

Article

How Can China's Carbon Emissions Trading Pilot Improve New Quality Productivity?

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Abstract: Our research investigated whether the carbon emissions trading pilot policy (CET), while mitigating environmental pollution externalities and fostering green economic and social transformation, can also enhance China's new quality productivity (NQP) as a key driver of economic growth. This study addresses a research gap by examining the CET from an integrated perspective of economic development and environmental protection. We have developed an NQP evaluation indicator system based on three productivity factors, revealing that the CET can elevate NQP levels in pilot provinces through the advancement of green finance (GF) and industrial structure upgrading (ISU). Furthermore, we analyzed the relationship between the CET and NQP from the perspective of low-carbon energy consumption (LCEC), demonstrating that the level of LCEC can reinforce the CET's positive impact on NQP and moderate the path before and after the mediating process. Our findings offer valuable insights into leveraging market-based environmental regulation tools to support NQP development, thereby facilitating its cultivation and enhancement.

Keywords: carbon emissions trading pilot; new quality productivity; green finance; industrial structure upgrading; low-carbon energy consumption



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1. Introduction

Since the inception of reform and opening up in 1978, China's economy has undergone a transformative trajectory, evolving through three distinct phases: initial industrialization (1978–2000), deep industrialization coupled with global integration (2001–2012), and the current new normal of quality-driven development (2013–present) [1]. This unprecedented economic metamorphosis has propelled China to the forefront of global economic governance, with its GDP surpassing CNY 130 trillion (about USD 18.3 trillion) by the end of 2024, securing its position as the world's second-largest economy while contributing approximately 30% to annual global economic growth. However, the rapid industrialization–urbanization nexus predominantly relied on resource-intensive development models characterized by high pollution coefficients and energy consumption intensities, exerting critical pressure on the ecological carrying capacity [2]. Evidence from the China Energy Outlook 2060 (2025 Edition) reveals that in 2024, national terminal energy consumption reached 4.26 billion tons of standard coal equivalent (tce); energy-related CO₂ emissions (excluding chemical product carbon fixation) totaled 10.66 billion tons; the industrial sector energy demand constituted 2.86 billion tce (67% of terminal consumption); and industrial carbon emissions accounted for 6.93 billion tons (65% of energy-related emissions).

Facing the increasingly severe environmental challenges, achieving green and high-quality growth has become an imperative for China's economic development. Green and

high-quality growth means abandoning the traditional extensive development model, promoting industrial upgrading and restructuring, developing green industries, improving resource utilization efficiency, and reducing pollutant emissions [3]. New quality productivity (NQP) is the core driving force for achieving green and high-quality growth. It is an advanced productivity based on the innovative achievements of the new generation of information technology, new energy, new materials, biotechnology, and other fields. Driven by innovation and characterized by high technology, high efficiency, and high quality [4], NQP can break through the bottleneck of traditional productivity development and achieve a virtuous interaction between economic development and environmental protection. For example, the development of the new energy vehicle industry not only reduces the dependence on traditional fuel but also lowers carbon emissions and drives the innovative development of related fields, such as battery technology and intelligent driving technology. The application of artificial intelligence technology in industrial production has improved production efficiency, optimized resource allocation, and reduced waste in the production process. The development of NQP provides a new path and support for the green and high-quality growth of China's economy [5].

Before the innovative concept of NQP was put forward, since 2011, China had been planning to implement the carbon emissions trading pilot policy (CET) in multiple provinces and cities in order to alleviate the contradiction between industrialization and environmental quality and promote the green and low-carbon transformation of industries, and officially launched the pilot work by the end of 2013 [6]. As of the end of 2020, the industries covered by the CET had exceeded 20. The successful implementation of China's CET laid the foundation for the national trading of carbon emission rights. The national carbon emissions trading market started with the power generation industry and launched online trading in July 2021. The Progress Report of China's National Carbon Market (2024) shows that, as of the end of 2023, the cumulative trading volume of carbon emission allowances in China's power generation industry's carbon emissions trading market was 442 million tons, and the cumulative transaction value was CNY 24.919 billion. China's carbon emissions trading market has become the largest market in the world in terms of the covered carbon emissions. In September 2024, the Ministry of Ecology and Environment of the People's Republic of China expressed its intention to expand the scope of the national carbon market, which once again sparked discussions in the academic community about the role of China's CET. At the micro level, the CET can reduce the pollution emission intensity of enterprises [7], reduce enterprises' greenwashing behaviors [8], alleviate enterprises' financing constraints, and promote enterprises' green technological innovation [9]. In addition, with the facilitating effect of the ESG performance, the CET has a stronger promoting effect on enterprises' productivity [10]. At the macro level, the CET can not only improve energy and environmental efficiency [11] and promote the development of green transportation [12], but also foster practical technological advancements and improve green total factor productivity [13].

Given that existing research has confirmed the promoting effect of the CET on technological innovation and productivity improvement, this paper focuses on the internal correlation mechanism between the CET and NQP. As an advanced form of productivity with innovation as the core driving force and green attributes [14], NQP serves as a ^{2re} engine in the process of promoting green and high-quality development. The CET improves green production efficiency by constructing a market-oriented emission reduction mechanism, which forms a co-evolutionary relationship with NQP: on the one hand, it drives the optimized allocation of production factors to the green field, and, on the other hand, it encourages the iterative innovation of clean technologies. An in-depth study of the relationship between the CET and NQP, and an exploration of the roles of green finance

(GF), industrial structure upgrading (ISU), and low-carbon energy consumption (LCEC) in the impact pathway, has theoretical value in revealing the transmission mechanism of market-oriented factor allocation reforms for productivity innovation. The practical value is reflected in exploring the collaborative path between economic development and ecological protection under the dual-carbon goals, and, at the same time, providing a replicable institutional innovation sample for global climate governance. Based on the above analysis, this study focuses on the key nodes and impact pathways through which the CET affects NQP, aiming to construct a theoretical framework for the green factor market development and productivity enhancement and providing decision-making references for sustainable development in the process of Chinese-style modernization.

2. Literature Review

2.1. Policy Effects of CET

Prior to the advent of a new wave of intense discussions, as an effective market-based measure for China to achieve the “dual-carbon” objectives, the research conducted by scholars on the CET predominantly centered on two aspects: economic effects and environmental effects.

One is the economic outcomes. Hubler et al. [15] affirmed that the CET yields cost-saving economic effects, but achieving the established goal of reducing carbon emission intensity may lead to certain welfare losses. However, Wu and Gong [16] argued that the CET can partially offset the GDP decline caused by carbon emission reduction measures. Qi et al. [17] confirmed that the emission reduction effect in pilot areas does not compromise economic development. Zeng et al. [18] highlighted that the CET significantly contributes to economic stability and promotes high-quality economic development.

The other is environmental outcomes. Tang et al. [19] demonstrated through simulations that the CET positively influences China’s carbon reduction and energy structure optimization. Hu et al. [20] found that, relative to other regions, the pilot areas experienced a 22.8% decrease in energy consumption and a 15.5% reduction in carbon emissions. Jia et al. [21] argue that the CET not only significantly reduces carbon emissions and intensity but also facilitates the transformation of the energy consumption structure in pilot provinces. Zhang et al. [22] suggest that the CET can alleviate the trilemma of security, equity, and sustainability faced by the energy sector by promoting green technological innovation and improving the energy consumption structure.

2.2. The Connotation of NQP

NQP signifies the innovation and evolution of Marxist productivity theory in the new era of socialism with Chinese characteristics [23], serving as both an intrinsic requirement and a pivotal focus for fostering high-quality development [24]. NQP represents more advanced forms of productivity, which stem from continuous improvements in the quality of productivity components. These advancements primarily depend on innovation and emerging technologies, transforming them into intelligent production technologies and methodologies that optimize production processes and achieve more efficient resource allocation [25].

Advanced science and technology are of vital importance to NQP [26], and the development of NQP helps promote technological innovation, drives the transformation of production methods, and facilitates high-quality economic development [27]. In agriculture, Lin et al. [28] confirmed the positive impact of NQP on the development of high-quality agriculture. Meanwhile, Xu et al. [29] studied how GF and digital inclusive finance contribute to the sustainable economic development of Jiangsu Province through NQP. Furthermore, Shao et al. [30] discovered a positive correlation between NQP and ISU, indi-

cating that NQP can narrow the industrial structure gap and promote industrial upgrading. Xue and Chen [31] found that patent quality and digital transformation positively moderate the relationship between the ESG performance and NQP, enhancing its positive effect.

Previous research has provided valuable insights and conceptual frameworks that inform our study. However, several limitations persist. First, most studies on the CET predominantly focus on either economic or environmental effects individually, failing to comprehensively evaluate the high-quality development impacts of policies from both economic and environmental perspectives, whereas NQP underscores the simultaneous advancement of the economy and environment. Second, there is a lack of literature that examines the relationship between the CET and economic development drivers through the lens of the energy consumption structure. Third, the existing research on NQP primarily focuses on spatial disparities or utilizes NQP as an explanatory variable to analyze its influence on other macroeconomic factors, which limits the ability to fully capture the heterogeneous sources of this complex concept.

Therefore, our paper contributes to the literature in three key dimensions. First, we constructed a comprehensive evaluation indicator that integrates environmental protection, innovation and entrepreneurship, and resource utilization, thereby providing a holistic assessment of NQP for green and high-quality development. Second, we elucidated the mediating role of GF and ISU between the CET and NQP. We analyzed the theoretical mechanisms through which the CET impacts GF and ISU performance and conducted empirical tests to provide policy recommendations for the government on how to effectively leverage GF tools and guide industrial structure changes to promote NQP. Third, we examined the moderating effect of LCEC on both the direct and indirect promotion of NQP in pilot provinces, offering insights into optimizing local energy consumption structures to support NQP development.

3. Hypothesis

3.1. *The Direct Impact of the CET on NQP*

The President of China proposed that the essence of NQP lies in advanced productivity. A statistical indicator system for NQP encompassing laborers, labor objects, and labor materials can be established. As an essential market-based environmental regulatory tool, the CET plays a pivotal role in promoting green development. We can analyze the impact of the CET on the NQP of pilot provinces from three dimensions: laborers, labor objects, and labor materials.

Laborers are individuals who possess specialized scientific knowledge and technological expertise, have accumulated practical production experience and proficient labor skills, and can engage in specialized labor within social production processes. The implementation of the CET has enhanced environmental awareness among laborers in the pilot provinces [32]. Laborers will embrace a green lifestyle by leveraging clean energy, minimizing carbon footprints, and endorsing environmentally friendly products. This transition to sustainable living will place significant pressure on related industries and enterprises, compelling them to consciously adopt green production technologies. As a result, specialized training enterprises focused on green production technologies have emerged, aiming to enhance the professional competence of laborers in clean production to meet future workforce demands. To comply with local government regulations and reduce carbon emissions, enterprises in pilot provinces must continuously innovate in environmental protection technologies and products. Enhanced environmental awareness will not only influence employees but also become an integral part of corporate culture.

