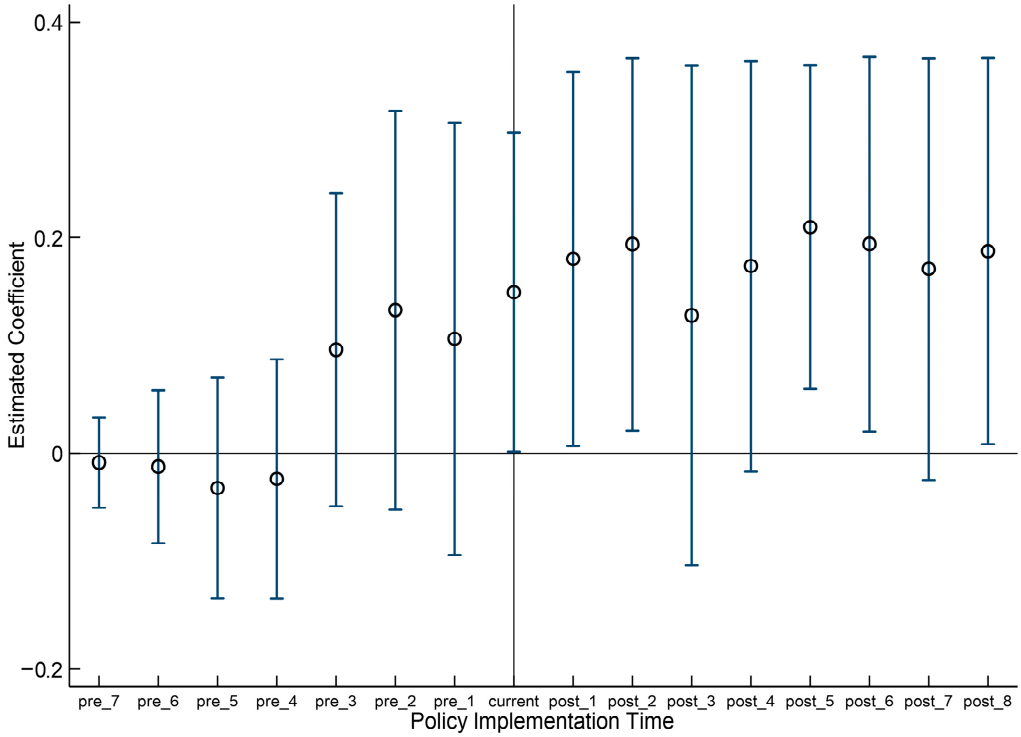


Figure 2. Parallel trend test.

5.3. Placebo Test

Over time, certain key characteristics of individual provinces may change. The unobservability of these changes may introduce bias into estimation results, leading to distorted regression outcomes. To avoid this issue, this study draws on the study of Ferrara et al. and Liu et al. to construct a dummy variable for a placebo test [21,73]. Specifically, a number of regions that is equal to the actual number of regions implementing CETP is randomly selected as a sham treatment group. A dummy variable representing this fictitious policy is then generated and incorporated into Model (1) for estimation. The process is repeated randomly 500 times, and the specific placebo test results are shown in Figure 3. If the benchmark regression results are unaffected by unobservable factors, randomly replicating the construction of pseudo treatment groups should not substantially affect LTIE.