Labor objects encompass all materials upon which laborers apply their labor. The CET has facilitated enterprises in pilot provinces to adopt more environmentally friendly,

clean production technologies [33], such as utilizing renewable energy sources, optimizing production processes, and refining product designs. This advancement in technology not only facilitates the development of a circular economy and enhances comprehensive resource utilization but also drives the growth of high-end, clustered, and large-scale industries, thereby upgrading and transforming traditional industries. Furthermore, it supports the development of future industries centered on information technology and data elements, building upon traditional production factors. Consequently, the implementation of the CET promotes ISU in pilot provinces and achieves economies of scale.

Labor materials encompass all resources or conditions that laborers utilize to transform or influence their labor objects during the production process. The CET can incentivize enterprises in pilot provinces to explore more environmentally friendly alternative resources or materials, thereby reducing the reliance on high-carbon-emission materials [34]. For instance, substituting traditional energy sources with renewable energy and utilizing recycled materials instead of disposable ones can effectively decrease carbon emissions and resource consumption. In response to stringent environmental regulations, enterprises can also adopt green supply chain practices by selecting suppliers and partners that adhere to environmental standards. This approach enables the control of carbon emissions and minimizes environmental impacts at the source [35]. Consequently, the implementation of the CET facilitates the environmentally friendly transition and sustainable development of the entire industry chain, ultimately driving high-quality growth.

Therefore, we propose Hypothesis 1:

H1: *The CET could improve the level of NQP in pilot provinces.*

3.2. The Indirect Impact of GF on NQP

GF encompasses economic activities aimed at supporting environmental enhancement, mitigating climate change, and efficiently conserving resources. It includes financial services provided for activities such as the investment, financing, operation, and risk management of energy conservation and environmental protection projects. The development level of GF serves as an indicator of the maturity of the GF market. Its improvement signifies increased attention and investment from financial institutions and investors in green projects, thereby accelerating the adoption of green technologies to improve the quality and efficiency of productivity. [36]. The maturity of the GF market also indicates that more resources will be directed towards environmental protection projects and green industries rather than traditional high-pollution and high-energy-consuming sectors. This reallocation of resources fosters sustainable economic development and enhances NQP.

In the carbon market, carbon emissions quotas and voluntary emissions reductions at both municipal and national levels can be traded via agreement transfer, public auctions, or other regulatory-compliant methods. This signifies that carbon emissions quotas have evolved into a new type of standardized quasi-monetary asset with financial attributes and functional characteristics, serving as a critical component of GF. Furthermore, these assets can be utilized to develop various financial instruments, such as carbon emissions quota pledge loans, futures contracts, forward contracts, and delivery guarantee insurance. These instruments increase the sources of funds for enterprises' green technology innovation and mitigate their innovation risks, thereby facilitating the transformation of production modes while promoting the deepening and innovation of GF in the pilot provinces [37]. In 2017, the People's Bank of China introduced the Green Macro Prudential Assessment system, which incorporates key indicators, such as the growth rate of green credit and the proportion of green credit, into enterprises' evaluation framework. The aim is to actively promote GF and enhance the supply of green credit.

Therefore, we propose Hypothesis 2:

H2: *The CET could promote NQP in pilot provinces by enhancing the development level of GF.*

3.3. The Indirect Impact of ISU on NQP

ISU denotes the transformation of a country or region's economic growth model, such as transitioning from labor-intensive to capital-intensive, knowledge-intensive, and other advanced growth models. The emergence of new market demands acts as the primary catalyst for ISU, reallocating resources like materials, capital, and talent towards new technologies, processes, products, and management practices. This reallocating promotes the rise of emerging industries, compels traditional industries to either decline or integrate with emerging industries, and ultimately results in ISU, significantly enhancing production efficiency and economic benefits [38]. NQP is propelled by groundbreaking technological advancements, the strategic reallocation of production factors, and profound industrial transformation and upgrading, all characterized by a substantial increase in total factor productivity. Consequently, ISU can facilitate the enhancement of NQP levels.

The CET has increased the abatement costs for enterprises in pilot provinces, compelling them to adjust their production factor inputs and product types or pursue technological innovation [39]. High-emission enterprises may choose to purchase carbon quotas from low-emission enterprises to meet their reduction obligations. However, the escalating abatement costs present significant challenges to their market competitiveness. This pressure will compel high-emission enterprises to adopt technological innovations to improve production efficiency and meet emission reduction targets. Consequently, emerging industries focused on low-carbon, environmental protection and clean energy are experiencing growth, while high-pollution, low-efficiency industries are gradually being phased out, thereby promoting ISU. Low-carbon emission enterprises generate additional revenue by selling surplus carbon quotas [40], which they allocate as research and development funds to invest in low-carbon technologies, thereby further reducing emissions. The circulation of carbon quota sales represents an effective strategy for enterprises to maximize profits. This profit-motivated behavior stimulates the development of new technologies and materials, enhancing labor productivity and promoting ISU. Technological innovations within these enterprises lead to increased production intelligence and scale, which in turn release surplus labor into the tertiary sector. This shift also fosters the emergence of corresponding specialized service enterprises, such as those offering carbon quantification and verification, carbon financial services, and carbon planning. Consequently, the thriving tertiary sector further supports ISU.

Therefore, we propose Hypothesis 3:

H3: *The CET could improve NQP in pilot provinces by ISU.*

3.4. The Moderating Effect of LCEC on NQP

LCEC denotes the extent to which the consumption of fossil fuels is diminished in the energy utilization process [41]. Typically, a higher LCEC in the pilot provinces signifies the greater utilization of clean energy sources, such as wind, solar, and hydroelectric power, which correlates with reduced carbon emissions [42]. Enterprises within these pilot provinces may experience carbon emissions that are either below or marginally above the government-issued carbon quotas. Compared to enterprises in pilot provinces with lower LCEC, these enterprises incur lower carbon emission costs and can allocate more resources toward low-carbon technology research and development, thereby further mitigating carbon emissions. Furthermore, the adoption of clean energy necessitates advanced technological support, indicating that the energy technology level in the pilot province is relatively sophisticated. Consequently, local enterprises are better equipped to achieve green transformation in production methods, leading to improved environmental

performance and contributing positively to NQP. In contrast, for pilot provinces with lower LCEC, local enterprises exhibit a strong reliance on traditional fossil fuels and limited capability in adopting low-carbon technologies. This may result in carbon emissions exceeding government-issued quotas, necessitating the purchase of additional carbon allowances and thereby increasing production costs. To offset these increased costs and maximize profits, enterprises are compelled to enhance efficiency through technological innovation [43]. In this process, the optimal allocation of innovative talents and resources forms the foundation for establishing NQP.

GF depends on the attractiveness of green investments and the funding requirements of enterprises for low-carbon projects. Under the CET, the high levels of LCEC in pilot provinces indicate that these regions possess advanced low-carbon technologies. Consequently, the likelihood of related enterprises seeking green investments decreases, leading to a reduced demand for green financial products in the financial market. This scenario is detrimental to the inflow and subsequent growth of GF funds. However, the existing green production technologies in these provinces, supported by GF instruments, can enhance the quality and efficiency of local productivity. Furthermore, the high LCEC levels in pilot provinces signify the rapid expansion of emerging industries such as clean energy, electric vehicles, and energy storage. These industries possess significant development advantages under the CET, which in turn promotes local ISU and facilitates the formation of NQP. For pilot provinces with a lower LCEC, the CET can channel more funds into green projects and technologies. This not only supports the application and advancement of green technologies but also stimulates innovation and development in GF products, ultimately contributing to local sustainability.

Therefore, we propose Hypothesis 4 and Hypothesis 5:

H4: *LCEC could strengthen the promotion effect of the CET on NQP.*

H5: *LCEC could simultaneously regulate the two paths before and after the mediating process and thus have direct and indirect moderating effects on NQP.*

4. Models and Materials

4.1. Sample Range

The EEA report indicated that China became the world's largest greenhouse gas emitter in 2006. By examining the period from 2006 to 2022, we can effectively analyze the dynamic impact of China's CET within a high-carbon emissions context. Due to insufficient statistical data for Hong Kong, Macau, and Taiwan, these regions have been excluded from our study. Additionally, Qinghai Province was excluded because its statistical yearbook only dates back to 2010. Inner Mongolia, Guangxi, Xizang, Xinjiang, and Ningxia are autonomous regions with distinct demographic, cultural, topographical, and administrative characteristics, which make their statistical data less comparable. To ensure consistency and comparability in our research, we have also excluded these regions.

So, our research sample encompasses 25 provinces in China from 2006 to 2022, except Hong Kong, Macao, Taiwan, Qinghai, Inner Mongolia, Guangxi, Xizang, Xinjiang, and Ningxia. Our study seeks to explore the possible effects of China's CET on NQP. The pilot provinces include Beijing, Tianjin, Shanghai, Chongqing, Hubei, and Guangdong, and the distribution of the pilots is illustrated in Figure 1. Since 2013, China's regional carbon emissions trading schemes have gradually started to go online for trading, with Beijing starting in November 2013 and Shanghai following in December 2013. Consequently, we designate 2014 as the policy implementation benchmark year.

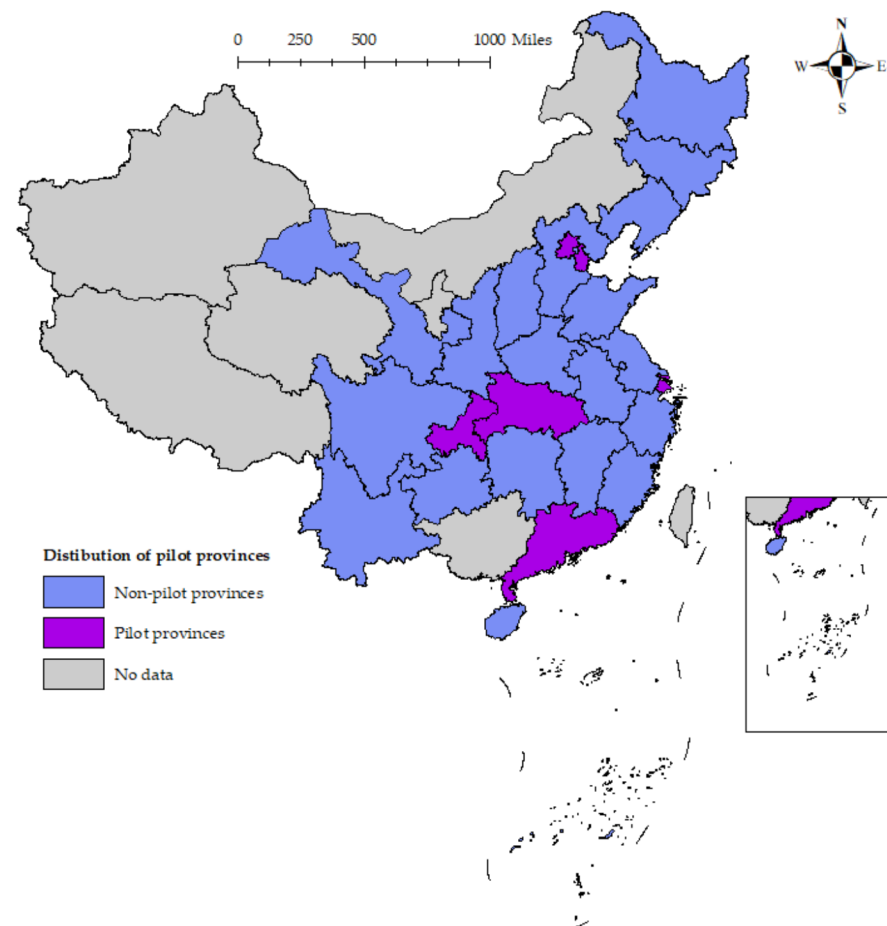


Figure 1. Distribution of pilot provinces in China.

All data in this paper are from the National Bureau of Statistics of China, the statistical yearbooks of Chinese cities over the years, the China National Intellectual Property Administration, the Ministry of Science and Technology of the People’s Republic of China, the Ministry of Industry and Information Technology of the People’s Republic of China, the official websites of Chinese provincial governments, CEADs, and QCC’s database. Some missing data were calculated using interpolation and linear prediction methods.

4.2. Empirical Models

We investigate whether the CET can enhance the NQP of pilot provinces, which is essentially an estimation of the effect of the CET. The difference in differences model (DID) is a widely recognized method for analyzing quasi-natural experiments. By eliminating the influence of time-invariant fixed factors from the double difference between the treatment and control groups before and after the intervention, this model reduces external interference and minimizes selection bias, thereby obtaining a more precise estimate of the treatment effect. The CET has a clearly defined implementation time and pilot region, making it suitable for a quasi-natural experiment. We can employ DID to isolate the effects attributable to policy implementation. Therefore, we employ DID to test the hypotheses. Given that the successful implementation of the CET is a prerequisite, we first assess whether the CET has effectively reduced CO₂ emissions in the pilot provinces. To this end, we construct model (1) and the baseline regression model (2).

$$CDE_{it} = \alpha_0 + \alpha_1 \text{region}_i \times \text{post}_t + \alpha_2 \text{controls}_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

$$NQP_{it} = \beta_0 + \beta_1 \text{region}_i \times \text{post}_t + \beta_2 \text{controls}_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (2)$$

The dependent variable CDE_{it} in model (1) denotes the CO₂ emissions of province i in year t . The dependent variable NQP_{it} in model (2) represents the NQP of province i in year t . The core independent variable, $region_i \times post_t$ consists of two components: $region_i$, a regional dummy variable where pilot regions are coded as 1 and non-pilot regions as 0; and $post_t$, a time dummy variable that takes the value 1 for years 2014 and beyond, and 0 for earlier years. $controls_{it}$ encompasses control variables at the regional level, while μ_i captures the regional fixed effects and δ_t accounts for the time fixed effects. α_1 measures the direct impact of the CET on CO₂ emissions in pilot provinces, and a significantly negative coefficient suggests that the policy is effective. β_1 measures the direct impact of the CET on NQP in pilot provinces, and a significantly positive coefficient indicates that the policy may enhance NQP in these regions.

H2 and H3 posit that the development of GF and ISU mediates the impact of the CET on NQP. Drawing on the research framework established by Wen and Ye [44], we formulate the following models to test this mediation mechanism.

$$Mediator_{it} = \theta_0 + \theta_1 region_i \times post_t + \theta_2 controls_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (3)$$

$$NQP_{it} = \gamma_0 + \gamma_1 region_i \times post_t + \gamma_2 Mediator_{it} + \gamma_3 controls_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (4)$$

$Mediator_{it}$ is the mediating variable, representing GF and AIS. The meanings of other variables are the same as those in the previous text. We mainly focus on the significance and direction of coefficient θ_1 in model (3), and the significance and direction of coefficients γ_1 and γ_2 in model (4).

H4 and H5 posit that LCEC moderates the relationship between the CET and NQP. Drawing on the methodology outlined by Wen and Ye [45], we develop the following models to examine the moderated mediation effects.

$$NQP_{it} = c_0 + c_1 region_i \times post_t + c_2 DECS_{it} + c_3 region_i \times post_t \times DECS_{it} + c_4 controls_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (5)$$

$$Mediator_{it} = a_0 + a_1 region_i \times post_t + a_2 DECS_{it} + a_3 region_i \times post_t \times DECS_{it} + a_4 controls_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (6)$$

$$NQP_{it} = c'_0 + c'_1 region_i \times post_t + c'_2 DECS_{it} + b_1 Mediator_{it} + b_2 DECS_{it} \times Mediator_{it} + c'_4 controls_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (7)$$

$$NQP_{it} = c'_0 + c'_1 region_i \times post_t + c'_2 DECS_{it} + c'_3 region_i \times post_t \times DECS_{it} + b_1 Mediator_{it} + b_2 DECS_{it} \times Mediator_{it} + c'_4 controls_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (8)$$

$DECS_{it}$ is a dummy variable for LCEC of province i in year t . The meanings of other variables remain consistent with those defined in the previous text. Our primary focus is on the significance and direction of coefficient c_3 in model (5), coefficients a_1 , a_2 , and a_3 in model (6), coefficients b_1 and b_2 in model (7), and coefficient c'_3 in model (8).

4.3. Variables

4.3.1. Dependent Variable

Our dependent variable is NQP. We develop an indicator system for NQP based on the three key components of productivity: laborers, labor objects, and labor materials. The specific indicators are detailed in Table 1.

Table 1. Evaluation indicator system for NQP.

One-Level Indicators	Two-Level Indicators	Three-Level Indicators	Attribute
laborers	The quality of laborers	The average years of education	positive
		The proportion of people with higher education	positive
	The employment structure of laborers	The proportion of full-time R&D personnel	positive
	The innovative and entrepreneurial ideas of laborers	The number of patent authorizations The number of start-ups	positive positive
labor object	Emerging industries	Software business revenue	positive
		Technology market transaction volume	positive
		The profit margin of high-tech industries	positive
		The number of green patents authorizations	positive
	Future industries	The number of artificial intelligence patent applications	positive
		The number of industrial robot patent applications	positive
		The greening rate of built-up areas	positive
		Industrial wastewater discharge intensity	negative
	Environmental protection	Industrial sulfur dioxide emission intensity	negative
		Industrial smoke and dust emission intensity	negative
		CO ₂ emission intensity	negative
labor materials	Production organization	The number of high-tech industry enterprises	positive
		The number of artificial intelligence enterprises	positive
		Per capita Internet broadband access ports	positive
	Digital infrastructure	The government's attention to the digital economy	positive
		The number of data exchanges	positive
		The intensity of R& D investment	positive
	Resource utilization	Energy efficiency	positive
		Electricity efficiency	positive

Laborers were measured in three dimensions: the quality of laborers, the employment structure of laborers, and the innovative and entrepreneurial ideas of laborers. The quality of laborers includes the average years of education = (number of primary school graduates $\times$ 6 + number of junior high school graduates $\times$ 9 + number of high school and vocational school graduates $\times$ 12 + number of bachelor's and above graduates $\times$ 16)/total population over 6 years old and the proportion of people with higher education = number of bachelor's and above graduates/total population over 6 years old. The employment structure of laborers was represented by the proportion of full-time R&D personnel; the innovative and entrepreneurial ideas of laborers included the number of patent authorizations and the number of start-ups.

Labor objects were evaluated from three dimensions: emerging industries, future industries, and environmental protection. Specifically, emerging industries were assessed through indicators such as software business revenue, technology market transaction vol-

ume, profit margins of high-tech industries, and the number of authorized green patents. Future industries encompassed the number of artificial intelligence patent applications retrieved by searching patent numbers according to the Reference Table for Classification of Strategic Emerging Industries and International Patent Classification (2021) (Trial). Additionally, it included the number of industrial robot patent applications obtained through a search using the following criteria: Application Date $\leq$ 31 December 2022 AND Applicant's Province = (Beijing) AND Abstract = (Industrial Robot OR Robot Arm) AND (Joint OR coordinate OR welding OR handling OR paralleling OR sorting OR assembly OR packaging OR unpacking OR unloading OR cutting OR polishing OR spraying). Environmental protection encompassed the following key indicators: the greening rate of built-up areas, industrial wastewater discharge intensity (the volume of industrial wastewater discharged per unit of GDP), industrial sulfur dioxide emission intensity (the volume of industrial sulfur dioxide emitted per unit of GDP), industrial smoke and dust emission intensity (the volume of industrial smoke and dust emitted per unit of GDP), and CO₂ emission intensity (the volume of CO₂ emitted per unit of GDP).

Labor materials were evaluated across three dimensions: production organization, digital infrastructure, and resource utilization. Production organization encompassed the number of high-tech enterprises and artificial intelligence firms. Digital infrastructure included per capita Internet broadband access points, government focus on the digital economy, and the number of data exchanges. Specifically, government focus on the digital economy was quantified by the frequency of mentions related to 121 digital economy keywords in provincial government work reports over different years, as detailed in Table 2. Resource utilization measured R&D investment intensity, energy efficiency (GDP per unit of energy consumption), and electricity efficiency (GDP per unit of electricity consumption).

The entropy weight–TOPSIS method was employed to calculate the NQP level of each province annually from 2006 to 2022. As shown in Figure 2, the national average level of NQP in China has exhibited a steady upward trend. This progression signifies continuous enhancements across provinces in areas such as talent development, technological advancement, and resource utilization efficiency.

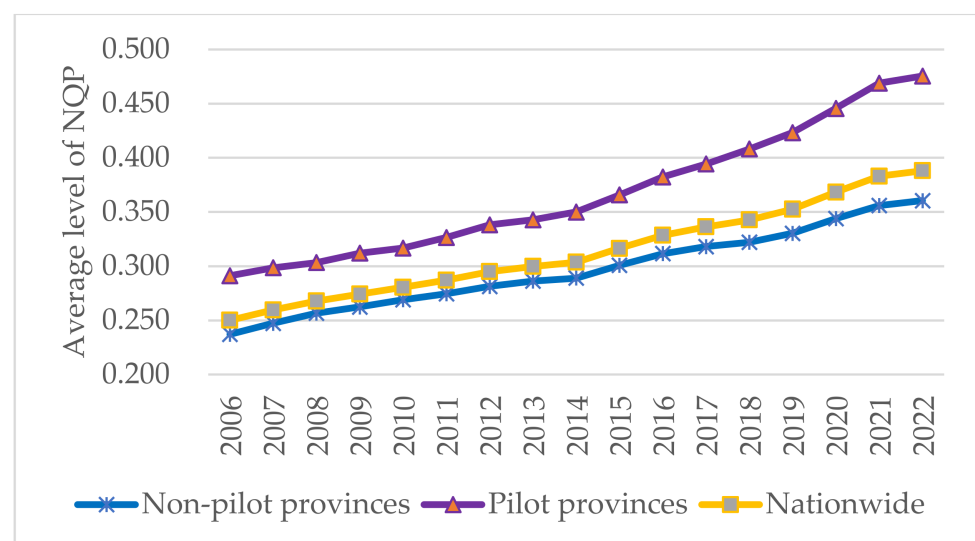


Figure 2. The average NQP in China.