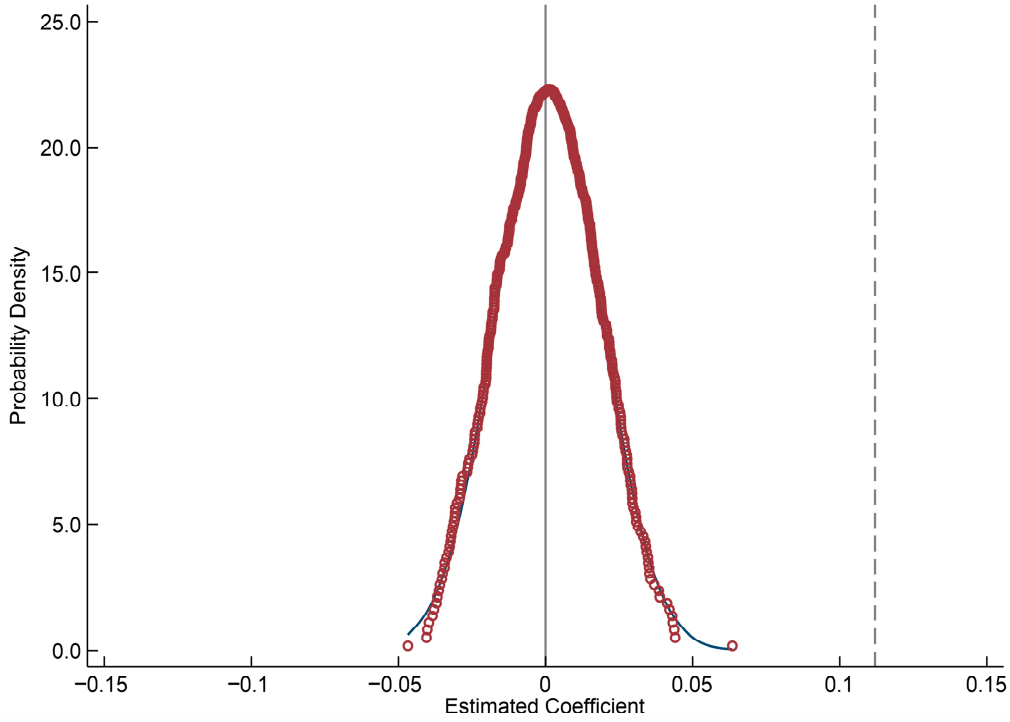


Figure 3. Placebo test.

Figure 3 demonstrates that the estimated coefficients from the randomly replicated dummy treatment groups for policy effect evaluation are concentrated around 0 and adhere to a normal distribution. All estimated coefficients are smaller than the baseline regression coefficient of 0.112. Therefore, the benchmark regression results in this study pass the placebo test, ruling out the interference of unobservable factors and demonstrating that the benchmark regression results are valid. This finding confirms that CETP has a robust enhancing effect on LTIE.

5.4. Bacon Decomposition Test

The fixed-effect estimator for the multiperiod difference-in-differences model represents the weighted average across different groups and periods. Given that the control group, which incorporates the treatment effect, struggles to reflect the true estimate, we draw upon the work of Goodman-Bacon and employ Bacon decomposition to identify the interference from heterogeneous treatment effects [74]. The weight of group "Treatment vs. Never Treated" is 97.0%. And the other two groups have very little weight. Therefore, this shows that the estimated coefficient of the multiperiod difference-in-differences method is essentially unbiased. Figure 4 presents a scatter plot of the weight distribution for the 2 × 2 DID estimator. The decomposition results indicate that the vast majority of the estimation outcomes stem from the comparison of treatment and control group states, providing strong evidence that our baseline results capture the average treatment effect.

At the same time, this study utilizes an event study approach to estimate the dynamic average treatment effects, following the methodology proposed by Clarke and Tapia-Schythe [75], to verify that the model is unaffected by heterogeneous treatment effects. No significant differences are observed prior to policy implementation (Figure 5). This notion indicates that the study's conclusions remain valid even after accounting for the heterogeneous treatment effects.

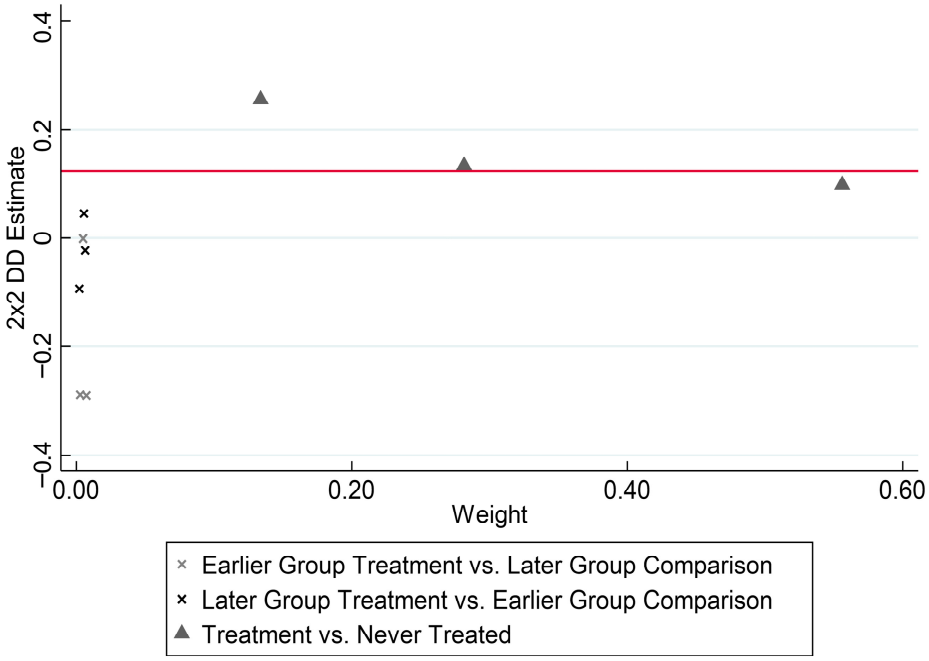


Figure 4. Bacon decomposition.