Table 2. Keyword list of digital economy.

One-Level	Two-Level	Three-Level Keywords
Digital Technique	Big Data	Big data, data mining, data warehousing, heterogeneous data, augmented reality, mixed reality, virtual reality, and digital twins
	Cloud Computing	Cloud computing, streaming computing, graph computing, in memory computing, multi-party secure computing, neuromorphic computing, green computing, cognitive computing, fusion architecture, billion level concurrency, EB level storage, Internet of Things, cyber physical systems, cloud platforms, and quantum computing
	Blockchain	Blockchain, digital currency, distributed computing, differential privacy technology, and smart contracts
	Artificial Intelligence	Artificial intelligence, machine learning, mining algorithms, intelligent algorithms, robots, expert systems, virtual reality, intelligent technology, computer vision, business intelligence, decision support systems, decision assistance systems, intelligent robots, and intelligent data analysis
	Communications Technology	Network security, 4G, 5G, 6G, communication, 5G network, and satellite
	Internet of Things	Internet of things, radio frequency identification, RFID, infrared sensors, positioning systems, laser scanners, intelligent sensing, navigation systems, and mobile internet of things
Digital Applications	Industry	Industrial Internet, intelligent manufacturing, digital supply chain, intelligent supply chain, driverless car, smart home, intelligent production equipment, industrial digitalization, intelligent wear, and intelligent transportation
	Agriculture	Digital agriculture, smart agriculture, agricultural big data, agricultural big data platform, unmanned farming, and unmanned agriculture
	Service Industry	Platform Internet, smart healthcare, smart pension, unmanned bank, e-commerce, mobile payment, online entertainment, mobile Internet, Internet health, electronic trading, third-party payment, NFC payment, smart energy, B2B, B2C, C2B, O2O, Internet connection, smart medical, smart customer service, smart furniture, automatic driving, smart investment advisor, smart culture and tourism, smart environment, smart grid, unmanned retail, Internet finance, digital finance, financial technology, quantitative finance, open banking, smart warehousing, unmanned selling, digital RMB, digital economy, and information industry
	Digital Government	Digital government, smart city, smart countryside, government platform, rural big data cloud platform, data center, intelligent computing center, digital service system, government service platform, and government application system

Figure 3 presents the average NQP level of provinces during the sample period. Although NQP exhibits an overall upward trend, it also demonstrates significant regional development disparities. Specifically, the NQP levels in certain eastern coastal provinces (such as Guangdong, Jiangsu, and Zhejiang) and municipalities directly under the Central Government (such as Beijing and Shanghai) have consistently been higher than those in other regions. This disparity can be attributed to factors such as greater economic openness, industrial clustering, and higher R&D investment in these areas.

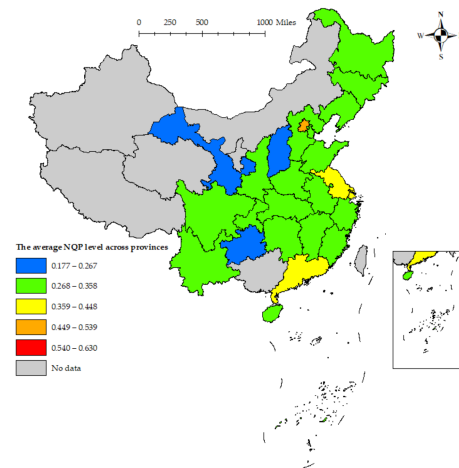


Figure 3. The average NQP level across provinces.

Figures 4–8 illustrate the NQP levels for each province in 2006, 2010, 2014, 2018, and 2022 within the sample period. From 2006 to 2010, NQP experienced a phase of steady growth, which was closely associated with the Chinese government’s evaluation metric focused solely on GDP growth rate during this period. From 2011 to 2018, NQP entered a phase of slower growth as the government shifted its focus towards economic restructuring and placed increasing emphasis on the quality of economic development. From 2019 to 2022, NQP witnessed a recovery in its growth rate, driven by the deepening implementation of green development policies. Provinces in the central and western regions, including Henan, Hubei, and Sichuan, have significantly benefited from industrial relocation and the regional coordinated development strategy. These provinces have experienced a notable increase in NQP. In contrast, the northwest provinces, including Shaanxi, have experienced persistently low NQP levels due to limitations in natural resource endowments and an underdeveloped industrial structure. This suggests that while China’s overall pattern of higher development in the east and lower development in the west remains largely unchanged, central provinces are demonstrating a clear trend of catching up, thereby gradually narrowing regional disparities.

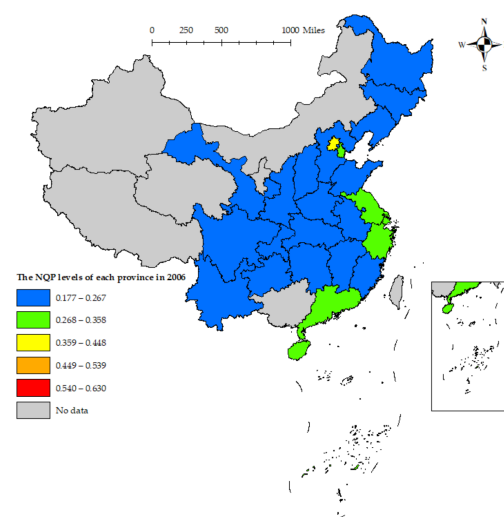


Figure 4. The NQP levels of each province in 2006.

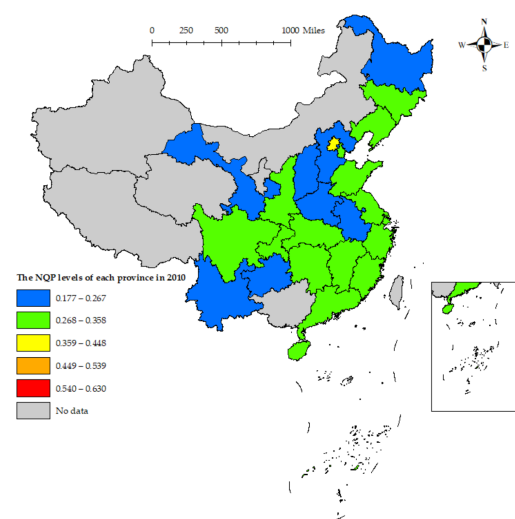


Figure 5. The NQP levels of each province in 2010.

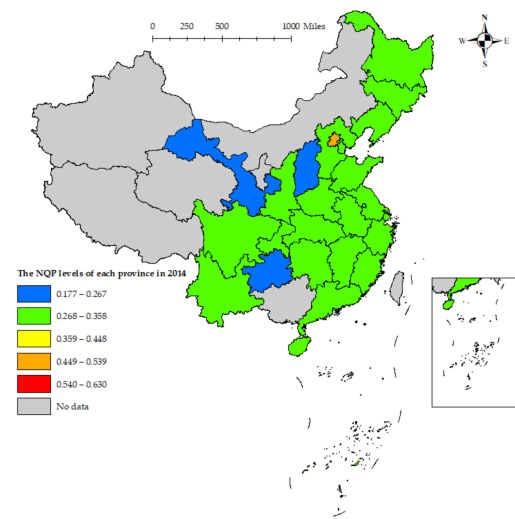


Figure 6. The NQP levels of each province in 2014.

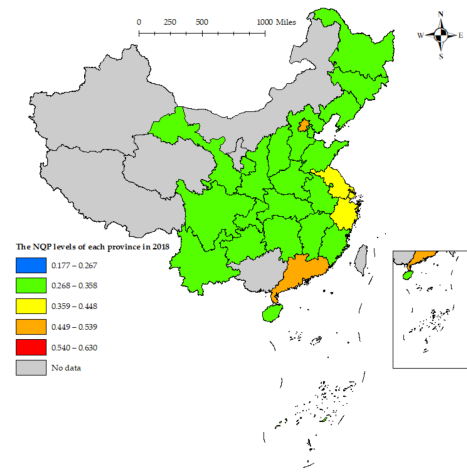


Figure 7. The NQP levels of each province in 2018.

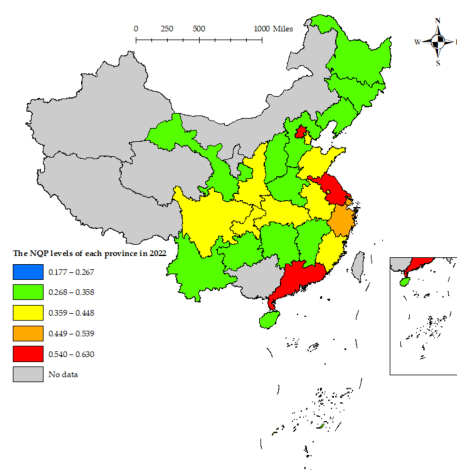


Figure 8. The NQP levels of each province in 2022.

Considering the CET, we further examined the changing trends of NQP in pilot provinces versus non-pilot provinces around 2014. We found that following the implementation of the CET, the level of NQP in pilot provinces exhibited a clear and progressively increasing trend, particularly during the middle and later stages of policy implementation. In contrast, the growth of NQP in non-pilot provinces was relatively modest. While some non-pilot provinces did experience improvements in NQP to a certain extent, these gains were generally less pronounced compared to those observed in pilot provinces. These findings suggest that there are significant differences in NQP development between pilot and non-pilot provinces, supporting the use of DID for further analysis.

4.3.2. Control Variables

We investigate whether the CET can enhance NQP in pilot areas. However, numerous factors that may influence NQP in these regions need to be controlled for accurate assessment. Government financial support (GFS), measured as the ratio of general budget expenditure to GDP, plays a crucial role. Substantial GFS typically leads to increased investment in infrastructure, scientific research and innovation, and enterprise subsidies, thereby effectively stimulating technological innovation. If both the government and enterprises re-focus on infrastructure and innovation, the long-term lag in the effects of these investments could affect the development of NQP. The intensity of environmental regulation (IER), measured as the ratio of investment in industrial pollution control to industrial added value, has a significant impact on regional sustainability. A higher IER in a given area promotes enhanced clean production and green innovation, leading to reduced emission pollution and consequently improving NQP. Population density (PD) was calculated as the ratio of the year-end resident population to the area of provincial-level administrative divisions. A higher PD can influence both energy consumption and human capital levels, ultimately impacting NQP. The level of informatization (LI) was quantified by the ratio of the total volume of postal and telecommunications services to GDP. A higher LI in a given region facilitates broader application of local e-commerce platforms, thereby more effectively aligning market demand with manufacturer production. This promotes the development and utilization of advanced data analysis and decision support tools, which in turn significantly enhances the response speed and market adaptability of enterprises. Consequently, this provides a robust micro-foundation for the development of NQP. Social consumption level (SCL) was measured by the ratio of total retail sales of consumer goods to GDP. When SCL in a certain area is high, local resources tend to be disproportionately allocated to the consumer goods sector, potentially at the expense of investment in tech-

nological research and innovation. This imbalanced resource allocation can hinder the development of NQP.

4.3.3. Mediator Variables

- GF

GF services primarily focus on projects in sectors such as environmental protection, clean energy, and green transportation. From the perspective of financial instrument application, drawing on the research of Liu et al. [46], we employed the entropy weight method to evaluate the GF level across seven dimensions: green credit, green investment, green insurance, green bonds, green subsidies, green funds, and green equity. To measure green credit, we used the proportion of loans allocated to environmental protection projects out of the total loan portfolio. Green investment was reflected by the share of investments in environmental pollution control as a percentage of GDP. For green insurance, we quantified it through the ratio of premiums from environmental pollution liability insurance to overall premium income. Green bonds were represented by the ratio of the total amount of green bond issuance to the total amount of all bond issuance. Green support was characterized by the fraction of government spending on environmental protection relative to total fiscal expenditures. Green funds were gauged by the ratio of the aggregate market value of green mutual funds to the total market value of all mutual funds. Finally, we represented the green rights and interests by the proportion of the three rights and interests, namely carbon emission rights trading, energy consumption rights trading, and pollutant discharge rights trading, in the total trading volume of the rights and interests market.

- ISU

High-quality collaboration between labor and capital is essential for ISU. To capture their roles, drawing on the research of Xia et al. [47], we employed the product of industry proportion and labor productivity, as indicated in Formula (9), as a proxy variable to measure the quality of ISU.

$$ISU = \sum_{i=1}^n \frac{Y_i}{Y} \times lp_i = \sum_{i=1}^n \frac{Y_i}{Y} \times \frac{Y_i}{L_i}, n = 3 \quad (9)$$

where Y represents output, L represents employment, i represents industry, n represents the number of industrial sectors, $\frac{Y_i}{Y}$ represents output structure, and $\frac{Y_i}{L_i}$ represents labor productivity. It is obvious that the larger the share of industries with higher labor productivity in an economy, the greater the height of its industrial structure.

4.3.4. Moderator Variable

We employed the low carbonization indicator of energy consumption structure as a proxy variable for LCEC level. Following Wan et al. [48], we first categorized the annual energy consumption of each province into three types: coal, oil and natural gas, and other energy sources. Second, we calculated the proportion of each type of energy consumption in year t for province n , forming a set of three-dimensional vectors $E_{n,t} = (e_{n,t}^1, e_{n,t}^2, e_{n,t}^3)$. Third, we computed the angles $\theta_{n,t}^1$, $\theta_{n,t}^2$, and $\theta_{n,t}^3$ between the three-dimensional vectors $E_{n,t}$ and the reference vectors $E_0^1 = (1, 0, 0)$, $E_0^2 = (0, 1, 0)$, and $E_0^3 = (0, 0, 1)$, which are arranged from high-carbon to low-carbon, as shown in Formula (10). Fourth, we weighed all vector angles for year t in province n to form the low carbonization indicator of energy

consumption structure $gec_{n,t}$, as presented in Formula (11). A higher value indicates a greater LCEC level in the province.

$$\theta_{n,t}^j = \arccos \left(\frac{\sum_{i=1}^3 (e_{n,t}^i \times e_0^i)}{\left(\sum_{i=1}^3 (e_{n,t}^i)^2 \times \sum_{i=1}^3 (e_0^i)^2 \right)^{\frac{1}{2}}} \right), j = 1, 2, 3, n = 1, 2, \dots, 25 \quad (10)$$

$$gec_{n,t} = \sum_{k=1}^3 \sum_{j=1}^k \theta_{n,t}^j \quad (11)$$

The LCEC levels of 25 provinces from 2006 to 2022 were calculated and then ranked in descending order based on their average values. For regions ranking within the top 12 in terms of high LCEC levels, DECS was assigned a value of 1; this category includes pilot areas such as Beijing, Tianjin, Shanghai, and Guangdong. For regions outside the top 12 with lower LCEC levels, DECS was assigned a value of 0; this category includes pilot areas such as Chongqing and Hubei.

5. Empirical Results

5.1. Descriptive Statistics

Table 3 presents descriptive statistics for the primary variables utilized in this study. The standard deviation of carbon emissions (CDE) is 310.0, indicating a substantial variation across provinces, which underscores the necessity to evaluate policy effectiveness. For the dependent variable NQP, there is a notable disparity between the minimum value of 0.007 and the maximum value of 0.589. The mean value of 0.100 is considerably lower than the maximum, highlighting significant inter-provincial differences in NQP and suggesting potential for overall improvement.

Table 3. Descriptive statistics.

Variable	Sample Size	Mean	Standard Deviation	Minimum	Maximum
NQP	425	0.314	0.0682	0.177	0.630
CDE	425	358.7	310.0	14.61	2146
GFS	425	0.212	0.0752	0.0870	0.465
IER	425	0.00310	0.00261	6.15×10^{-5}	0.0167
PD	425	538.4	717.3	57.91	3926
LI	425	0.0691	0.127	0.0147	2.513
SEL	425	0.381	0.0585	0.219	0.538
GF	425	0.332	0.0989	0.0782	0.632
ISU	425	11.53	6.211	2.449	37.42

5.2. Baseline Regression

Firstly, the effectiveness of the CET in reducing CO₂ emissions in pilot provinces is examined. As shown in columns (1) to (4) of Table 4, after progressively incorporating fixed effects and control variables, the coefficient of the interaction term decreases but remains significantly negative. This indicates that the CET has effectively reduced CO₂ emissions in the pilot provinces. This pilot policy is effective, and further analysis can explore whether the CET can also promote the development of NQP in these regions.

Table 4. Policy effectiveness and baseline regression results.

Variable	Policy Effectiveness				Baseline Regression			
	(1) CDE	(2) CDE	(3) CDE	(4) CDE	(5) NQP	(6) NQP	(7) NQP	(8) NQP
region × post	−159.136 *** (28.019)	−99.960 *** (18.254)	−93.876 *** (17.050)	−82.913 *** (18.685)	0.113 *** (0.013)	0.035 *** (0.007)	0.033 *** (0.007)	0.030 *** (0.007)
GFS			−23.813 (220.206)	−44.162 (226.919)			−0.109 *** (0.039)	−0.110 *** (0.039)
IER			−13,584.062 * (6991.813)	−13,151.086 * (6997.321)			1.140 ** (0.501)	1.077 ** (0.506)
PD				−0.109 ** (0.052)				0.000 (0.000)
LI				−23.461 ** (11.500)				0.007 *** (0.003)
SEL				−91.843 (147.430)				−0.025 (0.024)
_cons	378.895 *** (16.670)	−11.698 (36.193)	58.300 (54.851)	221.742 ** (102.580)	0.299 *** (0.003)	0.406 *** (0.008)	0.417 *** (0.011)	0.399 *** (0.034)
Fixed Effects	N	Y	Y	Y	N	Y	Y	Y
Sample Size	425	425	425	425	425	425	425	425
R-squared	0.029	0.852	0.857	0.858	0.306	0.909	0.912	0.912

Note: ***, **, and *, respectively, indicate significance at the 1%, 5%, and 10% levels, with robust standard errors in parentheses, N represents NO, and Y represents YES; the same applies below.

The baseline regression results are presented in columns (5) to (8) of Table 4. Column (5) illustrates the average effect of the CET on NQP in pilot provinces without controlling for any variables or fixed effects. The coefficient of the interaction term is 0.113 and is significant at the 1% level. Building upon column (5), column (6) introduces time and region fixed effects to control for omitted variables that vary over time or by region, resulting in a reduced interaction term coefficient of 0.035, which remains significant at the 1% level. Further expanding on column (6), column (7) incorporates GFS and IER, leading to a further reduction in the interaction term coefficient to 0.033, which is still significant at the 1% level. Based on column (7), column (8) controls for the PD, LI, and SEL. The coefficient of the interaction term decreases to 0.030 and remains significant at the 1% level. The diminishing regression coefficients as additional control variables are incorporated and suggest that these control variables might attenuate the relationship between the core independent variable and the dependent variable. This implies a potential correlation between the control variables and the core independent variable. However, the regression results remain significantly positive, indicating that the CET can substantially enhance NQP in the pilot provinces. Therefore, Hypothesis H1 is supported.

5.3. Parallel Test

We employed the DID to evaluate the impact of the CET on NQP in pilot provinces. However, applying the DID requires satisfying the key assumption that there are no substantial differences in NQP levels between pilot and non-pilot provinces prior to the CET implementation. While the previous text provides preliminary evidence suggesting parallel trends in NQP changes between pilot and non-pilot provinces before CET implementation, it remains essential to utilize the event study method proposed by Jacobson et al. [49] and construct the following model for further testing.

$$NQP_{it} = \beta_0 + \sum_{t=2006}^{2022} \beta_t \text{region}_i \times \gamma_t + \beta_2 \text{controls}_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (12)$$

Using 2014 as the baseline year for policy implementation, β_t represents a sequence of estimated values from 2006 to 2022, while other variables retain their original meanings. To mitigate multicollinearity, data from 2013 were excluded from the regression analysis. The results presented in Figure 9 indicate that there was no significant difference in NQP

between pilot and non-pilot provinces prior to the policy implementation. Following the policy implementation, the coefficient of the interaction term remained positive but insignificant for the first three years. It was not until the fourth year that this coefficient became significantly positive, suggesting that after an initial adjustment period, the positive impact of the CET on NQP gradually intensified.

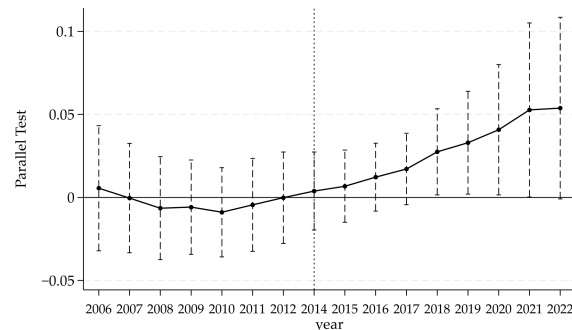


Figure 9. Parallel test of NQP.