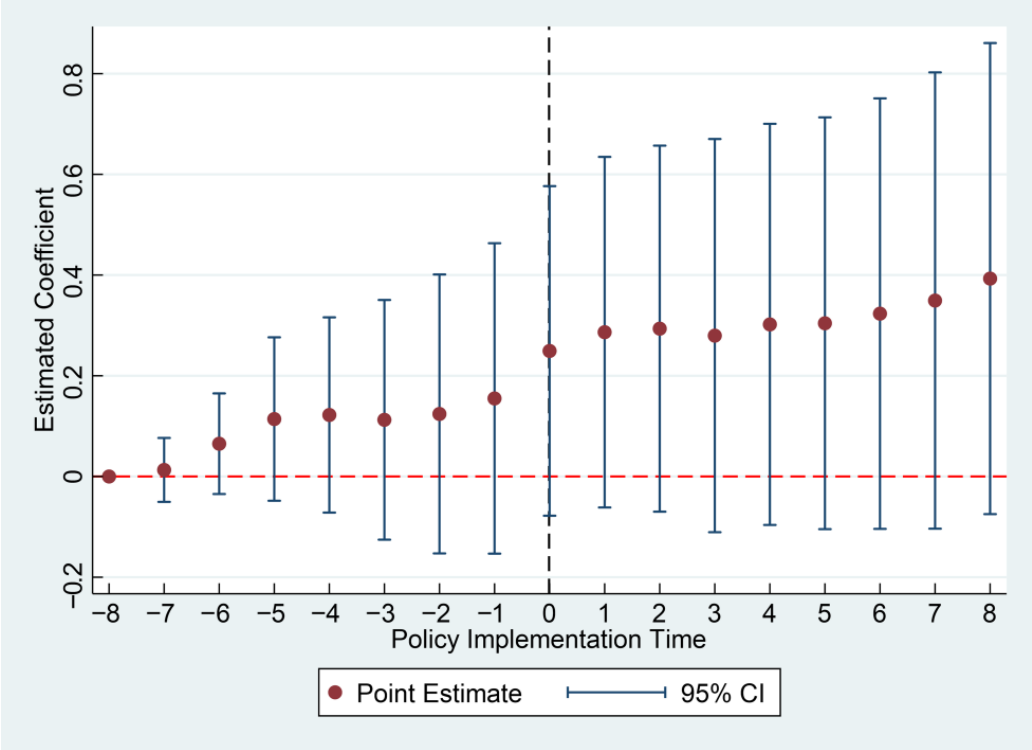


Figure 5. Heterogeneity-Robust Estimation Test.

5.5. Other Robustness Tests

This study utilizes a set of robustness tests to corroborate the previously stated conclusions, as detailed in Table 3. First, we exclude estimation errors caused by omitted variables. This study additionally includes air pollution ($lnSO_2$) and industrial solid waste (lnISP) as control variables, with the results displayed in Column (1) of Table 3. The regression coefficient for the policy is markedly positive, hence reinforcing Hypothesis 1. Second, interference from other policies is eliminated. Aside from CETP, other measures implemented by China may also affect LTIE. In June 2017, the People's Bank of China, alongside seven

other agencies, including the National Development and Reform Commission, released a five-year master plan for green financial reform and innovation pilot zones in designated regions of Zhejiang, Jiangxi, Guangdong, Guizhou, and Xinjiang Provinces. The primary objective of the pilot program is to further implement green finance policy and accelerate the green transformation of industries. To address potential bias from the pilot project, this study further considers the effect of the green financial innovation reform pilot zone policy by re-conducting regressions. The results in Column (2) of Table 3 are consistent with previous studies. Finally, the instrumental variable test. The phenomenon of thermal inversion will lead to the retention of pollutants. Due to the high concentration of pollutants in the CETP area, the frequency of thermal inversion will be higher, so the frequency of thermal inversion meets the correlation hypothesis. In the meantime, thermal inversion exhibits exogenous characteristics due to its dependence on geographical location and climatic features. Consequently, using the practice of Liu et al. [21], the annual temperature inversion frequency of each province is selected as the instrument variable(IV), and the specific results are listed in columns (3) and (4). In the first stage, the coefficient of the IV is significantly positive. Furthermore, the Kleibergen-Paap rk Wald F statistic for the first stage is 1129.887, which is greater than 16.38. This result rejects the hypothesis of weak instrumentality. In the second stage, the coefficient for IV remained significantly positive, consistent with the benchmark regression. This notion indicates that, after controlling for endogeneity, CETP still significantly drives LTIE, unaffected by the sample selection bias.