5.4. Robust Test

5.4.1. Endogenous Problem

Although the implementation of the CET is a quasi-natural experiment and there is no reverse causal relationship between the CET and NQP, the possibility of biased regression results due to omitted variables still cannot be excluded. In March 2011, the “Twelfth Five-Year Plan Outline” first proposed “gradually establishing a carbon emissions trading market”. To ensure the robustness of the conclusion, referring to the study of Jacobson [50], the average ventilation coefficient (tf) across provinces from 2000 to 2010 was used as an instrumental variable. Given the large magnitude and cross-sectional nature of the data, we transformed the variables by taking their logarithms and interacting them with a time dummy variable to construct panel data (tf). The ventilation coefficient, defined as the product of wind speed and the height of the mixing layer, serves as an instrumental variable in our analysis. The CET is a market-based environmental regulation tool designed to control CO₂ emissions from enterprises. Provinces with lower ventilation coefficients tend to have higher concentrations of CO₂, making them more likely to be targeted under the CET, thereby supporting the relevance assumption of the instrumental variable. The ventilation coefficient is determined by geographical and meteorological conditions, which are not directly influenced by enterprises’ responses to the CET, thus satisfying the exogeneity assumption of the instrumental variable.

The instrumental variable regression results are presented in columns (1) and (2) of Table 5. The first-stage regression indicates that the coefficient of the interaction term ($tf \times post$) is significantly negative at the 1% level, with an F-statistic well above the critical value, confirming that the instrumental variable satisfies the relevance condition. The second-stage regression results show that the instrumental variable passes the unidentifiable test, and the coefficient of the interaction term ($tf \times post$) is 0.051, which is significant at the 1% level. This suggests that after addressing potential endogeneity issues due to omitted variables, the CET continues to significantly increase NQP in the pilot provinces. Therefore, Hypothesis H1 is supported.

Table 5. Robustness testing.

Variable	Instrumental Variable Method		PSM-DID	Placebo Test
	(1) region $\times$ post	(2) NQP	(3) NQP	(4) NQP
tf $\times$ post	−0.467 *** (0.086)			
region $\times$ post		0.051 *** (0.015)	0.039 ** (0.019)	0.002 (0.004)
_cons	−1.664 *** (0.463)	0.428 *** (0.031)	0.499 *** (0.048)	0.468 *** (0.028)
F-statistic	29.73 ***		-	-
Unidentifiable Test	26.683 ***		-	-
Control Variables and Fixed Effects	Y	Y	Y	Y
Sample Size	425	425	129	125
R-squared	---	0.9091	0.916	0.988

Note: ***, and **, respectively, indicate significance at the 1%, and 5% levels.

5.4.2. PSM-DID

Due to the heterogeneity in regional development, direct comparisons between pilot and non-pilot provinces may not be appropriate. To ensure that the treatment group provinces are matched with similar control group provinces and to minimize sample selection bias, we employed 3-Nearest Neighbor Matching. The matching outcomes are presented in Table 6. According to Table 6, the absolute values of the standard deviations for the matched control variables are all less than 20%, and the corresponding t-values are not statistically significant. This indicates that after propensity score matching, the differences in these variables between the treatment and control group provinces are not statistically significant. In other words, there are no significant differences in these variables between the sample provinces, indicating that the sample provinces have successfully passed the balance test. The regression outcomes of the PSM-DID are displayed in column (3) of Table 5. The coefficient of the interaction term is 0.039, which is significant at the 5% level, indicating that the CET has significantly enhanced NQP in the pilot provinces. Therefore, Hypothesis H1 is supported.

Table 6. Results of balance test for control variables.

Variable	Matching	Mean Value		Standard Deviation (%)	Reduction in Standard Deviation (%)	t-Statistics	
		Experimental Group	Control Group			t	p> t
DGI	Before	0.19763	0.2146	−28.0	47.2	−1.55	0.121
	After	0.19631	0.18734	14.8		1.09	0.278
IER	Before	0.00166	0.00331	−76.0	94.5	−4.43	0.000
	After	0.0017	0.00161	4.2		0.34	0.731
PD	Before	1297.6	427.86	91.7	85.3	9.09	0.000
	After	1143.5	1015.4	13.5		0.59	0.558
LI	Before	0.06023	0.07035	−10.2	58.2	−0.55	0.585
	After	0.05953	0.05531	4.2		0.55	0.580
SEL	Before	0.41076	0.37648	47.2	79.1	4.10	0.000
	After	0.40973	0.4169	−9.9		−0.45	0.653

5.4.3. Placebo Test

We employed the counterfactual method to rigorously test a common trend between pilot provinces and non-pilot provinces. Specifically, we assumed that the CET was implemented in 2010 and constructed corresponding dummy variables for regression analysis.

If the coefficient of the interaction term is insignificant under this false policy assumption, it suggests that a common trend exists between the treatment and control groups, thereby confirming that changes in NQP are attributable to the CET rather than other factors. Conversely, if the coefficient of the interaction term is significant under the false policy assumption, it implies that the results may not be robust. Additionally, to minimize potential interference from the CET, we restricted the sample period to 2006–2010. The regression results of the placebo test are presented in column (4) of Table 5. The coefficient of the interaction term is 0.002 and statistically insignificant, suggesting that pilot provinces and non-pilot provinces exhibited similar trend characteristics prior to the policy implementation. This finding reinforces that the changes in NQP are likely attributable to the CET.

5.4.4. Other Robustness Test

The preceding analysis used the entropy weight–TOPSIS method to calculate NQP, refining the traditional entropy weight method. Here, we recalculated NQP using the basic entropy weight method for comparison. The regression results presented in column (1) of Table 7 indicate that the coefficient of the interaction term is 0.052, which is significant at the 1% level. Considering the challenges posed by the 2008 international financial crisis to China, including a decrease in exports, a deceleration of economic growth, the closure of enterprises, and intensified employment pressure, we excluded the samples from 2008 and 2009 to eliminate the uncertain influence of these extraordinary years on the research findings. The regression results are presented in column (2) of Table 7. Because the NQP of pilot provinces may be influenced by other policies, such as the water industry policy and the GF policy, we excluded samples from provinces piloting both the water industry policy (Hubei) and the GF policy (Guangdong). The results presented in columns (3) to (4) of Table 7 indicate that the coefficient of the interaction term remains significantly positive, thereby corroborating the robustness of our findings.

Table 7. Other robustness test.

Variable	(1) Entropy Weight Method	(2) Exclude Abnormal Years	(3) Water Industry Policy	(4) GF Policy
region × post	0.052 *** (0.013)	0.029 *** (0.007)	0.011 * (0.006)	0.011 *** (0.004)
_cons	0.182 *** (0.068)	0.402 *** (0.042)	0.404 *** (0.030)	0.403 *** (0.028)
Control Variables and Fixed Effects	Y	Y	Y	Y
Sample Size	425	375	340	408
R-squared	0.856	0.913	0.938	0.941

Note: ***, and *, respectively, indicate significance at the 1%, and 10% levels.

5.5. Mediating Effect

The analysis demonstrates that the CET can effectively enhance the NQP in pilot provinces. However, further research is required to elucidate the specific impact pathways. To this end, regression analyses were performed on models (3) and (4) to examine whether the CET improves NQP in pilot regions via GF and ISU. The regression outcomes are displayed in Table 8. To improve the comparability and interpretability of the data, the two mediator variables were standardized prior to the regression analysis.

Table 8. Mediating effect.

Variable	GF		ISU	
	(1) GF	(2) NQP	(3) ISU	(4) NQP
region $\times$ post	0.053 ** (0.026)	0.029 *** (0.007)	0.319 *** (0.064)	0.023 *** (0.008)
GF		0.026 *** (0.007)		
ISU				0.022 *** (0.007)
_cons	−1.468 *** (0.156)	0.438 *** (0.035)	−0.729 * (0.374)	0.415 *** (0.031)
Control Variables and Fixed Effects	Y	Y	Y	Y
Sample Size	425	425	425	425
R-squared	0.984	0.915	0.948	0.918

Note: ***, **, and *, respectively, indicate significance at the 1%, 5%, and 10% levels.

The first two columns examine the mediating effect of GF. In column (1), the regression coefficient of the interaction term is 0.053, significant at the 5% level, suggesting that the CET positively influences regional GF development. In column (2), the regression coefficients for the interaction term and for GF are 0.029 and 0.026, respectively, which are both significant at the 1% level. This indicates that GF partially mediates the relationship between the CET and NQP, with a mediating effect of 0.001378 (0.053×0.026). Under the CET, financial institutions leverage well-established financial instruments to facilitate the development of green industries by raising funds for green technology innovation and sharing innovation risks. This enhances the alignment between investment supply and demand, improves fund allocation efficiency, and promotes the transition of the economic structure towards a sustainable circular economy, gradually enhancing NQP.

The last two columns examine the mediating effect of ISU. The interaction term in column (3) has a regression coefficient of 0.319, which is significant at the 1% level, indicating that the CET has a positive effect on promoting ISU in the region. In column (4), the regression coefficients for the interaction term and ISU are 0.023 and 0.022, respectively, which are both significant at the 1% level. This suggests that ISU partially mediates the relationship between the CET and NQP, with a mediating effect of 0.007018 (0.319×0.022). Under the CET, low-carbon technological innovation has significantly enhanced resource utilization efficiency. Resources will naturally be allocated to enterprises with higher resource utilization rates through trading mechanisms, while those with lower rates will be phased out of the market, thereby fostering ISU. ISU represents a transformative process from quantitative improvements to qualitative advancements, characterized by enhancements in labor quality, increased investment in R&D, and the introduction of high-quality products. These developments are indicative of NQP.

5.6. Moderating Effect

Firstly, we utilized grouped regression analysis to assess the impact of the CET on NQP, GF, and ISU across regions with varying levels of LCEC. The regression results are summarized in Table 9. In pilot areas characterized by lower LCEC levels, the CET significantly improves local NQP, GF, and ISU. In contrast, in pilot areas with higher LCEC levels, the CET demonstrates a more pronounced positive effect on NQP, a reduced positive effect on ISU, and an insignificant negative effect on GF.

Table 9. Moderating effect.

Variable	Low LCEC Level			High LCEC Level		
	(1) NQP	(2) GF	(3) ISU	(4) NQP	(5) GF	(6) ISU
region × post	0.014 *** (0.003)	0.152 *** (0.036)	0.410 *** (0.047)	0.041 *** (0.012)	−0.053 (0.036)	0.253 ** (0.113)
_cons	0.109 *** (0.035)	−2.118 *** (0.644)	−2.142 *** (0.646)	0.470 *** (0.034)	−1.816 *** (0.176)	−0.633 (0.543)
Control Variables and Fixed Effects	Y	Y	Y	Y	Y	Y
Sample Size	221	221	221	204	204	204
R-squared	0.971	0.983	0.950	0.908	0.988	0.946

Note: ***, and **, respectively, indicate significance at the 1%, and 5% levels.

Secondly, we employed models (5) to (8) to investigate the moderating effect of LCEC on both direct and mediating effects. The regression outcomes are displayed in Table 10. To mitigate multicollinearity concerns, it is essential to center continuous variables, specifically the mediator variables. Given that the previous section has already standardized these variables, resulting in a mean of zero for the mediators, no further adjustments are necessary in this section. Column (2) examines the impact of the interaction term (region×post×DECS) between the LCEC dummy variable and the core independent variable on NQP. The findings indicate that the coefficient of the interaction term is 0.033, significant at the 1% level, while the coefficient of the core independent variable is 0.013, also significant at the 1% level. This suggests that LCEC enhances the positive relationship between the CET and NQP, indicating a significant positive moderating effect of LCEC. Therefore, H4 is supported, and a moderated mediation model can be considered for further analysis.

Table 10. Moderated mediating effect.

Variable	Conditional Test		Mediator Variable: GF			Mediator Variable: ISU		
	(1) NQP	(2) NQP	(3) GF	(4) NQP	(5) NQP	(6) ISU	(7) NQP	(8) NQP
region × post	0.030 *** (0.007)	0.013 *** (0.004)	0.167 *** (0.027)	0.031 *** (0.007)	0.018 *** (0.004)	0.355 *** (0.042)	0.027 *** (0.008)	0.019 *** (0.005)
DECS		0.174 *** (0.026)	−1.013 *** (0.162)	0.216 *** (0.024)	0.232 *** (0.026)	−0.596 * (0.329)	0.208 *** (0.019)	0.215 *** (0.020)
region × post × DECS		0.033 *** (0.012)	−0.214 *** (0.045)		0.023 ** (0.012)	−0.068 (0.113)		0.014 (0.011)
GF				0.009 (0.007)	0.015 ** (0.007)			
GF × DECS				0.027 *** (0.006)	0.024 *** (0.005)			
ISU							0.004 (0.008)	0.005 (0.007)
ISU × DECS							0.020 *** (0.004)	0.018 *** (0.004)
_cons	0.399 *** (0.034)	0.252 *** (0.012)	−0.631 *** (0.104)	0.283 *** (0.012)	0.284 *** (0.012)	−0.189 (0.184)	0.262 *** (0.010)	0.262 *** (0.010)
Control Variables and Fixed Effects	Y	Y	Y	Y	Y	Y	Y	Y
Sample Size	425	425	425	425	425	425	425	425
R-squared	0.912	0.915	0.985	0.922	0.923	0.948	0.926	0.926

Note: ***, **, and *, respectively, indicate significance at the 1%, 5%, and 10% levels.

Column (3) shows how LCEC influences the connection between the CET and the advancement of GF, as shown in model (6). The coefficient (a_1) is 0.167 and significant at the 1% level. The coefficient (a_2) is −1.013 and significant at the 1% level. The coefficient (a_3) is −0.214 and significant at the 1% level. These results suggest that LCEC reduces the positive impact of the CET on the development of GF. Most pilot provinces exhibit a high level of LCEC, and the positive effect of the CET on GF in pilot provinces with low

LCEC levels is negated, resulting in an overall weakening effect. Column (4) examines how LCEC affects the relationship between GF development and NQP, as described in model (7). The coefficient (b_1) is 0.009 but not statistically significant, whereas the coefficient (b_2) is 0.027 and significant at the 1% level. Column (5) examined the moderating effect of LCEC on both the direct and indirect effects between the CET and NQP, as outlined in model (8). The coefficient (c'_3) is 0.023 and significant at the 1% level, satisfying the model in Figure 10. Where $a_1b_2 \neq 0$ and $a_3b_2 \neq 0$, thereby rejecting the null hypothesis that the mediating effect is non moderating. It can be concluded that LCEC simultaneously moderates both paths before and after the mediating process. Specifically, in the mediating process through which the CET impacts NQP via the development of GF, the indirect moderating effect of LCEC is -0.001269 ($0.167 \times 0.027 - 0.214 \times 0.027$), while the direct moderating effect is 0.023.

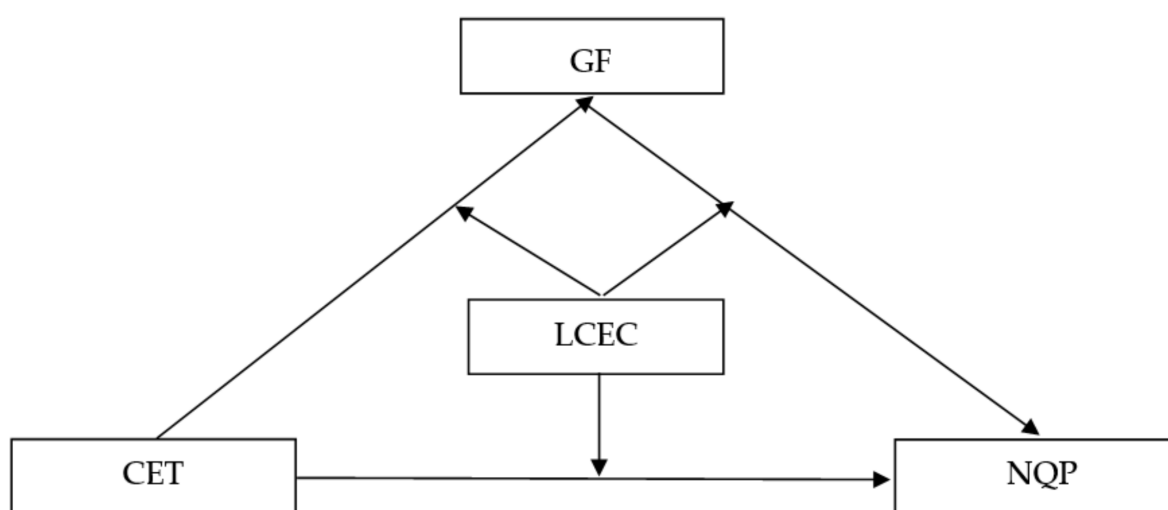


Figure 10. Moderating the path before and after the mediating process and the direct path.

Column (6) shows how LCEC influences the connection between the CET and ISU, as shown in model (6). The coefficient (a_1) is 0.355 and significant at the 1% level. The coefficient (a_2) is -0.596 and significant at the 10% level. However, the coefficient (a_3) is -0.068 and not statistically significant, indicating that LCEC does not moderate the relationship between the CET and ISU. Most pilot provinces exhibit a high level of LCEC. However, the positive promotion effect of the CET on ISU in pilot provinces with high LCEC is weaker compared to its effect in provinces with low LCEC, leading to an insignificant moderating effect. Column (7) examines how LCEC affects the relationship between ISU and NQP, as described in model (7). The coefficient (b_1) is 0.004 but not significant, while the coefficient (b_2) is 0.020 and significant at the 1% level. Column (8) examined the moderating effect of LCEC on both the direct and indirect effects between the CET and NQP, as outlined in model (8). The coefficient (c'_3) is 0.014 but not statistically significant, which satisfies the model in Figure 11. Where $a_1b_2 \neq 0$, thereby rejecting the null hypothesis that the mediating effect is non moderating. It can be concluded that LCEC simultaneously moderates both paths before and after the mediating process. Specifically, in the mediating process through which the CET impacts NQP via ISU, the indirect moderating effect of LCEC is 0.0071 (0.355×0.020), and there is no direct moderating effect.

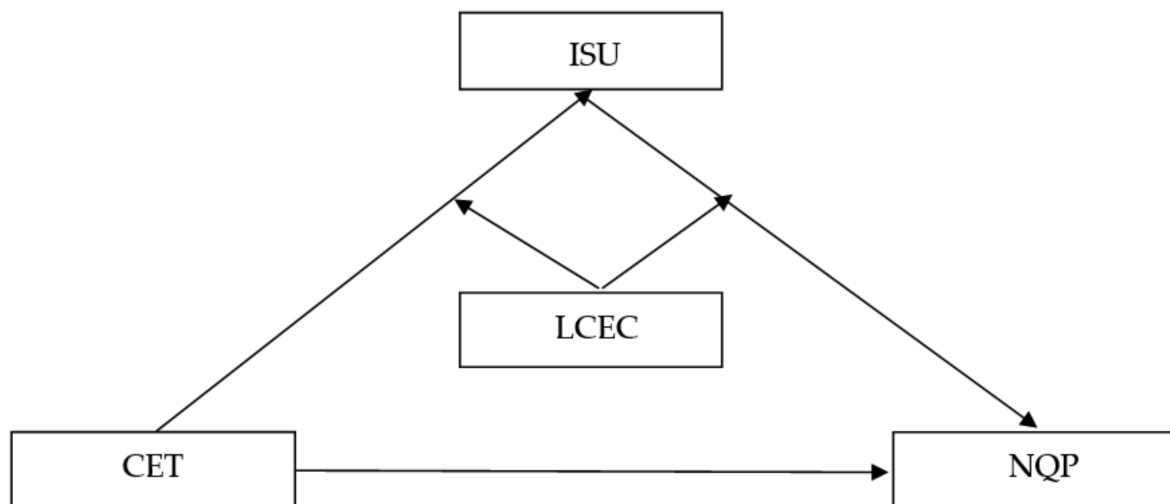


Figure 11. Moderating the path before and after the mediating process.

6. Discussion

This study is undertaken during the strategic transformation period of China’s ecological civilization construction and systematically investigates the intricate mechanisms between environmental regulation tools and new development drivers. Under the new development paradigm driven by the “dual carbon” goals, NQP, as a composite form of productivity that integrates digital technology innovation, green technology diffusion, and industrial ecological reconstruction, has emerged as a critical driver for high-quality economic development. Against this backdrop, we developed a theoretical framework encompassing an environmental regulation policy, transmission mechanisms, and a moderating tool, attempting to reveal the core issues at three progressive levels: First, can market incentive-based environmental regulation tools, such as the CET, break through the limitations of the traditional “compliance cost theory” and significantly enhance regional NQP levels by stimulating the Porter effect? Second, is there a dual transmission path of GF and ISU for this impact? Third, as an indicator of regional low-carbon energy utilization capacity, does LCEC play a moderating role between the CET and NQP? Based on the above questions, we have identified several significant findings.