Table 3. Robustness tests.

	(1) lnLCT	(2) lnLCT	(3) DID	(4) lnLCT
DID	0.076 **	0.112 ***		
	(2.538)	(4.223)		
GFP		0.003		
		(0.102)		
IV			0.005 ***	0.150 ***
			(8.837)	(5.243)
lnPGDP	0.174 ***	0.178 ***	0.034	0.180 ***
	(2.740)	(2.973)	(0.428)	(2.970)
lnFDI	0.010	0.007	−0.0170	0.020
	(0.585)	(0.408)	(−1.125)	(1.324)
lnPOP	−0.020	−0.052	0.124	−0.049
	(−0.203)	(−0.509)	(1.135)	(−0.455)
lnFAC	−0.260 ***	−0.273 ***	−0.026	−0.234 ***
	(−4.196)	(−4.456)	(−0.304)	(−3.804)
$lnSO_2$	−0.104 ***			
	(−4.533)			
lnISP	0.354			
	(0.917)			
Province FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
_cons	3.676 ***	3.491 ***	0.017	3.248 ***
	(7.121)	(7.339)	(0.015)	(6.191)
R2	0.273	0.240	0.895	0.227
F	7.475 ***	6.587 ***	69.369 ***	9.358 ***
N	510	510	510	510

** and *** denote significance at 5%, and 1%, respectively; t statistics are enclosed in parentheses.

6. Further Analysis

6.1. Mechanism Analysis

This study further investigates the influencing mechanisms of CETP from the perspectives of energy-saving and carbon-reduction innovations, industrial structure transformation, and government support. Table 4 presents the results on the effect of CETP on energy-saving and carbon-reduction innovations. The regression coefficients for DID in Columns (1) to (4) are all positive and statistically significant at the 1% level. This result indicates that this policy substantially promotes energy-saving and carbon-reduction innovations. Existing study indicates that energy-saving and carbon-reduction innovations promote LTIE [76] primarily because such innovations encourage enterprises to adopt green production methods that enhance energy efficiency and reduce carbon emissions. By leveraging economies of scale, these innovations enable enterprises to produce goods at costs lower than those associated with traditional methods, thereby facilitating a low-carbon transition [77]. Therefore, CETP can positively affect LTIE through energy-saving and carbon-reduction innovation.

Table 4. Testing the mechanism of influence: energy-saving and carbon-reducing Innovations.

	(1) Invent	(2) Utility	(3) Design	(4) Total
DID	0.211 ***	0.320 ***	0.041 ***	0.572 ***
	(9.391)	(10.585)	(7.671)	(10.715)
lnPGDP	−0.170 ***	−0.346 ***	−0.042 ***	−0.558 ***
	(−3.360)	(−5.079)	(−3.518)	(−4.643)
lnFDI	0.012	0.023	0.001	0.036
	(0.867)	(1.214)	(0.322)	(1.084)
lnPOP	−0.243 ***	−0.236 **	−0.003	−0.482 **
	(−2.823)	(−2.044)	(−0.136)	(−2.359)
lnFAC	0.045	0.120 *	0.027 **	0.192
	(0.886)	(1.752)	(2.206)	(1.586)
Province FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
_cons	1.209 ***	2.183 ***	0.170 *	3.561 ***
	(3.049)	(4.093)	(1.799)	(3.781)
R2	0.358	0.451	0.276	0.436
F	12.204 ***	17.921 ***	8.313 ***	16.896 ***
N	510	510	510	510

*, **, and *** denote significance at 10%, 5%, and 1%, respectively; t statistics are enclosed in parentheses.

Columns (1) and (2) in Table 5 present the results on the effect of CETP on industrial structure transformation. The results indicate that the regression coefficient for DID is positive and significant, suggesting that CETP not only promotes industrial upgrading but also drives the development of the green energy sector, ultimately facilitating industrial structure transformation. Industrial structure transformation reflects changes in resource allocation patterns and is closely linked to the orientation of economic policies and strategic adjustments [78]. Research demonstrates that the transformation of industrial structures can efficiently optimize energy consumption patterns and improve energy utilization efficiency [79], serving as a requisite condition for the progression of LTIE. Therefore, CETP can positively affect LTIE through industrial structure transformation.

Table 5. Testing the Mechanism of Influence: Industrial Structure Transformation and Government Support.

	(1) IDU	(2) GEI	(3) GEE	(4) GR&D
DID	0.204 ***	0.134 ***	0.001 *	0.313 ***
	(2.610)	(3.798)	(1.828)	(5.064)
lnPGDP	0.007	−0.461 ***	0.000	0.775 ***
	(0.038)	(−5.789)	(0.188)	(5.571)
lnFDI	−0.100 **	0.108 ***	−0.001	0.066 *
	(−2.032)	(4.877)	(−1.566)	(1.689)
lnPOP	0.035	−0.433 ***	−0.001	−0.003
	(0.117)	(−3.202)	(−0.265)	(−0.011)
lnFAC	−0.272	−0.557 ***	0.002	0.180
	(−1.534)	(−6.946)	(1.469)	(1.283)
Province FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
_cons	3.012 **	9.614 ***	−0.002	−7.307 ***
	(2.181)	(15.425)	(−0.213)	(−6.706)
R2	0.503	0.782	0.284	0.908
F	22.151 ***	78.525 ***	8.669 ***	215.647 ***
N	510	510	510	510

*, **, and *** denote significance at 10%, 5%, and 1%, respectively; t statistics are enclosed in parentheses.

Columns (3) and (4) in Table 5 display the findings on the impact of CETP on governmental assistance. The findings demonstrate that the regression coefficient for DID is both positive and significant, indicating that CETP enhances government environmental regulation and fosters government technological expenditure, together signifying the extent of government support. Policy support plays a crucial role in defining industrial development objectives, providing economic incentives and financial guarantees, and improving regulatory frameworks [57]. Existing study indicates that increased government support is a key driver for enterprises to achieve low-carbon energy transformation primarily because government support creates a favorable external environment for corporate transformation, such as enabling enterprises to receive government subsidies and enhance their technological innovation capabilities [80]. Government environmental regulation also ensures the sustained advancement of low-carbon energy transition [7]. Therefore, CETP can positively affect LTIE through government support.

6.2. Heterogeneity Analysis

To investigate the external factors influencing LTIE under CETP, this study examines regional disparities and industrial governance investments to validate their heterogeneous differences. The precise outcomes are detailed in Table 6.

Concerning geographical heterogeneity, disparities in economic development levels, industrial structures, resource endowments, and the intensity of policy implementation across various areas lead to significant regional variability in the impact of CETP on LTIE. The industrial energy consumption and carbon emission intensity in coastal regions are much higher than those in inland areas [81]. This study categorizes provinces into coastal and inland areas according to the classification standards set by the National Bureau of Statistics of China to analyze regional variation in policy effectiveness. Empirical examinations are performed with Model (1). Column (1) in Table 6 presents the results for inland samples, while Column (2) delineates the results for coastal samples. The regression coefficient for DID in Column (1) is 0.182, statistically significant at the 1% level. The regression coefficient for DID in Column (2) is −0.034, but it is not statistically significant.

The above results indicate that CETP is more efficacious in inland regions than in coastal places. The observed differences in the effects of carbon trading policies across regions may stem from distinct industrial structures. Coastal areas predominantly rely on export-oriented services and manufacturing, featuring a higher proportion of high-value-added industries with limited scope for energy restructuring [82]. In these regions, technological energy efficiency in certain sectors has approached its ceiling. By contrast, inland areas exhibit a greater reliance on coal and building materials industries, with coal constituting a larger share of their energy mix [83]. Consequently, carbon trading policies exert a more pronounced effect in driving the adoption of alternative energy sources in these inland regions.

Table 6. Test for heterogeneity.

	(1) Inland	(2) Coastal	(3) Low_IGI	(4) High_IGI
DID	0.182 ***	−0.034	0.059 *	0.133
	(4.924)	(−0.752)	(1.681)	(1.606)
lnPGDP	0.211 ***	0.178	0.304 ***	0.174
	(2.966)	(1.306)	(3.626)	(1.349)
lnFDI	0.015	−0.004	−0.014	0.094 *
	(0.577)	(−0.176)	(−0.748)	(1.861)
lnPOP	−0.134	0.687 *	−0.011	−0.192
	(−1.250)	(1.964)	(−0.067)	(−1.371)
lnFAC	−0.256 ***	−0.167	−0.291 ***	−0.362 ***
	(−3.492)	(−1.249)	(−3.586)	(−3.261)
Province FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
_cons	2.911 ***	2.680 ***	2.592 ***	3.850 ***
	(4.648)	(2.827)	(4.038)	(3.507)
R2	0.236	0.382	0.288	0.195
F	4.158 ***	4.566 ***	4.933 ***	1.859 **
N	323	187	307	203

*, **, and *** denote significance at 10%, 5%, and 1%, respectively; t statistics are enclosed in parentheses.