The development of NQP in China exhibits characteristics of spatial differentiation. This study’s analysis of the visualized spatial development trend of NQP shows that although the overall development level of NQP in China is on the rise, the “east–west gradient gap” still constitutes the main issue in spatial evolution. This finding confirms the validity of the “core–periphery” theory in economic geography in the context of productivity and reveals new manifestations of regional development imbalance. Relying on mature industrial carriers, such as the digital economy belt in the Yangtze River Delta and the advanced manufacturing clusters in the Pearl River Delta, the eastern region has constructed a positive cycle system of “innovation factor agglomeration–knowledge spillover–industrial upgrading” [51]. Moreover, the institutional potential difference formed by the free trade pilot zones and the independent innovation demonstration zones further catalyzes the formation of innovation consortia between transnational R&D centers and local unicorn enterprises [52] and accelerates technological iteration through Jacobs externalities. These factors have successfully promoted the NQP in the eastern region to exhibit the characteristics of increasing returns to scale. In contrast, although the western region possesses the advantage of energy endowment, it faces the dual dilemmas of the “resource curse” and the “innovation fault” due to the loss of human capital and the shortage of venture capital and naturally falls into the “low-level equilibrium trap”. Therefore, the “east–west

gradient gap” essentially reflects the development generation gap of the regional economic system in dimensions such as institutional innovation, factor allocation, and technological transformation. It reveals the dual embeddedness of the evolution of productivity. That is, the development of productivity is embedded not only in a specific socio-economic institutional environment but also in a specific technical system and the process of technological development. Moreover, it proves the theory that “New Quality Productivity is the cornerstone of high-quality economic development”.

Market incentive-based environmental regulation tools are conducive to the leapfrogging of China’s productivity. The effect of the CET on the promotion of NQP confirmed in this study (with an average treatment effect of 0.030) strongly supports the Porter Hypothesis [53], which means that well-designed environmental regulatory measures can achieve the “innovation compensation effect” by forcing enterprises to innovate. Specifically, the CET prompts enterprises to reassess the environmental externalities in the production process by internalizing the carbon emission costs, thereby enhancing regulatory compliance awareness and promoting green investment decisions [54]. To reduce production costs and maximize profits, enterprises can choose technological innovation [55] or improve energy efficiency [56] to reduce the cost of purchasing carbon quotas. In addition, when there is a surplus of carbon quotas, enterprises can also obtain economic benefits by selling them [57]. This “dual incentive” framework not only significantly improves the total factor productivity of enterprises [58] but also screens out more adaptable low-carbon enterprises through market competition [59], ultimately achieving the low-carbon adjustment of the overall industrial structure [60]. The dynamic efficiency of this market incentive-based environmental regulation tool (the policy effect of the CET increases year by year) echoes the theory of “New Structural Economics”, demonstrating how the carbon pricing mechanism reshapes the role and decision-making of micro-subjects in the production stage to guide the change in overall productivity.

The path effects of market incentive-based environmental regulation tools in driving productivity transformation exhibit disparities. Based on the empirical test of the transmission paths, it is found that GF and ISU are the two core paths through which the CET acts on NQP, but there is a difference in magnitude between them: the effect of ISU is 5.09 times that of GF. This differential transmission effect can be systematically explained by the theoretical framework of the “technology–institution complex” [61]. Specifically, GF guides capital to agglomerate in low-carbon technology research and development [62] and renewable energy projects [63] through the carbon pricing signaling effect, forming the initial innovation incentive of the “GF accelerator”. However, this path is constrained by the dilemma of the “valley of death” in the technological innovation cycle [64]. Its promoting effect mainly focuses on the capital supply in the research and development stage and fails to effectively integrate the whole process of technological commercialization and industrial application. In contrast, ISU constructs the driving force for systematic change through the mechanism of “production network externality” [65]. The CET, in this context, not only promotes the transformation of the regulated industry itself but also generates an innovation spillover effect through the connection of the industrial chain (for example, the low-carbon technology innovation of upstream enterprises forces downstream enterprises to upgrade their technologies). Eventually, it realizes the reconstruction of the industrial ecosystem from a high-carbon industry lock-in to a low-carbon technology-intensive one. This coordinated transformation of the entire industrial chain breaks through the limitations of a single technological path and forms an institutional driving force for continuously improving the level of NQP.

The transmission mechanism through which market incentive-based environmental regulation tools act on productivity transformation exhibits significant characteristics of

dependence on the energy consumption structure. This study finds that the moderating effect of LCEC on the CET confirms the limitations of a single policy tool. As revealed by the initial practices of the European Union Emissions Trading System, simply relying on the carbon pricing mechanism while lacking investment in supporting energy infrastructure poses a challenge to breaking through the existing lock-in effect of the high-carbon structure [66]. The internal mechanism of this structural constraint lies in the fact that a higher level of LCEC not only represents the systematic mitigation of regional carbon emission risks [67] but also reflects the maturity index of the low-carbon industrial system. It specifically covers dimensions such as supporting infrastructure, technological innovation capabilities, and project development qualifications, thus essentially constituting the dual advantages of the agglomeration of green capital and the development of industrial clusters. Against this backdrop, the CET can form a positive reinforcement mechanism in regions with LCEC advantages: through market transmission, the carbon price signal can directionally guide the flow of financial capital and innovation factors towards the decarbonization field, thereby forming a synergistic effect between the enhancement of the driving force for energy transformation [68] and the development of NQP. This transmission path is highly congruent with the three-dimensional framework for sustainable development proposed by Grubb [69], which emphasizes the dynamic coordination of the three dimensions of institutional norms, market mechanisms, and technological innovation. Notably, LCEC significantly enhances the intermediary transmission efficiency of ISU by strengthening the technological foundation of emerging industries. A typical example can be seen in the transformation practice of Shandong Province in China. As an important energy consumer and carbon emitter in China, the province has, through the strategic coordination of the CET and clean energy development, successfully cultivated high-end manufacturing industrial clusters covering advanced nuclear power equipment, large-scale offshore wind power equipment, etc. Meanwhile, it has reduced its dependence on coal, achieving a paradigm shift from a high-carbon economy to green growth.

In the process of exploring the mechanism of the CET's influence on NQP, although this study has constructed a relatively complete theoretical analysis framework, several deep-seated methodological dilemmas and epistemological limitations still need to be faced. As a multi-dimensional and dynamic composite concept, the ontological boundary of NQP has significant characteristics of an interdisciplinary nature and spatial-temporal heterogeneity, which leads the existing research to fall into the "simplification paradox" in the construction of the indicator system. Although the measurement feasibility is achieved through dimensionality reduction, it inevitably results in the deconstruction of the complexity of reality through theoretical abstraction. The evolution process of NQP displays typical characteristics of a complex adaptive system, and its nonlinear evolution trajectory forms a fundamental tension with the static structure of the indicator system. Although the currently constructed indicator system can capture the structural characteristics at a specific point in time, it shows a substantial decrease in explanatory ability when dealing with discontinuous changes, such as innovation emergence and path transitions. In the future, the measurement of NQP can start with the analytical paradigm of evolutionary economics. By introducing a dynamic stochastic general equilibrium model of the production function, endogenous variables such as the diffusion of technological innovation and the elasticity of institutional change can be incorporated into the generation function of NQP. This methodological shift can not only effectively capture the nonlinear interaction between elements but also provide a quantitative basis for the counterfactual simulation of policy interventions. At the same time, it is recommended to construct a three-level linkage estimation model at the provincial, municipal, and county level while maintaining the benchmark framework of provincial panel data. This multi-granular

analysis method can not only mitigate the risk of ecological fallacy but also enhance the robustness of research conclusions through multi-level verification.

7. Conclusions and Policy Implications

Under the background of the strategic transformation towards the “dual carbon” goals, this study breaks through the paradigm of element aggregation in traditional productivity research. By constructing a comprehensive evaluation system of new quality productivity (NQP) that incorporates elements of high-quality development, it reveals the dilemma of unbalanced NQP development between the eastern and western regions of China. Meanwhile, by combining the difference in differences model (DID) with mediating and moderating effect tests, it unveils the deep-seated relationship between China’s carbon emissions trading pilot policy (CET) and productivity leapfrogging.

The main conclusions are as follows: (1) The CET significantly enhances the NQP level in pilot provinces, and the policy effect shows a year-on-year increasing trend. This finding validates the core role of market incentive-based environmental regulation tools in driving the transformation of the productivity paradigm. It provides an empirical basis for constructing a paradigm of coordinated environmental and economic development with Chinese characteristics. (2) During the process of the CET acting on NQP, the differential effects of the two transmission paths, namely green finance (GF) and industrial structure upgrading (ISU), provide a basis for path selection to address the “low-carbon transformation paradox”. That is, to achieve green and high-quality development, it is necessary to prioritize the coordinated transformation of the entire industrial chain rather than financing for a single technology. (3) The multi-dimensional threshold effects of low-carbon energy consumption (LCEC) in policy transmission (on the one hand, directly enhancing the marginal effect of the CET on NQP, and on the other hand, amplifying the mediating efficiency of ISU by strengthening the technological foundation) demonstrate the limitations of a single policy tool. The carbon market needs to resonate with the reform of the energy system to realize its maximum potential, providing empirical support for constructing a trinity policy framework of “regulation–market–technology” for low-carbon transformation.

Based on the above conclusions, we propose the following policy recommendations for the Chinese government.

First, improve the carbon trading market mechanism. The government needs to implement differentiated quota allocations according to the characteristics of the “energy-economy” dual structure between the eastern and western regions. For regions in the east with strong industrial foundations, the government should implement a quota reduction system to encourage enterprises to accelerate technological innovation and industrial upgrading, and establish a supporting ecological compensation fund for industrial transfer. For resource-based regions in the west, the government should set a policy buffer period of a certain number of years and allow them to direct part of the carbon quota proceeds to the introduction of clean technologies.

Second, construct the “GF–ISU” collaborative path. Considering that GF can provide start-up funds for ISU, ISU can amplify the marginal benefits of GF. When developing NQP, the government can establish a targeted financing mechanism to guide funds to flow into the research and development of low-carbon technologies and high-end manufacturing. Through GF means, such as interest subsidies and guarantees, the government can reduce the costs of industrial transformation and improve the overall total factor productivity. The government can also give priority support to strategic industries, such as smart grids and new energy sources, by establishing a green technology database and a financing

whitelist, forming a closed loop of “technological breakthrough–industrial upgrading–capital appreciation–productivity transformation”.

Third, strengthen the “threshold amplifier” function of LCEC. When constructing the “GF–ISU” collaborative path, the government needs to embed the LCEC compliance rate into the GF standard system. It should provide subsidized loans and tax credits for LCEC-related projects, including clean energy technology R&D and smart grid renovation, to guide GF to precisely nourish the low-carbon industrial chain. The government also needs to rely on the carbon market to establish a “carbon price–LCEC–green technology” data center to dynamically optimize the matching degree of key areas between GF and ISU, and promote the diffusion of key LCEC technologies, such as hydrogen energy storage, to the entire industrial chain to form a closed loop of “financial empowerment–industrial upgrading–energy reshaping”.

Fourth, construct a collaborative development index of NQP–CET to quantify policy effectiveness. To ensure the precise implementation of the above policy recommendations of “regulatory tool–financial empowerment–industrial upgrading–energy reshaping”, when constructing the collaborative development index, the government can consider indicators such as the implementation efficiency of regional differentiated quotas, the GF–ISU collaborative multiplier, and the LCEC technology diffusion rate. The government can dynamically identify the regional policy adaptation deviations between the eastern and western regions according to the heat map of policy effectiveness to adjust the development strategies of the eastern and western regions in a timely manner.

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