The level of industrial governance investment reflects resource allocation efficiency and sectoral responsiveness. High industrial governance investment not only drives technological innovation and process upgrades but also mitigates policy and legal risks associated with the energy transition toward low-carbon development [84]. With regard to disparities in industrial governance investment levels, this study employs the ratio of industrial governance investment to GDP as the classification criterion. Provinces with ratios below the mean are categorized as Low_IGI, whereas those with ratios above the mean are classified as High_IGI. Empirical tests are conducted for each group by using Model (1). Column (3) in Table 6 presents the results for the Low_IGI group samples, while Column (4) exhibits the results for the High_IGI group samples. The regression coefficient in column (3) is 0.059, significant at the 10% level. However, it is not significant in column (4). The findings indicate that the CETP plays a highly pronounced role in enhancing LTIE in regions with low industrial governance investment. This situation arises because enterprises in areas with insufficient industrial governance investment lack adequate financial subsidies or technologies to achieve low-carbon transformation. In such contexts, the carbon emission trading market provides enterprises with new emission reduction pathways through market-based mechanisms [85]. For instance, enterprises can flexibly adjust production by purchasing allowances or selling surplus allowances, rather than relying on costly technological upgrades or equipment replacement [86]. This

market-based incentive mechanism may prove more effective and cost-efficient than direct government investment.

7. Discussion

Environmental risks threatening human survival and sustainable development—such as resource depletion, pollution, and the greenhouse effect—are becoming increasingly prominent. LTIE is now urgent, with a global consensus largely established on promoting green and low-carbon energy transformation. However, LTIE is a long-term process. The formulation of rational and effective decarbonization policies is crucial during the implementation of the "dual carbon" strategy [19]. This study confirms the significant role of CETP in advancing LTIE, highlighting that achieving carbon reduction targets relies on effective environmental policies—a finding consistent with prior studies [21–23]. In the international community, environmental policies are also recognized as key instruments for driving the LTIE systems [87]. The innovation of policy regulatory tools to address future challenges to human survival and development is vital [88]. The conclusions drawn from this study can provide valuable reference experiences for other countries and regions.

Unlike previous studies that overly focused on the effects of technological innovation, cost constraints, and energy consumption structure transformation [22–24], this study systematically reveals three specific transmission pathways from three dimensions: individual enterprises, industry as a whole, and external environment. These pathways are: energy-saving and carbon-reduction technological innovation, industrial structure transformation, and government support. The CETP leverages market mechanisms to prompt enterprises to autonomously select the most cost-effective emission reduction pathways, compelling them to increase R&D investment, achieve green technology diffusion, and facilitate resource shifts from high-energy-consuming industries to green industries. These mechanisms collectively form a closed-loop system of "market incentives–technological innovation–structural optimization". Unlike studies that emphasize solely administrative directives or fiscal subsidies [7,8], this study systematically demonstrates the synergistic effects among these three elements.

Furthermore, this study analyzes the heterogeneous effects of external factors, such as regional geography and industrial governance investments, yielding several key insights. Specifically, environmental policies in inland regions can effectively constrain high-carbon-emitting industries, likely due to differing industrial structures and marginal emission reduction potential. Firms, as market participants in carbon trading, can channel optimal capital allocation toward environmentally friendly projects. This finding aligns with the study by Chen and Yang [12]. Meanwhile, low industrial governance investment suppresses endogenous momentum for low-carbon transition but simultaneously creates a "last resort" opportunity window for the CETP. At this juncture, market mechanisms play a prominent role, rapidly driving corporate behavioral adjustments through price signals and economic incentives.

The above-mentioned findings indicate that greenhouse gas emission reductions are influenced by various interrelated factors, necessitating comprehensive consideration of their combined effects. Although this study is grounded in China's unique institutional context, its findings hold broad implications for global climate governance. This implication is particularly relevant for developing economies facing dual pressures of economic growth and carbon reduction, such as India and Vietnam. The design of India's carbon trading market [89] and the establishment of Vietnam's carbon reduction targets [90] involve ensuring policy appropriateness and effectiveness. The validation of CETP's effectiveness in this study offers crucial insights for these nations while providing relevant references for developed economies, such as the EU and the United States.

8. Conclusions and Policy Implications

8.1. Conclusions

LTIE embodies a fundamental shift in economic development models. Moreover, LTIE has substantial theoretical and practical value for reshaping national competitiveness, deepening the concept of sustainable development, and revealing the evolutionary trajectory of human civilization. CETP plays a crucial role in advancing LTIE, making studies in this area uniquely valuable. This study systematically examines the effect of CETP on LTIE in 30 Chinese provinces from 2005 to 2021 and the underlying mechanisms. The findings indicate that first, this policy has considerably accelerated LTIE. Following the implementation of parallel-trend, placebo, and further robustness assessments, the findings remain stable. Second, this policy primarily promotes LTIE through multiple avenues, including energy-saving and carbon-reduction innovations, industrial structure transformation, and government support. Third, the heterogeneous results indicate that in inland regions and areas with low levels of industrial governance investment, the policy demonstrates a pronounced effect on promoting LTIE.

8.2. Policy Implications

To augment the beneficial impact of CETP in advancing LTIE, the government can refine specific domains. First, initially, it must enhance policy execution and supervision to guarantee the efficacy of LTIE. It should further refine supporting regulations for CETP and standardize the trading process. The government must enhance the regulatory framework for the carbon emission trading market and reinforce oversight of trading activities, specifically concerning the monitoring, reporting, and verification processes for corporate carbon emission data, to guarantee the authenticity and precision of the data. Moreover, the implementation effectiveness of CETP should be evaluated regularly, and policy objectives and measures should be adjusted promptly on the basis of the evaluation results. Establish a mechanism for regular policy reviews and adjustments based on performance data and feedback from stakeholders.

Second, LTIE should be promoted through multipronged, coordinated efforts. Low-interest loans or risk compensation funds should be provided for key energy-saving and carbon-reduction technologies, such as hydrogen-based metallurgy and carbon capture, utilization, and storage technology, with a focus on pilot demonstration bases and first-of-a-kind equipment demonstration projects. Alternatively, reference could be made to Germany's energy transition fund model, which provides additional tax deductions on the basis of the proportion of R&D investment. In addition, the government should formulate industrial policies to guide capital toward low-carbon, environmentally friendly emerging industries and accelerate the green transformation of traditional industries. For example, restrictive policies can be implemented for high-energy-consuming and high-polluting enterprises, such as coal and building materials companies in western regions. Furthermore, the government should strengthen policy guidance for enterprises, establish clear low-carbon development goals and plans, and provide policy consultation and technical guidance to businesses. Financial support and market safeguards for LTIE should also be provided through government procurement, green finance, and other means.

Third, policies tailored to local conditions should be implemented to leverage regional strengths. For inland regions, policymakers should fully recognize the potential technical bottlenecks and financial constraints these areas may face, such as enterprises lacking funds to upgrade equipment and adopt advanced technologies. Therefore, when designing carbon emissions trading policies, carbon emission quotas for inland enterprises should be appropriately relaxed, accompanied by targeted technical training and talent support to enhance their energy conservation and emissions reduction capabilities. Simultaneously,

priority should be given to promoting cost-effective emission reduction technologies, such as waste heat recovery and utilization. In areas characterized by substantial industrial governance investment, the government ought to refine the investment framework, augment capital utilization efficiency, incentivize enterprises to amplify investments in energy conservation and emissions reduction infrastructure, and advocate for the adoption of advanced environmental management technologies and exemplary practices. Furthermore, pilot programs may be established to create regional carbon credit trading mechanisms based on carbon trading markets, encouraging eastern regions to purchase carbon credits from western regions to facilitate the regional transfer of carbon emission reduction benefits, thereby forming a mutually beneficial community of shared interests between eastern and western regions.

8.3. Limitations and Research Perspectives

This study has certain limitations resulting from practical constraints. First, this study focuses solely on 30 provinces in China due to the limitations of the country's unique economic system. Future studies can expand their scope to include other countries and regions, comparing differences and outcomes in the implementation of CETP across nations. This broadened perspective can provide extensive insights into the global LTIE. Second, this study primarily examines the overall effects of policies at the macro level, with insufficient attention paid to the meso and micro levels, such as industries and enterprises, due to the data limitations. Future studies can delve deeper using industry or enterprise-level data. Third, although the linear DID model captures average policy effects, it fails to detect nonlinear jumps beyond carbon price thresholds or lagged effects of technological transitions. Future studies can construct dynamic panel threshold models to systematically analyze the nonlinear pathways of policy effects.

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Appendix A

Steps for Constructing the Low-Carbon Transition of Industrial Energy Index:

The steps for constructing the low-carbon transformation of industrial energy (LTIE) index based on the improved weighted multidimensional vector angle method are as follows:

Step 1: Rank all energy sources. Assuming that n energy sources exist, rank them in descending order based on their carbon emissions. Use the consumption share of each energy source as a component of a spatial vector to construct an n-dimensional spatial

vector representing the energy structure. The spatial vector for period t is expressed as follows:

$$E_t\left(e_t^1, e_t^2, \ldots, e_t^n\right)$$

Step 2: Select the reference vector. Assume that a theoretical lower bound for the LTIE index exists, where all energy consumption originates from the energy type with the highest carbon emissions. The n-dimensional vector representing the energy consumption structure under this scenario serves as the reference vector, expressed as: $E_0(1,\ 0,\ 0,\ \ldots,\ 0)$. Here, E0 is an invariant and unique basis vector.

Step 3: Calculate the vector angle formed by the energy shift of the jth energy source. The vector angle computed using the traditional Moore structure value method lacks directionality, potentially resulting in identical vector angles from shifts in different energy sources. With E_0 as the reference, replace the value of the jth component in vector E_0 with the value of the jth component in E_t to construct the new vector E_a. The angle between vectors E_a and E_0 can be understood as solely resulting from the change in the jth energy source structure. Vector E_a is expressed as follows:

$$E_a = \begin{cases} \left(e_t^1,\ 0,\ 0,\ 0,\ \ldots,\ 0\right) & j = 1 \\ \left(1,\ 0,\ 0,\ 0,\ \ldots,\ e_t^j,\ 0,\ \ldots,\ 0\right) & j = 2,\ 3,\ \ldots,\ n \end{cases} \tag{A1}$$

At this point, the angle θ_{aj} between the vectors is:

$$\theta_{aj} = \begin{cases} 0 & j = 1 \\ \arccos\frac{1}{\sqrt{1 + e_t^j}} & j = 2,\ 3,\ \ldots,\ n \end{cases} \tag{A2}$$

With E_t as the reference vector, replace the value of the jth component in vector Et with the value of the jth component in E_0 to construct a new vector E_b. The angle between vectors E_b and E_t can be interpreted as the vector angle formed by the jth energy structure change. Vector E_b is expressed as follows:

$$E_b = \begin{cases} \left(1,\ e_t^2,\ e_t^3,\ \ldots,\ e_t^n\right) & j = 1 \\ \left(e_t^1,\ e_t^2,\ \ldots,\ e_t^{j-1},\ 0,\ e_t^{j+1},\ \ldots,\ e_t^n\right) & j = 2,\ 3,\ \ldots,\ n \end{cases} \tag{A3}$$

The angle θ_{bj} between vectors E_b and E_t is calculated as:

$$\theta_{bj} = \begin{cases} \arccos\frac{e_t^1 + \sum_2^n \left(e_t^j\right)^2}{\sqrt{1 + \sum_2^n \left(e_t^j\right)^2} * \sqrt{\sum_1^n \left(e_t^j\right)^2}} & j = 1 \\ \arccos\frac{\sum_1^{j-1} \left(e_t^j\right)^2 + \sum_{j+1}^n \left(e_t^j\right)^2}{\sqrt{\sum_1^{j-1} \left(e_t^j\right)^2 + \sum_{j+1}^n \left(e_t^j\right)^2} * \sqrt{\sum_1^n \left(e_t^j\right)^2}} & j = 2,\ 3,\ \ldots,\ n \end{cases} \tag{A4}$$

θ_{aj} and θ_{bj}, analogous to the Parshall index and the Lassell index, can lead to underestimation or overestimation of the angle. The geometric mean of the two is taken to obtain the angle formed by the shift in the jth energy structure, avoiding computational bias:

$$\theta_j = \sqrt{\theta_{aj}\theta_{bj}} (j = 1, 2,\ \ldots,\ n) \tag{A5}$$

Step 4: Weight the vector angles formed by the changes in the n energy structures to synthesize the LTIE index.

$$\text{LTIE} = \sum_{i=1}^n \sum_{j=1}^n \theta_j \tag{A6}$$

In practice, the calculation method of Formula (A4) involves assigning weights to the angles formed by changes in various energy sources using an arithmetic progression.

The LTIE index constructed through an improved weighted multidimensional vector angle method yields directionally consistent measurement results. This index eliminates the need to consider base period selection issues, thereby offering the advantages of intertemporal and cross-sample comparability and enhanced applicability.

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